California Environmental Protection Agency

Air Resources Board

LOCATION:
San Diego Marriott Del Mar
Grand Ballroom
11966 El Camino Real
San Diego, California 92130

This facility is accessible by public transit. For transit general information (619) 233-3004 or 1-800-266-6883, website http://www.sdcommute.com/agencies/MTS/SDTC/index.asp

(This facility is accessible to persons with disabilities.)

PUBLIC MEETING AGENDA

TO SUBMIT WRITTEN COMMENTS ON AN AGENDA ITEM IN ADVANCE OF THE MEETING GO TO:
http://www.arb.ca.gov/lispub/comm/bclist.php

May 24, 2007
9:00 a.m.

Item #

07-5-1: Report to the Board on a Health Update: Women and Air Pollution Impacts

A number of new studies in California and nationwide have shown that elderly women may be particularly sensitive to the impacts of air pollution. ARB's Research Program is also funding new studies to provide information on some of the unanswered questions on the role of air pollution in women's health. This health update will review the effects of long term air pollution exposure in women which results in increased cardiovascular disease and deaths in this newly discovered vulnerable population.

07-5-4: Public Meeting to Consider the Draft Planned Air Pollution Research, Fiscal Year 2007-2008

Through an annual public solicitation process, the Board evaluates ideas for potential research projects. The draft report, "Planned Air Pollution Research for Fiscal Year 2007-2008" represents the results of the review process and includes project concepts for the ARB's extramural research program for fiscal year 2007-08. The proposed concepts will be brought to the Board in the future as fully designed research proposals.

07-5-2: Public Meeting to Consider the 2007 San Diego State Implementation Plan (SIP)

Staff will recommend Board approval of revisions to the SIP for attaining federal air quality standards in the San Diego Air Basin. The proposed revision demonstrates how San Diego will attain the 8-hour ozone standard by the federal deadline and that other Clean Air Act requirements.

07-5-3: Public Meeting to Consider Allocations of $25 Million for Alternative Fuel Incentives

Staff will brief the Board on joint Air Resources Board/California Energy Commission recommendations for allocations of the $25 million for the Alternative Fuel Incentives Program.

07-5-5: Public Meeting to Consider Zero Emission Vehicle Program Review: Technology Status Report by the Independent Review Panel

The purpose of this agenda item is to present information gathered by an Independent Review Panel regarding the status of vehicle technologies needed to meet the Zero Emission Vehicle Program requirements. The information gathered by the panel, along with other information collected by ARB staff, will be used by the Board in determining if modifications to the current program are warranted. ARB staff would return to the Board with proposed modifications later this year if directed by the Board to do so.

May 25, 2007
8:00 a.m.

Item #

07-5-6: Public Hearing to Consider Proposed Amendments for In-Use Off-Road Diesel Vehicles

Off-road diesel vehicles are responsible for nearly a quarter of the total diesel particulate matter (PM) emissions from all sources and nearly a fifth of the total oxides of nitrogen (NOx) emissions from mobile diesel sources. These emissions pose a significant health risk because of their contribution to toxic ambient PM and ozone, which can lead to increased mortality. The proposed regulation would require fleet owners to reduce their diesel PM and NOx emissions by using strategies that include fleet modernization, such as replacing older engines or vehicles with newer cleaner ones, and installation of exhaust retrofits that capture and destroy pollutants before they are emitted to the atmosphere.

OPPORTUNITY FOR MEMBERS OF THE BOARD TO COMMENT ON MATTERS OF INTEREST.

Board members may identify matters they would like to have noticed for consideration at future meetings and comment on topics of interest; no formal action on these topics will be taken without further notice.

OPEN SESSION TO PROVIDE AN OPPORTUNITY FOR MEMBERS OF THE PUBLIC TO ADDRESS THE BOARD ON SUBJECT MATTERS WITHIN THE JURISDICTION OF THE BOARD.

Although no formal Board action may be taken, the Board is allowing an opportunity to interested members of the public to address the Board on items of interest that are within the Board's jurisdiction, but that do not specifically appear on the agenda. Each person will be allowed a maximum of three minutes to ensure that everyone has a chance to speak.

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http://www.arb.ca.gov/lispub/comm/bclist.php

IF YOU HAVE ANY QUESTIONS,
PLEASE CONTACT THE CLERK OF THE BOARD
1001 I Street, 23rd Floor, Sacramento, CA 95814

(916) 322-5594
FAX: (916) 322-3928
ARB Homepage: www.arb.ca.gov

To request special accommodation or language needs, please contact the following:

- **For individuals with sensory disabilities, this document is available in Braille, large print, audiocassette or computer disk. Please contact ARB's Disability Coordinator at 916-323-4916 by voice or through the California Relay Services at 711, to place your request for disability services.**
- **If you are a person with limited English and would like to request interpreter services to be available at the Board meeting, please contact ARB's Bilingual Manager at 916-323-7053.**

THE AGENDA ITEMS LISTED ABOVE MAY BE CONSIDERED IN A DIFFERENT ORDER AT THE BOARD MEETING. THOSE ITEMS ABOVE THAT ARE NOT COMPLETED ON MAY 24 WILL BE HEARD BEGINNING AT 8:00 A.M. ON MAY 25.

SMOKING IS NOT PERMITTED AT MEETINGS OF THE CALIFORNIA AIR RESOURCES BOARD

California Environmental Protection Agency

Air Resources Board

PUBLIC MEETING AGENDA

LOCATION:
San Diego Marriott Del Mar
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May 24, 2007 at 9:00 a.m.
&
May 25, 2007 at 8:00 a.m.

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CALIFORNIA AIR RESOURCES BOARD

NOTICE OF PUBLIC MEETING TO CONSIDER THE APPROVAL OF A DRAFT REPORT: *PLANNED AIR POLLUTION RESEARCH, FISCAL YEAR 2007-2008*

The Air Resources Board (the Board or ARB) will conduct a public meeting at the time and place noted below to consider a draft report, titled *"Planned Air Pollution Research, Fiscal Year 2007-2008."*

DATE: May 24, 2007

TIME: 9:00 a.m.

PLACE: San Diego Marriot Del Mar
Grand Ballroom
11966 El Camino Real
San Diego, CA 92130

This item will be considered at a two-day meeting of the Board, which will commence at 9:00 a.m., May 24, 2007 and will adjourn at 6:00 p.m. The meeting will then continue at 8:00 a.m., May 25, 2007. This item may not be considered until May 25, 2007. Please consult the agenda for the meeting, which will be available at least 10 days before May 24, 2007, to determine the day on which this item will be considered.

For individuals with sensory disabilities, this document is available in Braille, large print, audiocassette or computer disk. Please contact ARB's Disability Coordinator at 916-323-4916 by voice or through the California Relay Services at 711, to place your request for disability services. If you are a person with limited English and would like to request interpreter services, please contact ARB's Bilingual Manager at 916-323-7053.

The California Health and Safety Code (HSC), sections 39700 and 39703, established the Air Resources Board's research program. It directed the Board to coordinate and administer all air pollution research that is funded, to any extent, with state funds. To facilitate this process, HSC section 39705 directs the Board to appoint a screening committee to give advice and recommendations on all air pollution research projects proposed for funding.

The draft report is comprised of research ideas for the current fiscal year. The general public, business and academic communities, and ARB staff submitted the ideas. The approximate 200 research ideas that were submitted were provided to the Research Screening Committee (RSC) for review and comment. The RSC met on March 30, 2007 to review and approval the final list of projects.

Consistent with long-established policy, the Board meets annually with the RSC to review and discuss ongoing projects and research proposed for the next fiscal year. At the May 24, 2007 meeting, the RSC and ARB staff will present their draft report, *Planned Air Pollution Research, Fiscal Year 2007-2008,* to the Board for approval. The report describes projected funding allocations and proposed research projects, some recommended for funding and others recommended if funding becomes available.

ARB staff will present the draft report, *Planned Air Pollution Research, Fiscal Year 2007-2008* at the meeting. Copies of the report may be obtained from the Board's Public Information Office, 1001 "I" Street, 1st Floor, Environmental Services Center, Sacramento, CA 95814, (916) 322-2990, May 24, 2007. The report may also be obtained from ARB's internet site at http://www.arb.ca.gov/research/apr/apr.htm.

Interested members of the public may also present comments orally or in writing at the meeting, and in writing or by email before the meeting. To be considered by the Board, written comments submissions not physically submitted at the meeting must be received **no later than 12:00 noon, May 23, 2007** and addressed to the following:

Postal mail: Clerk of the Board, Air Resources Board
1001 I Street, Sacramento, California 95814

Electronic submittal : http://www.arb.ca.gov/lispub/comm/bclist.php

Facsimile submittal: (916) 322-3928

The Board requests, but does not require 30 copies of any written submission. Also, ARB requests that written and email statements be filed at least 10 days prior to the meeting so that ARB staff and Board members have time to fully consider each comment. Further inquiries regarding this matter should be directed to Annmarie Mora, Air Pollution Specialist, (916) 323-1517, Air Resource Board, 1001 I Street, Sacramento, California, 95814.

CALIFORNIA AIR RESOURCES BOARD

Catherine Witherspoon
Executive Officer

Date: May 8, 2007

PROPOSED
State of California

AIR RESOURCES BOARD

Resolution 07-17

May 24, 2007

Agenda Item No.: 07-5-4

WHEREAS, the Legislature has declared that an effective research program is an integral part of the broad-based statewide effort to combat air pollution in California, pursuant to Health and Safety Code section 39700;

WHEREAS, the Air Resources Board has been directed to administer and coordinate all air pollution research funded, in whole or in part, with state funds, pursuant to Health and Safety Code section 39703;

WHEREAS, the Air Resources Board has been directed to establish objectives for air pollution research in California, pursuant to Health and Safety Code section 39703;

WHEREAS, the Air Resources Board has been directed to appoint a Research Screening Committee to give advice and recommendations with respect to all air pollution research projects funded by the state, pursuant to Health and Safety Code section 39705;

WHEREAS, the Research Screening Committee has reviewed and approved a report entitled *Planned Air Pollution Research Fiscal Year, 2007-2008*, for air pollution research in California; and

WHEREAS, the Air Resources Board has met with the Research Screening Committee and discussed the report.

NOW, THEREFORE, BE IT RESOLVED, that the Air Resources Board, pursuant to the authority granted by Health and Safety Code sections 39703 and 39705, hereby concurs in the recommendation of the Research Screening Committee and approves the report entitled *Planned Air Pollution Research Fiscal Year, 2007-2008*.

California Environmental Protection Agency

Air Resources Board

PLANNED AIR POLLUTION RESEARCH

Fiscal Year 2007-2008

March 2007

The statements and conclusions in this paper are not necessarily those of the California Air Resources Board. The mention of commercial products, their source, or their use in connection with material reported is not to be construed as either actual or implied endorsement of such products. To obtain this document in an alternative format, please contact the Air Resources Board ADA Coordinator at (916) 322-4505, TDD (916) 324-9531, or (800) 700-8326 for TDD calls from outside the Sacramento areas. This report is available for viewing or downloading from the Air Resources Board's Internet site at http://www.arb.ca.gov/research/apr/apr.htm.

Acknowledgments

This report was prepared with the assistance and support of managers and staff from the Research Division, Mobile Source Control Division, Monitoring and Laboratory Division, Planning and Technical Support Division, and Stationary Source Division of the Air Resources Board. We would also like to acknowledge the members of the academic community, government agencies, private businesses, and the public who submitted research ideas.

Prepared by:

Annmarie Mora, Air Pollution Specialist
Sarah Barnett, Office Technician

Reviewed By:

Research Screening Committee
Harold Cota, Ph.D. (Chairman)
John Balmes, M.D. (abstained)
Robert Devlin, Ph.D.
Barbara Finlayson-Pitts, Ph.D.
Steven Japar, Ph.D.
Chung Liu, D.Env.
Rachel Morello-Frosch, Ph.D. (abstained)
Tracy Thatcher, Ph.D.
Forman Williams, Ph.D.

Ex Officio Member
Michael Prather, Ph.D.

Executive Research Review Committee
Catherine Witherspoon, Executive Officer
Thomas Cackette, Chief Deputy Executive Officer
Michael Scheible, Deputy Executive Officer
Lynn Terry, Deputy Executive Officer
Bart Croes, P.E., Chief, Research Division

External Reviewers and Collaborators
California Energy Commission
Coordinating Research Council
Health Effects Institute
South Coast Air Quality Management District
United States Environmental Protection Agency

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Summary

This report presents the Air Resources Board's planned air pollution research for the fiscal year 2007-2008. Twenty-six projects are proposed. Twenty-one projects are recommended for funding and five are recommended if funding is available. This research portfolio is organized into four main areas of research: Health and Welfare Effects, Exposure Assessment, Global Climate Change, and Technology Advancement and Pollution Prevention. Although the plan does not have a dedicated section to address agriculture and environmental justice, aspects of these areas can be found throughout several projects in other subject areas.

This annual plan proposes research in the four areas mentioned above, with a significant effort to determine heath effects of air pollution, improve emission inventory efforts, characterize and assess the behavior of pollutants in the atmosphere, and develop technologies to reduce and control greenhouse gases and determine corresponding impacts. The proposed budget for recommended projects is approximately $5,600,000.

Introduction

The Air Resources Board (ARB) sponsors a comprehensive program of research addressing the causes, effects, and possible solutions to air pollution problems in California, and provides support for establishing ambient air quality standards. The Board's research program was established by the Legislature in 1971 (Health and Safety Code Sections 39700 et seq.) to develop a better understanding of the various aspects of air pollution, including air pollution's effects on health and the environment, the atmospheric reactions and transport of pollutants, and the inventory and control of air polluting emissions. In recent years, several legislative mandates have expanded and further defined the scope of the program.

The ARB's mission to protect California's public health, welfare, and ecological resources is supported through a Strategic Plan for Research covering the years 2001-2010. The Strategic Plan is based on the ARB's regulatory priorities for the next several years and provides direction for the ARB's research program. The four main areas of research identified in the Strategic Plan are: Health and Welfare Effects, Exposure Assessment, Technology Advancement and Pollution Prevention, and Global Climate Change. They are also the categories that guide this plan. These areas encompass the comprehensive mission of ARB's air pollution research. A copy of the Plan can be downloaded at the following address http://www.arb.ca.gov/research/apr/apr.htm.

The proposed research projects are not intended to be exhaustive or exclusive. Unanticipated opportunities, unique or innovative study approaches, or urgency may lead to consideration of other projects.

Objective of the Research Program. The goal of the research program is to provide the timely scientific and technical information that will allow the Board and local districts to make the public policy decisions necessary to implement an effective air pollution control program in California.

Process for Developing this Research Plan. The Board sends out a public solicitation inviting and encouraging the public to contribute ideas for project consideration. Members of the public, the academic community, and ARB staff submit research ideas. To aid in the evaluation, the Board's Executive Officer established interagency committees, led by ARB staff, to review research ideas. In response to this year's solicitation, approximately 200 research ideas were submitted. Proposed projects were examined for relevance to regulatory questions facing the Board and modified as necessary. Committee members then prioritized candidate projects in order of urgency and importance. The Board's scientific external review committee, the Research Screening Committee (RSC), which was established by Health and Safety Code Section 39705, reviewed these candidate projects. The list of projects, along with comments from the RSC, was forwarded to the Executive Research Review Committee, whose members are the Executive Officer, her three deputies, and the Chief of the Research Division. The Executive Research Review Committee reviewed all of the proposed projects and established project priorities. Selected projects are then placed

into two categories: 1) those that are recommended for funding, and 2) those that are recommended if additional funding becomes available. The RSC reviewed the selected projects and recommended the Plan to the Board.

Implementation of the Plan. The next step for projects approved in the plan will be their development into full research projects. The submission and selection of an idea does not guarantee a resulting contract for the submitter. Rather, the ARB is required to consider public California universities for expertise to execute these projects. If the universities do not possess the expertise, then a public solicitation is issued or a sole source contract is awarded. There is a list serve that can be subscribed to in order to receive updates on research activities. For more information about the list serve, visit www.arb.ca.gov/listserv/research/research.htm.

Research Budget. The 21 recommended projects total approximately $5,600,000. The allocations for the proposed recommended projects among research categories are as follows:

RESEARCH CATEGORY	BUDGET
Health and Welfare Effects	$2,265,000
Exposure Assessment	$1,800,000
Global Climate Change	$1,055,000
Technology Advancement and Pollution Prevention	$ 500,000
TOTAL	**$5,620,000**

Project Co-sponsorships. The Research Division is continually looking for cofunding opportunities and other ways to leverage the state's research dollars. This effort allows the ARB to be part of projects and studies that may otherwise be out of the state's fiscal reach. ARB has had past success in working with other research organizations and has been part of collaborative multimillion-dollar. Several of the projects in this plan have either confirmed or have potential cofunding dollars included in the cost category.

Summaries of Past Research. Projects completed since the beginning of 1989 are summarized in the Research Division's publication, Air Pollution Research, at www.arb.ca.gov/research/apr/past/past.htm.

Electronic copies of all of the Research Division's final reports are available for downloading at the same web site.

RESEARCH PROJECT TABLE OF CONTENTS

HEALTH AND WELFARE EFFECTS – *the projects funded under this section are dedicated to the memory of Dr. William Friedman, former ARB Board Member who passed away on August 25, 2005. Dr. Friedman was a strong advocate for the ARB's health research and guided many of the projects that have increased the Board's understanding of how air pollution affects human health, especially children's health.*

Health and Air Pollution – *Recommended Projects*

In-vehicle Air Pollution Exposure Assessment of Pregnant Women in the National Children's Study, Orange County California Vanguard Center, $450,000 1

The objective is to collect in-vehicle air pollution data in Orange County, develop and validate models to predict in-vehicle exposure, and apply the models to estimate in-vehicle exposure of women in the Orange County California Vanguard Center.

Is Disparity in Asthma Among Californians Due to Higher Pollutant Exposures, Greater Susceptibility, or Both?, $300,000 3

The objective is to examine associations between long-term air pollution exposures and asthma among a diverse range of Californians.

Pre- and Post-Natal Air Pollution Exposure and Early Childhood Respiratory Disease in the UCLA Environment and Pregnancy Outcomes Study Cohort, $715,000..... 5

The objective is to assess the impact of both pre- and postnatal air pollution exposures on respiratory illness in an assembled cohort.

Cardiopulmonary Health Effects: Toxicity of Semi-volatile and Non-volatile Components Particulate Matter Near Sources, $450,000 7

The objective is to determine how the toxicity of fine and ultrafine particles depend on the concentration and characteristics of semi-volatile and non-volatile fractions of particulate matter emitted from vehicles and other sources.

Effect of GSTM1 Phenotype on Ozone-induced Allergic Airway Inflammation (proposed amendment to contract 03-315), $250,000..... 9

The objective is to investigate whether pre-exposure to allergen enhances the subsequent inflammatory response to ozone exposure and to investigate the influence of GSTM1 genotype on responses to allergen and ozone.

Anti-Wood Burning Campaigns with Concurrent Wintertime Reductions in Ambient Pollution and Childhood Respiratory Morbidity, $100,000 11

The objective is to identify communities where increases in wood burning regulations along with public outreach efforts have been followed by a decrease in particulate pollution during the burning season and evaluate if emergency room visits and hospital admissions have experienced a concurrent decrease.

Recommended if funding available

Respiratory Health Effects Related to Ultrafine Particle Concentrations and Properties, $50,000 13

The objective is to examine the existing ultrafine particulate matter and health data from the Southern California Children's Health Study to assess the relationships of the properties of ultrafine particles exposure to pulmonary health measurements.

EXPOSURE ASSESSMENT

Personal and Indoor – *Recommended Project*

Activity Patterns Study for Estimating California's Exposures to Air Pollutants, $600,000 15

The objective is to provide an updated, representative, statewide activity pattern database that can be used in exposure models to improve estimates of Californians' exposures to air pollutants, including information on time lived in residences and distance traveled for daily trips.

Atmospheric Processes – *Recommended Projects*

Foothill Ozone Isoprene Experiment: Measurements and Modeling of Isoprene in Central California, $200,000 17

The objective is to measure isoprene fluxes and concomitant meteorological and vegetation parameters used in biogenic volatile organic carbon emission models, at a range of spatial and temporal scales within an oak woodland site in California.

Source Apportionment of Carbonaceous Aerosols Using Integrated Multi-Variant and Source Tracer Techniques and a Unique Molecular Marker Data Set, $400,000 19

The objective is to generate a full year of hourly organic and elemental carbon measurements and daily molecular markers measurements that can be used for complementary source apportionment and statistical analysis methods to apportion the contributions of primary and secondary sources on carbonaceous aerosol concentrations.

Emissions Inventory – *Recommended Projects*
On-Road Motor Vehicle Emissions Measurements Including Ammonia, Sulfur Dioxide and Nitrogen Dioxide, $95,000. 21

To monitor carbon monoxide, hydrocarbon, carbon dioxide, and nitrogen oxide emissions from light duty vehicles in three regions of California, the Los Angeles basin, the Central Valley, and the Bay Area.

Improved Geospatial Forecasting of Commercial Marine Vessels, $40,000 23

To extend previous work to help reveal how different vessels types contribute to cargo ship emissions along major trade routes and how different growth rates among commodities shipped may affect the nation-level forcasts currenty used by ARB and SECA team agencies.

Development of a California-Specific Intermodal Freight Transport Model, $200,000..... 25

To develop a single, statewide intermodal freight modeling system linked to California freight flows, vehicle activity, and state/national transportation infrastructure.

Measuring Agricultural Fumigant Pesticide Emissions through In-Field Testing, $100,000..... 26

To conduct additional field research to build upon the ongoing work to estimate the emissions and potential volatile organic compound reductions from fumigant pesticides.

Multi-Media – *Recommended Projects*
Source Apportionment of Atmospheric Dry and Wet Deposition of Mercury and Other Toxic Metals through Linkage to Atmospheric Measurements, $165,000 27

The objective is to provide a more comprehensive assessment of toxic metal deposition in California, supplementing existing measurements that connect to the National Mercury Deposition Network.

Recommended if funding available
Environmental Exposures in Early Childhood Education Environments, $500,000 29

The objective is to assess environmental quality in a representative sample of child care facilities located in California's urban and agricultural communities.

Development of Improved Environmental Chamber Experiments for Evaluating Contributions of Oxidation Products Ozone Impacts of Volatile Organic Compounds, $200,000 31

The objective is to develop and evaluate the current chemical mechanisms that are used to predict the impacts of individual Volatile

Organic Compounds on ozone formation. Specifically, chamber experiments will be designed and conducted to improve sensitivities of chamber experiments to product reactions and other aspects of the mechanisms that are important in ambient conditions.

Formal Uncertainty Analysis for Modeling of Secondary Air Pollutants, $260,000 33

The objective is to evaluate air quality model performance against continuously measured ozone, gaseous ammonia and nitric acid, and PM nitrate.

Comparative Assessment Entrained and Directly Emitted Particulate Emissions of Agriculturual Field Equipment, $240,000 35

The objective is to develop an improved testing procedure to quantify agriculture field equipment emissions on a comparable basis.

GLOBAL CLIMATE CHANGE

Climate Change Emissions Inventory – *Recommended Projects*

Developing a California Inventory for Industrial Applications of Perfluorocarbons, Sulfur Hexafluoride, Hydrofluorocarbons, Nitrogen Trifluoride, Hydrofluoroethers, and Ozone Depleting Substances, $200,000 37

The objective is to quantify emissions rates (during production and use), application growth rates, chemcial substitution rates, banks, and end-of-life disposal emissions (if applicable) for high global warming potential greenhouse gases in each application.

Climate Change Impacts – *Recommended Projects*

A Spatial Synoptic Classification Approach to Projected Heat Vulnerability in California under Future Climate Change Scenarios, $175,000 39

The objective is to evaluate the heat vulnerability of the California population in the future, based on the air mass types most closely associated with observed current-day heat-related mortality.

Climate Change Mitigation – *Recommended Projects*

The Climate Change Industry in California: An Economic Analysis Assessing the Current Market and Prospects for Growth in the Global Economy, $200,000 41

The objective is to define and quantify the climate change industry, forcast future growth scenarios, and characterize California's place in this industry.

Evaluation of Efficiency Activities in the Industrial Sector Undertaken in Response to Greenhouse Gas Emission Reduction Targets, $100,000 42

The objective is to identify the characteristics of successful industrial sector greenhouse gas emissions reduction and energy efficiency programs in other countries in order to provide a summary of lessons learned and make recommendations for specific industrial sector program designs in support of AB 32.

Retail Climate Change Mitigation: Life-Cycle Emission and Energy Efficiency Labels and Standards, $300,000 44

The objective is to develop a framework that allows for the estimation of the potential emissions reductions that could be attained through the funding of incentives, product endorsements, performance labels, or public sector buying programs for low life-cycle greenhouse gas emission products.

Long Range Transport – *Recommended Project*

Asian Aerosol Impacts in Urban and Interior California, $80,000 46

The objective is to use a combination of an annualized lead emission inventory for Asia and transport analytical methodologies to assess low altitude Asian pollutant impact to major California air basins and to calibrate tropospheric mixing to low altitudes.

TECHNOLOGY ADVANCEMENT AND POLLUTION PREVENTION

Technology Advancement and Pollution Prevention – *Recommended Project*

Particulate Matter Measurement for the 21st Century: Implementing a Program to Quantify Internal Combustion Engine PM Using Real-Time Measurement Techniques, $500,000 48

To implement a comprehensive study for addressing particulate matter measurement issues by using various real-time instruments.

TITLE: In-vehicle Air Pollution Exposure Assessment of Pregnant Women in the National Children's Study, Orange County California Vanguard Center

PROBLEM: There are no known prospective cohort studies that are examining the effects of exposure to in-vehicle air pollution during pregnancy on birth outcomes and the occurrence of childhood respiratory disease and allergy. The Southern California Association of Governments (SCAG) predicts that commuting times will double by 2020 due to population growth in the Los Angeles area (SCAG, 1997), adding urgency to research evaluating the impact of increased vehicle-related exposures on children's health. In-vehicle exposure to toxic air pollutant components may dominate total exposures during the workweek. It has been estimated that over 50 percent of black carbon (BC) and ultrafine particle (UFP) exposures for nonsmoking urbanites in Los Angeles comes from time in vehicles (Fruin, 2004; 2005). The proposed study focuses on improving the exposure assessment of in-vehicle air pollution among 1,250 pregnant women and their newborn children enrolled in the National Children's Study (NCS) cohort of the Orange County California (OCCA) Vanguard Center.

PREVIOUS WORK: The University of California, Irvine was selected as one of six Vanguard Centers for the NCS, an unprecedented national effort that will follow more than 100,000 children from before birth until age 21 to examine environmental, genetic, social and behavioral determinants of health and disease. Relevant to this effort are recent asthma panel studies in southern California by Dr. Ralph Delfino and colleagues showing associations of personal and ambient PM, including carbon fractions, with lung function and asthma symptoms (Delfino et al. 2003; 2004; 2005). Previous work by co-investigator Beate Ritz and colleagues examined adverse birth effects due to air pollution and traffic density among infants in southern California (Ritz et al. 2000, 2002, Wilhelm and Ritz 2003). Their current study (Ritz, Wilhelm and Jerret) showed 52 percent of women worked outside of the home during pregnancy, and the risk of delivering a preterm or low birth weight infant increased 50 percent among women commuting 45 minutes or more compared with 5 minutes or less. Previous ARB studies have identified important conditions that contribute to in-vehicle exposures (Fruin 2004; 2005; Sabin 2005; Westerdahl 2005). In-vehicle UFP concentrations on freeways in Los Angeles were well predicted by annual average Caltrans truck counts (R^2 = 0.84, Fruin, 2005). Other important factors include particular road and direction, hour of day, vehicle followed, speed, and overall congestion. However, these studies were conducted mostly on freeways, in Los Angeles area, and for a single season. None of the studies were directly linked to any health outcome research.

OBJECTIVE: The goal of this project is to collect in-vehicle air pollution data in Orange County, develop and validate models to predict in-vehicle exposure, and apply the models to estimate in-vehicle exposure of 1,250 enrolled women in the OCCA Vanguard Center of the NCS.

DESCRIPTION: A mobile monitoring platform loaded with instruments will be driven on Orange County freeways, as well as major surface streets in and around 20 targeted OCCA NCS neighborhoods. In-cabin measurements will be conducted for pollutants

that have the potential to induce oxidative stress and adverse impacts on pregnancy and fetal development, such as UFP, polycyclic aromatic hydrocarbons (PAH), BC, NO, NO_2, CO, PM0.2, PM0.2-2.5, and PM2.5-10 mass, and other particle characteristics relevant to health effects (e.g., TSI EAD 3070A). Measurements will be conducted across the year to account for possible seasonal differences in exposure due to temperature, RH, and air stagnation. The measured data will be combined with roadway characteristics, e.g., proportion of gas versus diesel vehicles, traffic load by time of day, traffic congestion, and stop-and-go traffic patterns on surface streets, etc. Data from other regions (e.g., Los Angeles) will be incorporated if possible in case subjects commute outside of Orange County (Fruin 2004; 2005; Westerdahl 2005).

Prediction models will be developed from known driving conditions, season, time of day, roadway characteristics, and locations using the in-vehicle measurement data. It is anticipated that results from exposure prediction models may be similar for NO, ultrafine particles and polycyclic aromatic hydrocarbons since these were strongly correlated in the recent Los Angeles on-road study (R^2, 0.69-0.76) (Westerdahl 2005). The models will be translated into the questionnaire items needed to capture the predictive conditions, travel durations and times of day, and locations of in-vehicle exposures. The model will incorporate the Orange County geographic information system spatial-temporal grid of on-highway exposures using methods similar to the time-activity-based exposure model developed by Gulliver and Briggs (2005). Estimated exposure will be weighted based on type and age of car and modes of transportation based on other studies conducted in southern California (Sabin 2005; Y Zhu, personal communication). The prediction model will be tested in a representative subjects who will complete an NCS questionnaire on in-vehicle exposure and will wear global positioning system devices planned for NCS women during a selected period of the first trimester and second or third trimester. Test subjects will be followed on representative days with the chosen air pollutant measurements used for the final prediction models. Refinements may be needed for questionnaires, including different transformations of questionnaire data. The predicted in-vehicle air pollutant exposures will be combined with predicted exposure at home and work derived from our complementary concept proposal submitted with this proposal that will predict air pollutant exposures at home and at work during pregnancy using land use regression, and related modeling techniques based on traffic data, microenvironmental, neighborhood, and ambient monitoring data.

BENEFITS: This research augments in-cabin measurement data for the NCS, presenting a unique opportunity to examine whether exposure to in-vehicle air pollution adversely affects birth outcomes and promotes the occurrence of atopic sensitization and childhood respiratory diseases, including asthma. The results will allow quantitative estimates of in-vehicle exposure of various pollutants given known driving conditions and other parameters. It will guide other epidemiological studies focused on commuters' health outcomes, and help inform policy decision makers concerning motor vehicle emissions control.

COST: $450,000

TITLE: Is Disparity in Asthma Among Californians Due to Higher Pollutant Exposures, Greater Susceptibility, or Both?

PROBLEM: According to the 2003 California Health Interview Survey (CHIS 2003), 4.5 million Californians suffer from asthma and an additional 3.4 million Californians suffer from asthma-like breathing problems. The elderly, children, racial/ethnic minorities, women, and low-income Californians suffer disproportionately from asthma or asthma-like symptoms. There is no routine asthma registry in California. Questions remain whether the disproportionate health burden among these subpopulations is related to higher air pollution exposures, or greater susceptibility due to other risk factors, such as poor access to care and health behaviors, or both.

PREVIOUS WORK: Gunier et al. (2003) previously reported that Californians in the lowest quartile of median family income were three times more likely to live in high-traffic areas than those in the highest income quartile. Children of color were also about three times more likely to live in higher traffic areas than white children. In previous CDC-funded studies linking 2001 CHIS and ambient air monitoring and traffic data in Los Angeles and San Diego Counties, it was found that individuals living near heavy traffic or in areas with high ozone and PM10 levels were more likely to report chronic severe asthma (daily/weekly symptoms) or acute asthma exacerbations (emergency department visits or hospitalization due to asthma). Children, the elderly, and low income subjects were also more likely to have severe asthma. However, the sample size and data items were too limited in 2001 to perform meaningful sub-population analyses, e.g. impacts of race/ethnicity and related vulnerability factors on the pollutant-asthma outcome associations. CHIS 2003 and subsequent surveys provide better information on residential location, school location for children, housing conditions, indoor exposures, health behaviors, and asthma outcome measures.

OBJECTIVE: The goal of the project is to use CHIS 2003 data to identify: 1) which subpopulations among those with asthma or asthma-like-symptoms are more exposed and/or more susceptible to air pollution; and 2) what are the characteristics contributing to increased susceptibility, e.g. differences in underlying health status, access to medical care, and exposure to indoor triggers. Based on CHIS 2003, 7,509 respondents reported an asthma diagnosis and an additional 5,522 respondents reported asthma-like symptoms.

DESCRIPTION: CHIS 2003 data will be linked with measurement data for criteria air pollutants (O_3, PM10, PM2.5, and NO_2) from the California Statewide Air Monitoring Network, and with residential and school-based traffic density (TD) values based on daily traffic counts from Caltrans. CHIS, a geographically-stratified random-digit-dial telephone survey, has been conducted biannually since 2001. CHIS 2003 collected information on approximately 54,500 non-institutionalized Californians, including 12,500 children using five languages. About 15 percent of children and 12 percent of adults reported an asthma diagnosis. An additional 10 percent of Californians reported suffering from asthma-like breathing problems without having received an asthma diagnosis. Residential address information was collected from more than 90 percent of

households since CHIS 2003. Contractors will restrict the study population to respondents who lived in the same house or neighborhood for a certain length of time (e.g., 2 years), to ensure pollutant measures are accurate proxies for long-term exposures. The major tasks of the proposed study are as follows:

1. Characterizing air pollution exposures by: (1) linking geocoded subject residence locations to appropriate air monitoring stations and calculating annual average air pollutant concentrations for the year prior to the interview date; and (2) calculating traffic density values for each CHIS 2003 respondent based on their home addresses;
2. Identifying sub-populations that are highly exposed to a single pollutant or pollutant mixes, and quantify the degree to which their health is compromised due to outdoor air pollution. Specifically, for those with diagnosed asthma, the contractor will examine associations between estimated exposures and the following asthma outcomes: prevalence of chronic severe asthma (daily/weekly symptoms), asthma attacks or episodes, use of daily medication to control asthma, school or work absences, asthma emergency room visits, and the number of doctor visits for asthma in the previous 12 months. Among those with asthma-like breathing problems, associations with frequency of asthma-like symptoms, number of times medical care was sought for breathing problems, and work/school days missed for breathing problems in the previous 12 months will be examined.
3. Identifying factors that contribute to or modify the susceptibility to air pollution among sub-populations. The factors to be examined include: socioeconomic status (e.g., educational attainment, poverty, and employment status); access to care (health insurance status, received asthma management plan); health behaviors (overweight/obesity, smoking, walking for transportation or leisure, physical activity); exposure to indoor triggers (environmental tobacco smoking and indoor allergens, e.g., cockroaches, dogs and cats); housing conditions (e.g., type of house or household crowding); and neighborhood factors (neighborhood safety or, rural/urban neighborhoods).

BENEFITS: CHIS data provide a unique opportunity to examine associations between long-term air pollution exposures and asthma among a diverse range of Californians. The proposed research will provide crucial information on whether current federal or state air quality standards sufficiently protect vulnerable subpopulations. The project directly addresses a major goal of the ARB Environmental Justice Policy to support "research to better characterize the variety of air pollution exposures in communities and to better assess health impacts, especially non-cancer effects, cumulative effects, and effects from long-term low-level exposures." This project could also lay groundwork for future studies of the effect of air pollution on other diseases in vulnerable populations, such as diabetes and heart disease.

COST: $300,000

TITLE: Pre- and Postnatal Air Pollution Exposure and Early Childhood Respiratory Disease in the UCLA Environment and Pregnancy Outcomes Study Cohort

PROBLEM: A growing body of evidence suggests development and overall growth of the lung can be affected by exposure to chemicals and particles. In a recent review, Pikerton and Joad (2006) emphasized lung development is a multi-event process that is not restricted to prenatal life and the importance of examining exposures during critical development windows. Evidence is also accumulating that prenatal air pollution exposure leads to preterm and low weight birth suggesting an indirect route by which air pollution may be linked to adverse respiratory outcomes. However, few studies to date have examined the single or combined effects of outdoor air pollution exposures during pregnancy and early childhood on the occurrence of respiratory diseases during the first years of life.

PREVIOUS WORK: In 2003, data was collect for 2,543 infants born in Los Angeles County, California and assessed the influence of air pollution exposures on preterm and low weight birth. This National Institute of Environmental Health Sciences funded study – known as the Environment and Pregnancy Outcomes Survey (EPOS) – is one of only two U.S. studies to assemble a birth cohort to assess air pollution effects on pregnancy outcomes. The survey included data collection for a wide range of potentially important risk factors for perinatal health including family income, prenatal care, prenatal tobacco and alcohol consumption, exposure to indoor air pollution and allergen sources during pregnancy, and breastfeeding practices. There is now the unique opportunity to follow for six years this established birth cohort of 2,470 children (those who agreed to be re-contacted) to examine whether exposure to outdoor air pollution from conception to Kindergarten influences the occurrence of childhood respiratory and asthmatic diseases. The babies enrolled in the cohort are an especially vulnerable population since by design half of them were preterm and/or low weight births and many of them are living in disadvantaged neighborhoods in Los Angeles County.

OBJECTIVE: The goals of this project are to re-contact the women who participated in EPOS to collect data that will allow examination whether: (1) exposure to outdoor air pollution during pregnancy and/or in early childhood alone or in combination contribute to early childhood infections, respiratory diseases, and asthmatic symptoms; (2) effects are stable when adjusting for individual and neighborhood risk factor (confounder) information obtained in surveys and from other data sources; (3) exposures to additional indoor, in-vehicle, or occupational air pollution sources during pregnancy and early childhood confound and/or modify the effect observed for outdoor pollutants; (4) pollutant effects vary between population subgroups (girls vs. boys, children born and living in various neighborhoods, with a specific nutritional status [obesity], born preterm/low weight, atopic versus non-atopic children, etc.), due to increased or decreased susceptibility or additional exposures. Furthermore, in a nested case-control approach home visits will be conducted for children reporting asthmatic symptoms or allergies during follow-up and unaffected matched controls to perform skin prick testing

for common allergens to assess atopy and to assess lung function through testing using portable spirometers.

DESCRIPTION: The first step will be to actively follow 2,470 children included in the first birth cohort survey with two additional telephone surveys conducted at approximately 3.5 and 5.5 years of age to gather information on residential history, daycare attendance, exposure to indoor air pollution sources, commuting habits, and other individual- and neighborhood-level risk factors for respiratory diseases including asthmatic symptoms (the 3.5 year age interviews as discussed below are currently being conducted). The incidence and prevalence of respiratory diseases and allergic and asthmatic symptoms will be assessed at each survey using a modified version of the International Study of Asthma and Allergies in Childhood (ISAAC) questionnaire (applicable to this very young age group). Home visits will be conducted to perform lung function testing using portable spirometers and skin prick tests in a nested group of children who screen positive in the interviews for asthmatic symptoms and atopy and a group of unaffected matched controls selected from the cohort (approximately 700 children total). Maternal and childhood air pollution exposures will be derived using air pollution concentration data from existing ambient monitors, traffic density metrics and pollution surfaces estimated through land use regression (LUR) and geostatistical modeling. Exposure estimates will take into consideration the residential, daycare and school mobility patterns of mothers and children based on our survey data. These methods have been successfully employed in our previous and current studies. We will determine the influence of individual level risk factors (individual level data collected in our repeated surveys) and use multi-level models to evaluate neighborhood and health care related factors (neighborhood or community level factors) for the diseases studied, including the potential of certain risk factors – individual or neighborhood level – to modify effects of air pollutants.

BENEFITS: There is a unique opportunity to assess the impact of both pre- and postnatal air pollution exposures on respiratory illnesses in an assembled cohort, which has only been done in four other studies, only one of which has been in the U.S. Los Angeles' diversity of population characteristics and the availability of an extensive air monitoring network in combination with current LUR modeling work in this region creates an ideal situation for studying the effects of air pollution on respiratory health in early childhood. Although increases in respiratory diseases due to outdoor air pollution may be small in a relative sense, the potential for disease prevention may be enormous since millions of mothers and young children are and in the future will be exposed to similar (or greater) air pollution concentrations worldwide. Improving child health early in life is an important public health goal. The results of this research will provide information for future air quality standard setting in California and the United States.

COST: $715,000

TITLE: Cardiopulmonary Health Effects: Toxicity of Semi-volatile and Non-Volatile Components Particulate Matter Near Sources

PROBLEM: Epidemiological and *in vivo* exposure studies demonstrate that particles (fine and ultrafine) in close proximity to mobile source emissions are more toxic than particles in the air more distant from the source. The reason for this change in toxicity is not known. Coincident with the reduction of toxicity with distance, the size and composition of the ultrafine particles undergo rapid changes. However if these changes are responsible for the changes in toxicity of the particles, the phenomenon cannot be effectively tested using collected samples because of the apparently short-lived duration of causal agents involved. The problem can however be addressed with *in vivo* inhalation studies.

PREVIOUS WORK: Studies of mice exposed to fine and ultrafine particulate matter (PM) 50 meters from a freeway showed that these exposures had significant biological activity which was associated with elemental and organic carbon fractions of the aerosol. When exposures were performed 150 meters downwind of the freeway the biological activity was greatly diminished and there were no measurable exposure-related effects (Kleinman et al., 2006). Careful measurements in a roadway tunnel (Phuleria et al. 2006) and near a major freeway with heavy-duty diesel traffic (Kuhn et al., 2005; Biswas et al., 2006) have demonstrated that there are rapid shifts in aerosol size and composition within minutes of emission and that the volatility of the PM increases with decreasing particle size. Sioutas and colleagues have developed the capacity to couple a thermal denuder to a Versatile Aerosol Concentration Enrichment System (VACES). The thermal denuder heats the aerosol to a specified temperature to evaporate and remove semi-volatile components, and then returns the aerosol to the original temperature. The VACES can increase the concentration of the processed aerosol by factors of 20 to 30 to provide adequate concentrations for performing acute *in vivo* toxicology exposure studies.

OBJECTIVE: The goal of the project is to determine how the toxicity of fine and ultrafine particles depends on the concentration and characteristics of semi-volatile and non-volatile fractions of PM emitted from vehicles and other sources. The proposed hypothesis is that the toxicity of near-source PM is due to nanoparticles that are composed largely of semi-volatile components and that biological activity will be attenuated by removal of those components from the aerosol. Use of *in-vivo* rodent exposure system will be used in combination with the VACES thermal denuder technology to separately study the cardiopulmonary effects of PM, before and after the removal of the semi-volatile components. The PM will be studied at sites scheduled for detailed chemical and physical characterization examination of PM emitted by specific sources as part of the Southern California Particle Center (SCPC) research program. The sites will be in proximity to the Los Angeles-Long Beach Harbor and at a dynamometer facility where emissions from vehicles with and without exhaust mediation (catalysts, filter traps etc.) are being tested.

DESCRIPTION: Acute and chronic cardiopulmonary inflammation and injury will be examined using rats implanted with ECG and blood pressure telemetry devices to test the hypothesis that exposure to ultrafine particles composed of semi-volatile compounds causes inflammation and oxidative stress resulting in pulmonary and cardiovascular injury. The study will address the question of whether adverse effects associated with exposures in close proximity to sources of mobile source emissions are due to specific classes of reactive organic compounds such as aldehydes or other oxygenated hydrocarbons. Endpoints will include markers of inflammation, histological examinations for evidence of pathology, heart muscle cell hypertrophy and cardiopulmonary function measurements. The *in vivo* biological responses will be correlated with physical and chemical composition of the particles and the *in vitro* potential of these particles to produce free radicals and induce cytotoxicity, which will be measured by the SCPC. These experiments will be conducted over a period of three years.

BENEFITS: This project could provide improved understanding of the mechanism of toxic action of freshly-emitted combustion aerosols and identify fractions of the aerosol causally related to health effects. This information will also aid regulators and planners in developing air quality regulations and land use guidance to better protect the health of California residents.

COST: $450,000

TITLE: Effect of GSTM1 Phenotype on Ozone-induced Allergic Airway Inflammation (proposed amendment to contract 03-315)

PROBLEM: Controlled human exposure studies that have investigated the effect of ozone exposure on asthmatics have not consistently found ozone-induced enhancement of responses to a subsequent allergen challenge. In contrast, ambient ozone has been associated with asthma exacerbation in several epidemiologic studies. This raises several questions, including (1) whether there is more than one subpopulation of asthmatics, each with a different degree of vulnerability that is genetically determined, or (2) whether the timing of O_3 challenge relative to allergen challenge is a significant factor in explaining the discrepancies in the literature.

PREVIOUS WORK: Ozone exposure is known to induce oxidative stress in the lungs, which leads to airways inflammation. There is also evidence, at least in some asthmatics, that ozone enhances allergen-induced airway inflammation. The GSTM1 gene regulates a key antioxidant enzyme involved in protection from and repair of damage from oxidative stress reactions in the lungs. Several studies also suggest that a common genetic variant in GSTM1 (null type) results in the absence of a key antioxidant enzyme that appears to play a key role in the toxicity of inhaled ozone, and may be a basis for differences between individuals in susceptibility to adverse effects from ozone inhalation. In addition, most studies investigating possible interactions of ozone and allergen have presented the allergen challenge after ozone exposure, while the opposite pattern, with the allergen challenge prior to ozone exposure, is more representative of the real world, and has only been investigated in one paper.

Contract 03-315 with the University of California, San Francisco (UCSF), was approved in September 2004. The project, as approved, was designed to investigate three objectives: (1) whether ozone exposure enhances specific lower airway inflammatory responses of asthmatic subjects during late-phase reactions to inhaled allergen, (2) to determine whether the GSTM1 null genotype is an important predictor of susceptibility of asthmatic subjects to develop enhanced late-phase reactions to allergen challenge presented after ozone exposure, and (3) to determine whether pre-exposure to allergen enhances the subsequent inflammatory responses to ozone exposure.

The UCSF human subjects committee will not approve the protocol as funded, based on their belief that the study involves too many bronchoscopies per subject. Staff proposes to address this issue by splitting the funded project into two independent experiments, each with a different group of subjects, and augmenting the original contract so as to maintain the original intent of the project.

Experiment one would address objectives one and two of the currently funded project, and would consist of two experiments: (1) filtered air – allergen, and (2) ozone – allergen. There would be a total of 30 mild to moderate asthmatic subjects, 15 who are GSTM1 positive, and 15 who are GSTM1 null, as outlined in the funded project.

Objective three would be moved to experiment two, which would have a different group of subjects. This research idea would provide the funding augmentation required to complete the proposed experiment two, which is described below in more detail.

OBJECTIVES: The goals of the project are to investigate whether pre-exposure to allergen enhances the subsequent inflammatory response to ozone exposure and to investigate the influence of GSTM1 genotype on responses to allergen and ozone.

DESCRIPTION: Fifteen subjects with mild to moderate asthma who are specifically sensitized to house dust mite will participate in two exposures, one to filtered air (FA), and one to 0.16 ppm ozone. Local endobronchial allergen challenge will occur the day before both exposures, with the sampling bronchoscopy following the O_3 exposure. The exposures will be four hours in duration, and will involve intermittent exercise. Various cellular and biochemical indices of airway inflammation will be assayed in bronchoscopically obtained samples. Subjects will also be genotyped for GSTM1 and several other genes that may be related to susceptibility to adverse effects of O_3 exposure (GSTT1, GSTP1, NQO1, SOD2, GPX1, and catalase). The distribution of variants of these genes, except for GSTM1, in the population is unknown, and consequently these will be exploratory analyses. However, the results from these exploratory analyses will help guide development of future investigations into the biological foundations of susceptibility to O_3 exposure.

BENEFITS: Greater understanding of how ozone might be causing exacerbations of asthma will accrue from this study. In addition, the study will investigate the responses of a vulnerable population using a relevant outcome (allergic airway inflammation).

COST: $250,000

TITLE: Anti-Wood Burning Campaigns with Concurrent Wintertime Reductions in Ambient Pollution and Childhood Respiratory Morbidity

PROBLEM: Concern over the health effects from residential wood burning has risen over the past decade. In some California communities, wood smoke from home heating can comprise over one third of ambient particulate pollution during the wintertime. Wood smoke is comprised of several pollutants, including: CO, NO_2, PM10 and PM2.5, and subsequent polycyclic aromatic hydrocarbons (PAHs). Residential wood burning affects ambient and indoor air quality throughout the neighborhood. Other factors contributing to wintertime pollutants include fuel-burning heat sources and cooking smoke. An inversion layer often forms in cooler, dryer weather and prevents pollutants from dispersing. Infants and children are particularly susceptible to the effects of these wintertime pollutants. Their respiratory and immune systems are immature, and mobile infants and young children spend time on the floor where particles and PAHs bind to dust. Enormous costs are associated with the care and treatment of these infants, and long-term effects from early life exposures are unknown. Respiratory-related symptoms and disease are the most common reasons for hospitalization of children in California. Concern over air quality has prompted several communities to regulate and/or ban residential burning when air quality forecasts are poor. Implementation of these regulations has been coupled with public education and there are indications that some of these campaigns have been successful in improving air quality.

PREVIOUS WORK: Previous work has shown that wood smoke is positively associated with adverse health effects such as asthma, and respiratory-related emergency room and hospital visits. Pino et al. has linked PM2.5 with wheezing in infants. However, potential changes in air quality and health responses to community/district actions against residential wood burning have not been addressed.

OBJECTIVE: The goals of the project are to (1) identify communities within the Bay Area Air Quality Management District and the San Joaquin Air Pollution Control District where increases in wood burning regulations along with public outreach efforts have been followed by a decrease in particulate pollution during the burning season, and (2) evaluate if postneonatal emergency room visits and hospital admissions due to respiratory causes have experienced a concurrent decrease in these specific communities.

DESCRIPTION: This study is comprised of two phases. The first phase includes identifying communities within the Bay Area AQMD and the San Joaquin APCD that have implemented wood burning regulations and public education/outreach campaigns over the past decade. Programs will be evaluated on the 1) intensity of their outreach, 2) if they have instituted recommendations, regulations, and/or bans of residential burning, and 3) if they offer rebates for change-outs. Intensity of outreach is defined by the use of billboards, radio, television, and newspaper advertising, and information booths at public events. After identifying these communities, there will be a determination of whether ambient monthly average and maximum concentrations of CO, NO_X, PM10 and PM2.5, and subsequent PAHs decreased significantly during the

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burning season following implementation of public education and regulations, compared to the burning season in the prior year. These potential differences will be adjusted for change in climate, etc. A pre- and post-intervention analysis will be performed, with each community serving as its own control. If these communities are not experiencing similar decreases in pollutant concentrations, it will provide further evidence that decreases identified are attributable to interventions. In this study, the wood-burning season is defined from November 1 through March 31 of each year, although this differs slightly among AQMDs. Following identification of communities with a reduction in pollution during burning season, we will begin the second phase of the study by examining the rates of respiratory related hospitalizations among infants and children aged 28 days through under 18 years. Statewide, there are over 100,000 of these respiratory related admissions among children per year. Eligible major diagnostic categories include: respiratory infections and inflammations, simple pneumonia and pleurisy, bronchitis and asthma, respiratory signs and symptoms, and other respiratory system diagnoses, except influenza. Outcome data will be obtained from the Office of Statewide Health Planning and Development (OSHPD). There will be a determination if there were significant decreases in the rates of these outcomes that were concurrent with decreases in pollution. Some individual level covariates are available through admission records, while zip code level variables are available from U.S. Census data. We will examine communities with large populations in isolation, while we may lump together smaller communities.

BENEFITS: This study will help determine if current wood burning regulations and outreach efforts are effective in reducing wintertime pollution and postneonatal respiratory morbidity in California. Evidence will be generated that can be used to evaluate which methods are most effective.

COST: $100,000

TITLE: Respiratory Health Effects Related to Ultrafine Particle Concentrations and Properties

PROBLEM: Health effects are now well documented for particulate matter pollution. The ultrafine fraction of the PM, which is largely dominated by combustion sources, appears to be of particular importance in the cause of health effects. This is often inferred to be a factor of exposure to traffic related pollution. In many studies the traffic density is used as a surrogate for pollutant exposures. There remains a question as to what property of ultrafine PM is most responsible for the respiratory health effects associated with the ultrafine PM (number count concentration, surface area, mass concentration, count median size, etc.) This project will use the health and ultrafine particle datasets generated by the Southern California Children's Health Study (CHS) to assess these relationships.

PREVIOUS WORK: A number of studies have looked at ultrafine PM counts and health, but most commonly these studies use a single central site monitor as an indicator of exposures. Transect studies have shown that ultrafine PM is very sensitive to the proximity to the source; the particle counts have been shown to drop off exponentially downwind from a highway and by approximately 300 meters from the highway the count has returned to approximately the level seen upwind of the highway. The CHS datasets include health and ultrafine PM exposure data from 12 communities in southern California reflecting a variety of community exposure and health profiles. Although a number of analyses have been conducted relating the pollutant concentrations and respiratory development of children, the ultrafine PM data collected in the CHS has not been analyzed to date; this remains a missing piece of the health and exposure puzzle.

Preliminary examination of the CHS data from publicly available data sources indicates the relationship between accumulation mode size particles and the FEV1 measure of lung health is stronger than other sizes or the total ultrafine counts. Other properties have not yet been examined, but *in vitro* and rodent studies have implied that the particle source, size, and surface area may have significant effects in addition to the total count concentration.

OBJECTIVE: The goal of the project is to examine the existing ultrafine PM and health data from the Southern California Children's Health Study to assess the relationships of the properties of ultrafine particles exposure to pulmonary health measurements (asthma, FEV1, FEF, etc.).

DESCRIPTION: The project will analyze lung function data available from the CHS health dataset and ultrafine particle data available from the CHS ambient exposure dataset and from the ARB's SMPS project conducted by the University of Southern California. The ultrafine PM data used will include hourly data so factors in addition to the annual average can be calculated and analyzed. The ultrafine particle number, surface area, mass, size (several size bins: e.g. <50 nm, 50-100 nm, >100 nm), and count median size using daily, monthly, seasonal, annual averages, seasonal variation, diurnal variation, and average highest hour will be used to the extent possible. The

analyses will analyze within and between community variation of exposure and health effects.

If enough subjects are available for statistical validity, subjects will be restricted to areas near monitors to get maximum similarity of subjects and exposures. Or subjects will be restricted to similar areas (near freeways or other roads, etc.) if possible. These subject restrictions will attempt to adjust for the usual problems of ultrafine PM spatial variability.

BENEFITS: The results from this work will improve our understanding of the respiratory health effects of ultrafine PM.

COST: $50,000

TITLE: Activity Patterns Study for Estimating California's Exposures to Air Pollutants

PROBLEM: The data used to understand the activity patterns of Californians, and their potential exposure to air pollution, are nearly 20 years old. For accurate exposure assessment, current data are needed that reflect the ways in which people now carry out the activities of their lives. For example, a wide range of electronic products (personal computers, printers, cell phones) are now commonly in use that either were unavailable or rarely used by most people 20 years ago, potentially resulting in increased exposure to ozone, PBDEs, fine particles, and other pollutants. Also, previous studies did not obtain data on the time (years) Californians live at their different residences over their lifetime, and on the distances traveled on their daily trips for commuting, errands, and so on. This has been a significant data gap in recent population exposure assessments.

PREVIOUS WORK: In 1986 and 1987, the Survey Research Center (SRC) of the University of California, Berkeley conducted two projects for ARB to study the activity patterns of California adults and children. These studies provided extensive information about potential exposure of Californians to emissions from indoor and outdoor air pollutants. The data were collected by telephone interview and contained minute-by-minute detail of the activities and the locations of the respondents over a 24-hour period. These projects provided a representative database that was subsequently incorporated into an ARB exposure model, the California Population Indoor Exposure Model (CPIEM). The data have been used in other ARB exposure projects, especially for the Toxic Air Contaminants Program, and also by the Office of Environmental Health Hazard Assessment to develop their stochastic exposure guidelines. These projects also served as the research models for a subsequent national study, the National Human Activity Pattern Survey (NHAPS) sponsored by the U.S. Environmental Protection Agency (EPA) that was conducted between 1992 and 1994. This national project provided comprehensive exposure information over broad geographical and temporal scales, particularly for use in probabilistic population exposure models.

OBJECTIVE: The primary goal of the project is to provide an updated, representative, statewide activity pattern database that can be used in exposure models to improve estimates of Californians' exposures to air pollutants, including additional information on time lived in residences and distance traveled in daily trips. A secondary objective is to accomplish this at a proportionately lower equivalent cost and more rapid timeframe than previous studies.

DESCRIPTION: The core of the 1986-87 activity pattern studies will be replicated by conducting a statewide representative sample telephone survey of both adults and children, but to enhance that work by including questions on residence time and distances traveled and incorporating various improvements in the methodology. In order to enhance the ability to identify precise locations where activities take place, the survey will ask questions about the zip code, the address and/or other location identifiers for each travel endpoint reported. The interviews will be conducted using a Computer-

Assisted Telephone Interviewing (CATI) survey instrument to collect 24-hour retrospective diaries of the activity patterns of household members, along with answers to a number of exposure-related questions for each respondent. The resulting diary records will contain beginning and ending times for each distinct combination of location and activity occurring during the diary day. Additionally, the ancillary questions will obtain current information on people's use of and proximity to selected sources of indoor and outdoor pollutants.

BENEFITS: A key benefit of this new project is that it will provide current activity pattern data to update and enhance ARB's exposure models and estimates. The data are now nearly 20 years old and there have been a number of major changes in American society that need to be better reflected in the exposure models used by ARB and other agencies. In addition, children's activity patterns may have changed during this time. Reduced levels of outdoor activity by some children may have contributed to the national problem of childhood obesity; while at the same time, some children have grown increasingly active in sports and other physical activities. This study will provide valuable information about the current state of their activity patterns and their current potential exposure to air pollutants.

COST: $600,000

TITLE: Foothill Ozone Isoprene Experiment (FOZIE): Measurements and Modeling of Isoprene in Central California

PROBLEM: Photochemical models are essential tools used to develop State Implementation Plans (SIPs) for ozone and particulate matter. Models are sensitive to spatial and temporal distribution and source strengths of VOCs, NO_X, meteorological fields, sinks, and chemical reactions. Isoprene is the most abundant biogenic VOC (BVOC) emitted in North America (Guenther et al., 2000), and is several times more reactive than vehicle exhaust (Carter, 1994). BVOCs comprise significant fractions of emission inventories within California. The role of isoprene chemistry in tropospheric ozone production is well understood, but the magnitude and spatial and temporal distribution of isoprene emissions in California remain uncertain. Current BVOC emissions models such as U.S. EPA's Biogenic Emission Inventory System (BEIS), National Center for Atmospheric Research (NCAR) Model of Emissions of Gases and Aerosols from Nature, and ARB's Biogenic Emission Inventory Geographical Information System predict significant emissions of isoprene from oak woodlands distributed throughout the foothills and the Sierra-Nevada mountains of California. However, there have been no measurements of isoprene flux in these oak woodlands at a spatial scale larger than leaves and branches. Measurements at Blodgett Forest, approximately 30 km upwind of major sources of BVOCs show that isoprene and its oxidation products are dominant contributors to VOC reactivity in this region (Lamanna and Goldstein, 1999). Three-dimensional photochemical transport modeling suggests that large isoprene emissions may contribute to the ozone burden in adjacent urban areas of central and southern California, and this is supported by analyses of ozone contributions from isoprene oxidation based on measurements of isoprene oxidation products (Dreyfus et al., 2002). A coordinated set of isoprene flux measurements at leaf, canopy, landscape, and regional scales is needed to evaluate methods used to extrapolate leaf- and branch-level emission measurements to regional model scales, and to evaluate BVOC emission model performance. Such measurements would reduce uncertainty in BVOC emission inventories from oak woodland ecosystems that are likely the dominant isoprene contributors in California.

PREVIOUS WORK: Research supported by ARB's Biogenic Working Group (http://www.arb.ca.gov/research/ecosys/biogenic/biogenic.htm) generated essential databases and tools used in the development of ARB's BVOC emissions model BEGIS (Scott and Benjamin, 2003). Measured BVOC concentrations in ambient air and emission measurements taken from leaf to canopy scales have shown that BVOCs are emitted throughout California (Arey, et al., 1991, 1995; Baker et al., 1999; Corchnoy, et al., 1992; Harley, et al., 1998; Helmig and Arey, 1992; Karlik and Winer, 2001; Klouda et al., 2002; Kurpius and Goldstein, 2003; Goldstein and Schade, 2000; Schade et al., 1999, 2000; Schade and Goldstein, 2001; Winer et al., 1992). Satellite observations suggest areas of very high isoprene emissions in areas of California (Palmer, et al., 2003) which are home to native oak species with high isoprene emission potential (Karlik and Winer, 2001; Geron et al., 2001). Detailed isoprene flux measurements at scales ranging from leaf to region have been reported for emission model development elsewhere in the U.S., but none in California.

OBJECTIVE: The goal of this project is to measure isoprene fluxes and concomitant meteorological parameters (e.g., temperature, sunlight, sensible and latent heat flux) and vegetation parameters (e.g., species canopy cover, leaf biomass density, leaf density, leaf area index) used in BVOC emission models, at a range of spatial and temporal scales within an oak woodland site in California. Scales would include leaf (and/or branch) enclosure, canopy (micrometeorology tower), and regional (aircraft). The measurements will be used to provide a critical comparison of how well BVOC emission and 3-D photochemical models predict observed emissions rates and atmospheric isoprene mixing ratios.

DESCRIPTION: An oak woodland site will be selected that is representative of oak density in the foothills of the central Valley of California and is well suited to eddy covariance flux measurements from a tower. Quantitative descriptions of biomass, leaf mass, and leaf area index (LAI) for isoprene-emitting plant species at the site will be assessed though ground-based surveys and will be compared to regional estimates based on remote sensing. Canopy-scale fluxes of isoprene will be measured continuously for one year using an instrumented tower that will extend to above the height of the plant canopy. Aircraft-based measurements will be used to extrapolate the tower-based measurements of isoprene flux to a regional scale. The data collected from these measurements will be used to evaluate the performance of the California BVOC model Biogenic Emission Inventory Geographic Information System for isoprene. In addition, the measurements will be used to evaluate the combined performance of the emissions, chemical, and dynamical components of regional air quality models for predicting isoprene concentrations.

BENEFITS: Measurements at the range of proposed scales will provide bounds on regional isoprene emission and photochemistry air quality models. These measurements will also provide a test of approaches and factors used for scaling various types of plant emission measurements to regional models. The measurements will specifically address the magnitude and spatial variability of isoprene from California oak woodlands.

COSTS: $200,000 (Additional funds to be requested from the South Coast Air Quality Management District and the San Joaquin Valley Air Pollution Control District for a total project budget of $500,000.)

TITLE: Source Apportionment of Carbonaceous Aerosols Using Integrated Multi-Variant and Source Tracer Techniques and a Unique Molecular Marker Data Set

PROBLEM: Organic carbon and elemental carbon are important contributors to fine particle concentrations throughout the State of California. This carbonaceous material is important to human health, visibility and regional climate forcing. Although significant advances have been made in mechanistic and receptor based source apportionment models, there still exists significant uncertainty in the contributions primary and secondary sources make to carbonaceous particulate matter (PM) in non-attainment areas of California. There is a great need to apply tools that can provide a more definitive understanding of the impact of gasoline powered vehicles, diesel engines, biogenic derived secondary organic aerosol and anthropogenic derived secondary organic aerosol in California to develop effective PM control strategies and to support health and climate forcing studies.

PREVIOUS WORK: The Midwest St. Louis Supersite, funded by U.S. EPA, generated a time series of carbonaceous aerosol measurements that includes hourly fine particle organic carbon and elemental carbon concentrations, daily fine particle organic speciation measurements for a full two years. In addition, these measurements have been supplemented by monthly average molecular markers for both primary and secondary sources at five cities in the Midwestern United States. The unique data set, that has been made possible by analytical and instrumental advances for carbonaceous aerosol measurements, have led to significant advances in the application of receptor based source apportionment models and statistical methods to understand sources of organic carbon, elemental carbon and fine PM. Parallel measurements and subsequent receptor modeling efforts have yet to be employed in California.

OBJECTIVES: The goal of the project is to generate a full year of hourly organic and elemental carbon measurements and daily molecular markers measurements at a central site in the Los Angeles basin that can be used for complementary source apportionment and statistical analysis methods to apportion the contributions of primary and secondary sources on carbonaceous aerosol concentrations. A secondary objective of the project is to quantitatively determine the viability and uncertainty of using simple measurements, such as water soluble carbon, elemental carbon, and water soluble potassium, as source tracers in the Los Angeles basin.

DESCRIPTION: The project can be divided into two major thrusts: measurements and data analysis. The measurement thrust of the project will generate a year long time series of hourly elemental carbon and organic carbon measurements, daily molecular marker measurements, and daily measurements of bulk fine particle parameters including water soluble organic carbon, water soluble potassium and ultrafine particle number. The data analysis thrust of the project involves the applications of parallel source apportionment models methods including molecular marker chemical mass balance modeling (MM-CMB), molecular marker positive matrix factorization (MM-PMF) modeling, molecular marker iterative confirmatory factor analysis (MM-ICFA) modeling, as well as statistical analysis to identify trends in day-of-the-week, time-of-day, and

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plume analysis to identify the strengths and weaknesses of these complementary models. The data analysis thrust of the project will also include a comparison of the source apportionment results with elemental carbon, water soluble organic carbon, water soluble potassium, and particle number to determine accuracy of using these simple measurements as tracers for diesel PM, secondary organic aerosol, wood smoke, and mobile source emissions for health and climate forcing studies. More details on these efforts are provided below.

Measurements: Hourly organic and elemental carbon concentrations will be obtained using a Sunset Labs semi-continuous elemental and organic carbon analyzer, which were operated continuously at the St. Louis Supersite for four years (Bae et al. 2004). Twenty-four hour fine PM samples will be collected with a medium volume sampler designed by the University of Wisconsin-Madison and commercially sold by URG (Chapel Hill, NC) that operates at 92 lpm. Section of the daily samples will be analyzed by optimized GCMS methods that allow the required 400 samples to be cost effectively measured for primary and secondary organic tracers. The optimized gas chromatography/mass spectrometry methods have been developed under funding from the U.S. EPA and Electric Power Research Institute and were used for the analyzed of parallel samples from the St. Louis Supersite. Sections of the 24-hour fine PM samples will be extracted in high purity water and analyzed for water soluble organic carbon and water soluble potassium using a total organic carbon analyzer and ICPS-OES. In parallel to the filter based measurements, ultrafine particle number and fine particle mass will measured in real time using and ultrafine particle condensation nucleus detectors and a TEOM.

Data Analysis: The proposed data set will be analyzed using a MM-CMB model originally developed by Schauer et al. (1996) under funding from ARB using updated source profiles from the DOE Gas/Diesel Split Study and source profiles that are being generated from the Southern California PM Center (SCPC), which were based on samples analyzed by the University of Wisconsin-Madison. The MM-CMB model will also include source profiles for biogenic and anthropogenic derived secondary organic aerosol developed at the U.S. EPA, which have been previously integrated in the MM-CMB analysis though collaboration between the U.S. EPA and the University of Wisconsin, Madison. In parallel to the MM-CMB analysis, the MM-PMF and MM-ICFA models, which are multivariate receptor models that does not require source profiles as inputs, will be applied to the data. In addition other statistical methods will be used for the analysis of the data including day-of-the-week analysis (Lough et al. 2006), hour-of-the-day analysis (Bae et al. 2004), and plume analysis (Bae 2006) will be employed to further elucidate information about sources.

BENEFITS: The project will significantly reduce the uncertainty in the contributions of primary and secondary sources to carbonaceous aerosol concentrations in the Los Angeles basin and will help identify the most cost effective strategies for source apportionment efforts associated with State SIP development and future health studies.

COST: $400,000

TITLE: On-Road Motor Vehicle Emissions Measurements Including Ammonia, Sulfur Dioxide, and Nitrogen Dioxide

PROBLEM: There is very little information on ammonia emissions from real vehicles on the road. Ammonia is a major component of airborne PM2.5 and there are few other ammonia sources in the Los Angeles basin. Dynamometer studies at UC Riverside have shown that ammonia emissions vary with load and with the tier of emission control. Sulfur dioxide emissions, especially from diesel vehicles, are a potential indicator of misfueling.

PREVIOUS WORK: There has been one published study of on-road ammonia emissions measured by means of on-road remote sensing (Baum et al. 2000) which observed a relatively small number of vehicles. There is now an ultraviolet (UV) based on-road remote emissions sensor which reliably gives not only CO, HC, CO_2 and NO fuel-based mass emissions readings from passing light duty vehicles but also provides the same quality of data for nitrogen dioxide, ammonia, and sulfur dioxide. This development was described by Burgard et al. at the April 2006 Coordinating Research Council (CRC) Meeting in San Diego. The results from the only on-road light-duty diesel vehicle (LDDV) studies in Tulsa and Denver will be published shortly in Environmental Science and Technology. An emission inventory for the Los Angeles basin published by Huai et al. predicts that ammonia emissions are currently dominated by the ammonia emissions from older cars.

OBJECTIVE: The goal of the project is to monitor the above pollutants from approximately 60,000 light duty vehicles, 20,000 each in three regions of California, the Los Angeles basin, the Central Valley and the San Francisco Bay Area. The results, when combined with fuel sales data, will provide a fuel-based emission inventory and will investigate if there are any differences between the three regions in terms of emissions and in terms of potential misfueling.

DESCRIPTION: The FEAT 3000 is the University of Denver's routine on-road emissions monitor. It has been used in California for the IMRC in 1999 at several sites and for the CRC every two years at a single site, at the intersection of LaBrea Boulevard. and I-10 in Los Angeles. The instrumentation and the normally available data including speed and acceleration and vehicle make and model year are fully described in CRC E-23 reports available on the web at www.feat.biochem.du.edu. The new features which have been added include new optics and a wider UV detector array which allow NO_2, SO_2, and NH_3 to be monitored simultaneously with the routine pollutants.

In operation, a mobile van sits at the roadside during daylight hours for about one week at each location. The sites to be monitored will be the La Brea site in Los Angeles, a return to the interchange ramp (101N to 880N) in San Jose, and a suitably chosen site in the Central Valley. The techniques or research methods to be employed are identical to those used in two recent studies in the Denver area and in Tulsa OK which were reported at CRC 2006 in San Diego by Burgard et al. Other than the addition of the three new pollutant channels they are identical to those used in the CRC E-23 studies.

Tasks to be achieved include: 1) location of a suitable central valley site, preferably one used in previous ARB remote sensing studies, 2) apply to CALTRANS for permits for all sites, 3) ensure that all calibration gases are available and certified by appropriate authorities, 4) carry out the studies, 5) read license plates and match plates for make and model year with California DMV, 6) and report the findings.

BENEFITS: New knowledge of the current mobile-source ammonia, nitrogen dioxide and sulfur dioxide emissions inventory. An indication as to whether these emissions vary from region to region within California.

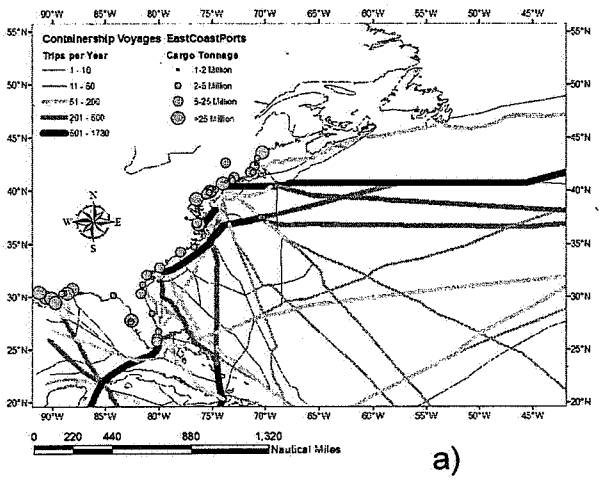
COST: $95,000

TITLE: Improved Geospatial Forecasting of Commercial Marine Vessels

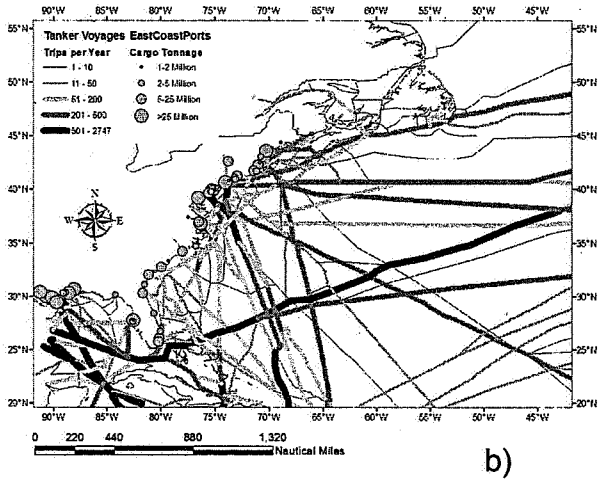
PROBLEM: Growth in goods movement, particularly seaborne imports and exports, is expected to remain strong for California over the next decades. These insights follow from forecast scenarios developed for and with ARB by Professor James Corbett, as cited in ARB documents for the California Goods Movement Action Plan. However, the current mix of types of ships and cargos are expected to change as containerized shipping dominates overall trade growth compared other cargo types, such as tankers and general cargo carriers. These differences can be modeled in the abstract from currently available data, but GIS-based modeling is needed to understand how asymmetric growth among vessel types will affect forecasts of ship emissions off the U.S. West Coast.

PREVIOUS WORK: A baseline inventory model for commercial marine vessels engaged in foreign commerce has been developed that uses "complete" arrival and departure data for ships calling on U.S., Canadian, and Mexican ports. This Ship Traffic Energy and Emissions Model (STEEM) was used to produce the first set of North American emissions inventories for a base-year of 2002 and forecast years 2010 and 2020. ARB and the Council on Environmental Cooperation supported its application as part of the multi-agency effort to understand the benefits of emissions reductions from ships, particularly a SO_X emissions control areas (SECA) designation. This work produced aggregate inventories for all vessel types and used national average growth rates to produce forecast scenarios. California-specific forecasts were developed from the methodology used in the North American forecasts, but not implemented regionally in the model due to potential discontinuities with national inventory results.

Similar work to separate traffic by vessel type was part of National Oceanic Atmospheric Administration funded work using an East Coast domain for STEEM. Routes dominated by different route types are illustrated in the figure below for a) container ships, and b) tankers. One may surmise that common routes or routes dominated by faster growing containership traffic would result in higher emissions in future years than routes that do not serve containerized shipping.



a)



b)

OBJECTIVE: The goal of the project is to extend the previous work to help reveal how different vessel types contribute to cargo ship emissions along major trade routes and how different growth rates among commodities shipped may affect the national-level forecasts currently used by ARB and SECA team agencies.

DESCRIPTION: This project will re-run 2002 base year data by vessel type and by month to better correlate observed port calls with coastal and offshore emissions. It will use these vessel-specific results for 2002 and available forecasts developed by Dr. Corbett and by SECA team contractors to perform more detailed forecasting for 2010 and 2020 (or different and/or additional years as needed).

BENEFITS: This work will continue to utilize the full North American data set, which means that improved insights for California will also be comparable with forecasts at the national level. This enables ARB to continue to understand how its Goods Movement Action Plan may benefit the state in the context of global seaborne trade. These results can enable both air quality modeling and climate change impact assessment to understand the impact of freight transportation on these issues, according to California's regulatory and policy priorities. Moreover, these results will advance STEEM capabilities to link with multimodal/intermodal models for freight transportation, providing both the most advanced waterway network and a source from which to estimate the numbers of truck and rail trips generated by imports and exports through California ports.

COST: $40,000

TITLE: Development of a California-Specific Intermodal Freight Transport Model

PROBLEM: It is expected that goods movement through California's ports will increase dramatically in the next twenty years, significantly impacting the state's transportation network and air quality. However, California does not have a freight transportation model that relates truck, locomotive, and ocean-going vessel activity with emissions models and commodity flow data. Such a tool is needed for decision makers to assess different strategies for mitigating the air quality impacts of goods movement.

PREVIOUS WORK: There are no known freight models that link emissions models and commodity flow data. The U.S. Department of Transportation (DOT) is currently funding development of a multi-modal freight transportation model on the East Coast, which will provide a GIS-based tool to describe and optimize freight flows across existing and modified transportation networks including ocean-going vessels, trucks, and trains as well as domestic and international commodity flows. That work would serve as a fundamental basis for this contract, and could incorporate California-specific elements through collaboration with current projects.

OBJECTIVE: The goal of this project is to develop a single, statewide intermodal freight modeling system linked to California freight flows, vehicle activity, and state/national transportation infrastructure.

DESCRIPTION: This project will build upon the national freight network being developed for the U.S. DOT by applying the national model framework to California. The model will integrate existing California-specific emission inventory tools and commodity flow data in a GIS environment. A multi-criteria optimization framework implicit in the model design will allow for comparative analyses of preferred routing and tradeoffs (economic, energy, fuel use, emissions/air quality) under both existing and alternate transportation scenarios.

BENEFITS: Development of an intermodal freight transport model will allow for analysis of the greenhouse gas and ozone precursor emissions impact of potential goods movement infrastructure improvements in California.

COST: $200,000

TITLE: Measuring Agricultural Fumigant Pesticide Emissions through In-Field Testing

PROBLEM: Fumigant pesticides are the largest contributors to the pesticide volatile organic compound (VOC) inventory. Under current assumptions, nearly 100 percent of the VOC emissions from fumigants are thought to be released to the atmosphere. Although there is ongoing work to obtain in-field measurements, additional research is needed to validate and expand on the work that is currently being done.

PREVIOUS WORK: In fiscal year 2004-2005, Dr. Scott Yates of the University of California, Riverside was granted a contract by ARB to look at different methods to reduce fumigant pesticide emissions. Dr. Yates will conduct a series of field experiments that are designed to estimate the emissions and potential VOC reductions for three fumigant pesticides that are most commonly used in California: metam sodium, 1,3-dichloropropene (1,3-D), and chloropicrin. The purpose of the experiments is to determine emissions estimates based on different application techniques including (a) broadcast shank fumigation with and without intermittent water seals, (b) shank fumigation comparing surface packing with an intermittent water seal, and (c) broadcast-shank fumigation with and without a surface treatment. Each of the experiments will be conducted on 5-acre fields in the San Joaquin Valley. Due to the high cost of in-field research, a limited number of parameters are included in this research. Therefore, additional work is needed to consider other parameters that may also reduce fumigant pesticide emissions.

OBJECTIVE: The goal of this project is to conduct additional field research to build upon the ongoing work to estimate the emissions and potential VOC reductions from fumigant pesticides.

DESCRIPTION: Perform in-field testing on commercial agricultural fields to measure fumigant pesticide emissions. Examples of additional work may include variations in application technique, water sealing practices, mitigation measures, fumigant type, soil type, and/or geographic region.

BENEFITS: This additional research will improve the accuracy of ARB's pesticide emissions inventory. It will also benefit the development of State Implementation Plans and assist in identifying additional mitigation strategies.

COST: $100,000 (Cofunded by the California Department of Pesticide Regulation)

TITLE: Source Apportionment of Atmospheric Dry and Wet Deposition of Mercury and Other Toxic Metals through Linkage to Atmospheric Measurements

PROBLEM: Atmospheric deposition is an important contributor to the overall input of mercury and other toxic metals to California's aquatic habitats. The inputs of these toxic metals threaten critical aquatic habitats, and in the case of mercury, present a probable human health threat. However, considerable uncertainty exists in the understanding the sources and atmospheric processes that control deposition of toxic metal deposition to California watersheds and water bodies. The contributions of wet and dry deposition from point and non-point sources need to be quantified to support efforts to develop control strategies to protect California aquatic habitats.

PREVIOUS WORK: There have been numerous studies to identify atmospheric sources and deposition fluxes of toxic metals. These studies include the Lake Michigan Mass Balance Study, an ongoing Natural Science Foundation (NSF) funded Greenland project, a Health Effects Institute (HEI) funded study addressing metal emissions from mobile sources, and U.S. EPA funded studies of speciated atmospheric mercury that have examined sources of mercury in St. Louis, Milwaukee, rural Wisconsin, Yellowstone National Park, and the Los Angeles basin. The tools developed in the completed and ongoing studies are readily adaptable to studying the sources of toxic metals depositing to California aquatic habitats. In addition, the project team has pioneered methods to measure mercury, methyl mercury, and toxic metals in the atmosphere, rainwater, lake and estuary water, and biota, which are needed to assess the impact of atmospheric deposition on aquatic habitats.

OBJECTIVE: The goals of the project are to: (1) enhance the measurements of toxic metals in wet deposition at an existing California site of the National Mercury Deposition Network (MDN) to include methyl mercury and toxic metals for one full year; (2) obtain collocated dry deposition measurements of toxic metals and mercury species; (3) obtain collocated measurements of speciated atmospheric mercury and toxic metals in parallel with the wet and dry deposition measurements; and (4) employ existing receptor based source apportionment models and dry deposition models to quantify the source and receptor relationships for atmospheric transport and to quantify the air/deposition relationships.

DESCRIPTION: Through a coordinated effort with the ARB and other California stakeholders, the specific sampling site for the project will be selected. If one of the four active MDN sites that currently exist in California (i.e. Yurok Tribe-Requa (CA20), San Jose (CA72), Sequoia National Park-Giant Forest (CA75), and Converse Flats (CA94)) is not appropriate, then project efforts will be directed at one of the twelve California NADP sites or another suitable location. There will be collaboration with the network operators to obtain wet deposition samples from the network site that would be suitable for mercury, methyl mercury and trace metals analysis to avoid the need to duplicate sampling. Researchers at the University of Wisconsin, Madison Water Science and Engineering Laboratory have a long history of working with the MDN network to obtain samples from the Great Lakes region for these purposes.

Dry deposition sampling, atmospheric particulate sampling and real-time atmospheric mercury speciation measurements will be conducted in parallel to the wet deposition sampling for a full year. Dry deposition will be directly measured using passive samplers and surrogate surfaces, and values compared with those calculated from indirect approaches. Size resolved atmospheric particulate matter samples will be collected using a PCIS (SKC) cascade impactor, which has been widely used in the past by the project team for metal analysis and atmospheric metal speciation efforts. The cascade impactor will be operated every third day to obtain three particulate matter size fractions (>2.5 µm, 1-2.5 µm, and <1 µm) for trace metals analysis by ICPMS analysis. The ICPMS methods developed by the project allow the quantitative determination of about 40 elements using microwave assisted acid digestion and high resolution ICPMS analysis. Mercury will be analyzed using established cold vapor atomic florescence (CVAF) methods. Although all 40 elements are not important toxic elements, the comprehensive analysis of 40 elements supports source apportionment efforts and deposition velocity calculations. The same suite of elements will be analyzed in the rain water sample, the dry deposition samples and the particulate matter samples.

A Tekran mercury speciation monitor that measures hourly reactive gaseous mercury (RGM), particulate mercury and elemental mercury (Hg^0) will be operated at the site for one full year. The project team has previously operated the Tekran speciation monitor for a full year in Milwaukee and Wisconsin and Devil's Lake State Park (Mercury TMDL site). Such data sets provide important insight into the dynamics of atmospheric mercury including plumes from sources impacting the sites as well as diurnal and seasonal patterns that can be linked to sources and atmospheric processing.

The data analysis portion of the project will focus on three major activities: 1) source apportionment, 2) quantifying wash out ratios and deposition velocities for toxic metals, and 3) assessing the seasonality of wet and dry deposition fluxes. Source apportionment tools will include identification of mercury plumes, as well as multi-variant receptor modeling and size resolved metals clustering methods to identify sources of the toxic metals.

BENEFITS: The proposed project will provide a more comprehensive assessment of toxic metal deposition in California, supplementing existing measurements that connect to the National MDN network. In addition, the project will provide critical information on the sources of toxic metal deposition in California, while providing a new framework for monitoring to support atmospheric source/deposition relationships for future studies and source apportionment efforts. The study will also provide critical data for the validation of mechanistic atmospheric transport models that are being used to predict present and future dry and wet deposition of toxic metals.

COST: $165,000 (Additional funds to be requested from the State Water Resources Control Board for total project budget of $300,000)

TITLE: Environmental Exposures in Early Childhood Education Environments

PROBLEM: Almost no information is available about environmental exposures in California's Early Childhood Education (ECE) facilities, although school environments are known to contribute to children's exposure to several pollutants, including molds, lead, and pesticides. These exposures can cause or exacerbate asthma and other respiratory illnesses or impair neurocognitive functioning in children. A total of 550,000, 50 percent of California children ages 3-5 years and 345,000, 23 percent of children under 3 years attend child care or preschools, and may spend up to 40 or more hours in these environments each week. Additionally, 146,000 staff work in the approximately 40,000 licensed facilities in California. Collectively, ECE facilities are varied and include home-based providers, centers operated like private schools or programs run by government agencies (e.g. pre-school in school districts or Head Start), or religious institutions. Few states, including California, have developed policies to protect infants and children in childcare and preschools.

PREVIOUS WORK: The First National Environmental Health Survey of Child Care Centers, conducted by the U.S. EPA and Department of Housing and Urban Development (HUD), was a probability-based study that tested 168 childcare centers for allergens, pesticides, and lead. These compounds were commonly detected, however few sites were tested in the western U.S. (~20), and data are not available to project exposures in California. This study also did not test for other pollutants, including endotoxin, phthalates, and VOCs, compounds potentially associated with childhood asthma. A questionnaire-based survey of 284 California facilities found that problems with mold, cockroaches, and other factors potentially associated with respiratory disease problems were common. However, no on-site inspections to validate the questionnaire were completed, and the response rate was less than 25 percent. Several studies have shown that poor housing quality, and allergen and pollutant exposures to children are highest among low-income communities. Thus, it is likely that levels of unhealthy environmental exposures are higher in ECE facilities located in low-income communities.

OBJECTIVE: The goal of the project is to assess environmental quality in a representative sample of child care facilities located in California's urban and agricultural communities.

DESCRIPTION: The assessments will include environmental monitoring, administration of detailed questionnaires, and facility inspections. There will be an identification of all licensed ECE facilities in one urban (Alameda) and one rural (Monterey) county. According to the California Child Care Resource and Referral Network, there are approximately 627 facilities in Monterey and 2,522 in Alameda. Using publicly available data, all licensed facilities will be grouped into home- or center-based facilities, and further subdivide center-based facilities into private for-profit, governmental, or non-profit categories. Address information will be used to map the facilities by census tract. Two hundred facilities will be randomly selected, ensuring general representation based on socioeconomic characteristics and urban/rural classification. Directors of these

facilities will be invited to participate in a detailed phone questionnaire to collect data about each facility's environment. If a director refuses to participate, the next facility on the list will be contacted.

For a subset of 45 facilities (23 in Alameda County and 22 in Monterey County), detailed environmental health inspections will be performed to validate the questionnaire data, and extensive environmental sampling will be performed. Pesticides, brominated flame retardants, phthalates, perfluorinated compounds, allergens, and endotoxin in dust will be measured. VOCs (EPA Method TO-15), aldehydes, pesticides, endotoxin, and particulates in air samples will also be measured. The inspection protocols will follow developed procedures, HUD, and school districts to inspect homes and schools that will adapted for use in ECE environments. Standard analytical methods such as GC-MS and immunoassays for allergens will be used to quantify indoor contaminants in air and dust samples. Standardized methods previously validated will include appropriate quality assurance and quality control procedures

The environmental measurement data will be used to characterize contaminant levels in ECE environments and estimate potential health risks associated with specific exposures. Factors associated with the presence of these substances, including pesticide use, building materials, pest and mold infestations, and local land use such as agriculture and industrial facilities will also be identified.

BENEFITS: Specific benefits include the development of new indoor concentration and exposure data for several volatile and semivolatile Toxic Air Contaminants and other chemicals for which there are little or no data in California. This information will allow ARB to greatly improve exposure assessments for young children by focusing on an environment where young children and their teachers spend large amounts of time. This work will include community partners to highlight findings from the study. Through these partnerships, knowledge and support efforts are built to improve environmental and public health for California's children.

COST: $500,000

TITLE: Development of Improved Environmental Chamber Experiments for Evaluating Contributions of Oxidation Products Ozone Impacts of Volatile Organic Compounds

PROBLEM: For maximum accuracy in assessing effects of control strategies on ground-level ozone formation, models must use chemical mechanisms that have been shown to correctly predict the impacts of individual volatile organic compounds (VOC) on ozone formation. Because of this, chemical mechanisms used in airshed models need to be evaluated using environmental chamber data. However, it has been found that for some VOCs the magnitude of the impact of the VOC on ozone formation is different in chamber experiments than in atmospheric simulations. A modeling analysis indicates that this is due to chamber experiments being much less sensitive to the effects on ozone of the reactions of the VOCs' oxidation products than is calculated to be the case for the atmosphere. This means that an important aspect of the mechanism affecting predictions of ozone in the atmosphere is not being adequately tested, and may not be giving correct predictions in airshed models. This is a particular concern because reactions of products tend to be the most uncertain aspect of the mechanisms of most VOCs, and most mechanisms represent them in a highly simplified manner.

PREVIOUS WORK: There is a large database of environmental chamber experiments used in the development and evaluation of the SAPRC-99 mechanism. This includes experiments in the University of California, Riverside Environmental Protection Agency (UCR EPA) environmental chamber, which was developed to improve representation of ambient conditions and permit use of lower, more representative, reactant concentrations. Compounds such as higher molecular weight alkanes and glycol ethers and esters used in coatings are found to have low or negative impacts in chamber experiments but the same mechanism that simulates the chamber results predicts positive ozone impacts in the atmosphere. A modeling analysis indicates that this is due to lower integrated radical levels in chamber experiments compared to the atmosphere. Exploratory calculations indicate that integrated radical levels can be increased by increasing the light intensity, duration, and/or UV intensity or by adding radical initiators in the experiments. However, some of these modifications result in lower sensitivities of the experiments to other aspects of the mechanism that are important in the atmosphere.

OBJECTIVE: The objective of this project is to develop and evaluate the current chemical mechanisms that are used to predict the impacts of individual VOCs on ozone formation. Specifically, chamber experiments will be designed and conducted to improve sensitivities of chamber experiments to product reactions and other aspects of the mechanisms that are important in ambient conditions.

DESCRIPTION: Methods to modify the UCR EPA chamber experiments to improve sensitivities of chamber experiments to product reactions and other aspects of the mechanisms that are important in ambient conditions will be investigated, first by modeling analysis and then by experimental tests. This may include increasing reaction durations, light and ultraviolet intensity, and experiments with injection of HONO, and

probably several types of experiments will be investigated. Evaluations will be conducted using representative compounds with various types of mechanisms and reaction products. The new methods will be used to evaluate mechanisms for compounds important in coatings and other emissions sources.

BENEFITS: If successful, environmental chamber experiments will give results that correlate better with predictions of atmospheric reactivity, which will increase the confidence in atmospheric reactivity predictions, and reduce chances for compensating errors in models. A significant source of uncertainty in model predictions of ozone impacts of individual VOCs, and ozone impacts in general, would be reduced.

COST: $200,000

TITLE: Formal Uncertainty Analysis for Modeling of Secondary Air Pollutants

PROBLEM: Atmospheric models are used to study the effects of future emission changes, and to demonstrate that comprehensive emission control strategies will lead to attainment of air quality standards. Models also synthesize understanding of relevant processes including emissions, transport, chemical reaction, and removal. Though use of models is required for regulatory purposes, there is widespread skepticism about model results due to uncertainties in model formulation and input data. A formal scheme for quantifying and ranking uncertainty contributions would facilitate improved communication of uncertainties and research needs among modelers, experimentalists, and policy makers.

PREVIOUS WORK: Comprehensive uncertainty analyses for atmospheric models are scarce, especially for the case of spatially-resolved models where computational costs are high. The few studies that have been done have only addressed ozone. Monte Carlo analysis of Lagrangian and Eulerian model results for ozone have been reported previously (Bergin et al. 1999, Hanna et al. 1998, 2001). Martien et al. (2006) describe and apply an adjoint sensitivity analysis procedure (ASAP) to a 3-D air quality model in southern California. They computed model sensitivity to approximately 900 model inputs, including emission rates, boundary and initial conditions, reaction rate coefficients, and surface deposition velocities. The adjoint method is especially well-suited to the case where there are many uncertain inputs and a few model outputs of interest. In contrast, the direct decoupled method (DDM-3D; Yang et al., 1997) is well-suited for studying effects of changes to a few model input parameters on many model outputs.

OBJECTIVES: The goals of this project are to: 1) evaluate air quality model performance against continuously measured ozone, gaseous ammonia and nitric acid, and PM nitrate; 2) conduct sensitivity analysis for ozone, nitric acid, and PM nitrate; and 3) calculate and rank input parameter/data uncertainties contributing to model uncertainty for each pollutant.

DESCRIPTION: Air pollution will be modeled in southern California for a weeklong period in the second half of August 1997 when continuous online measurements of ozone, PM nitrate and precursors were made at Riverside (Stolzenburg and Hering 2000). Retrospective emission estimates for summer 1997, as well as emission forecasts for 2010 will be considered, both factoring in the State's newly updated EMFAC 2007 model. CMAQ with SAPRC chemistry, driven by un-nudged MM5 model runs already done by ARB will be used. The adjoint sensitivity analysis procedure (Martien and Harley 2006) will be used to compute sensitivities for ozone, nitric acid, and PM nitrate at Riverside to hundreds of model inputs including all reaction rate coefficients, emissions of each species, boundary conditions, and deposition velocities. Quantifying sensitivity of population-weighted integrals of each pollutant throughout the study domain will also be performed. Sensitivities to anthropogenic VOC and NO_X emissions will be apportioned spatially and mapped, showing the emission grid cells that most strongly influence the model predictions.

The rate parameters of gas-phase reactions identified in previous studies as critical for ozone and nitrate production will be considered uncertain variables. Uncertainty factors for rate parameters of inorganic reactions will be obtained from the most recent atmospheric chemical kinetics panel reviews (e.g., Sander et al. 2006). Uncertainty estimates developed by Stockwell et al. (1994) and Wang et al. (2000) for parameters specific to the SAPRC mechanism will be updated for this study. Uncertainties in anthropogenic VOC and NO_x emissions, and biogenic VOC emissions will be estimated based on literature review and consultation with ARB staff. Uncertainty estimates for ozone and nitric acid deposition velocities will be developed based on the Wesely (1989) resistance model. A first-order uncertainty propagation will be done using sensitivity analysis results, and uncertainty contributions will be ranked for each model response listed above.

As a preliminary step in extending adjoint sensitivity and uncertainty analysis capabilities to secondary aerosol concentrations, an uncertainty analysis will be performed for the ISOROPIA aerosol thermodynamics model (Nenes et al., 1998) used in CMAQ. This analysis will be conducted with ISOROPIA used in a box model, with specified values of relative humidity and temperature and total concentrations of sodium, sulfate, nitric acid, chloride and ammonia. A range of conditions relevant to southern California will be studied. The results will be used to help guide the sensitivity and uncertainty analysis for PM nitrate in the full CMAQ model.

PM nitrate and precursor concentrations will be evaluated against continuous surface observations at Riverside over the same weeklong period modeled above. There will be an examination of vertical profiles of PM nitrate, as Neuman et al. (2003) have measured strong vertical gradients, with higher PM nitrate aloft where temperature is lower, within an otherwise well-mixed daytime boundary layer above Riverside.

BENEFITS: The quantification and ranking of model uncertainties provides a rational basis for prioritizing research to improve understanding of relevant processes. California would be well-served by application of a new analytical framework for air quality modeling, proposed here, that includes communication of uncertainties.

COST: $260,000

TITLE: Comparative Assessment Entrained and Directly Emitted Particulate Emissions of Agricultural Field Equipment

PROBLEM: While the agricultural community has demonstrated a willingness to consider actions to reduce emissions (established by positive, cooperative response to San Joaquin Valley Air Pollution Control District Conservation Management Practices process), very little information is available to allow the comparison of field equipment operations on the basis of air pollution fugitive particulate (PM10) emissions. The comparative fugitive emissions of various field equipment types have not been quantified. This information would be valuable for decision-making processes for selection of controls to reduce fugitive particulate missions.

PREVIOUS WORK: USDA-funded University of California, Davis field studies did not successfully include equipment comparison. The California Regional PM10/PM2.5 Air Quality study obtained extensive funding through USDA to assess agricultural field operation emissions. The results of this research were used to develop improved emission estimates for many agricultural activities. The type of equipment used to conduct activities was documented; however, when different equipment types were studied, the ambient measurement methods were not able to establish differentiation with statistical confidence. Soil variations that occur within agricultural fields make it difficult to establish equivalent testing for comparisons.

OBJECTIVE: The goal of this project is to develop an improved testing procedure to quantify agriculture field equipment emissions on a comparable basis. The improved test method will be used to identify the PM10 reduction potential of various types of currently available agricultural field equipment. Frequently used techniques, practices and equipment types that have a significant likelihood of providing a potential for reduction of PM10 emissions from agricultural activities will also be assessed.

DESCRIPTION: Measurement protocols will be developed for improved methodology for equipment fugitive emission comparisons. Project selection will identify advanced methods, using laser based measurements or other techniques that have a demonstrated ability to make field measurements to compare equipment operation and fugitive particulate emissions from the agricultural activity. The next step in the project will be to evaluate and certify the improved methodology. The improved methodology will be used to evaluate the particulate entrainment of various implements, whether used individually or in combination with other implements. A classification system of equipment options for various agricultural practices and their applicability to various crop and animal husbandry practices will be developed as the final aim of the project.

Equipment for review would include devices in current use for:

- Land preparation activities,
- Manure management activities
- Harvest activities
- Activities for reducing agricultural burn (e.g. shredding)
- Cultural activities (e.g. weed management)

Assessment will include comparison of fuel use to ensure that additional direct particulate emissions from fuel combustion are included in the comparison. Decreased fuel efficiency or increased operating hours to conduct the same operations with different methods will be included in the comparative analysis.

The latest PM10 emission inventory shows nut crops as having the highest emission factor for harvest activities of 40.8 lbs of PM10 per acre compared to the lowest emission factor of 0.085 lbs of PM10 per acre for tree fruits. A similar analysis can be done for the other agricultural activities. Based upon the emissions estimates for crop activities, priorities can be established for the review of equipment in common use for the higher emitting activities. Evaluation of operational constraints for applicability of equipment use, such as farm size, may assist in identifying reasonable equipment limitations and usage.

BENEFITS: Evaluation will be helpful in reducing PM10 emissions by providing improved methods for assessment and quantification of emissions that subsequently guide control efforts of the agricultural operators. The information will also be useful for the update and improvement of emissions inventory estimates and the quantification of control measures that are implemented.

COST: $240,000

TITLE: Developing a California Inventory for Industrial Applications of Perfluorocarbons, Sulfur Hexafluoride, Hydrofluorocarbons, Nitrogen Trifluoride, Hydrofluoroethers, and Ozone Depleting Substances

PROBLEM: With the passage of AB 32, the California Air Resources Board (ARB) is charged with developing and implementing workplans to enable the State of California to reach its goal of CO_2-equivalent greenhouse gas (GHG) emission reductions to 1990 levels by 2020. Originally, the Climate Action Team (CAT) only examined hydrofluorocarbons (HFC) reduction strategies, but upon further investigation, it has become apparent to ARB staff that greater global warming potential (GWP) greenhouse gas reductions are possible if other, high GWP GHGs are considered in addition to HFCs.

Roughly 3.75 million metric tons (MMT) of SF_6 (in CO_2-equivalents) and 5.4 MMT of perfluorocarbons (PFC) (in CO_2-equivalents) were emitted in CA in 2005[1]. The 2020 CAT target is estimated to be 400 MMT, and although high GWP gas emissions from non-refrigerant and air conditioning (RAC) industrial applications do not account for a large percentage of the total emissions, cost-effective GHG emissions reductions may be possible. Additionally, potential emissions from other high GWP GHGs used in non-RAC industrial applications are unknown, but may significantly contribute to overall GHG emissions.

PREVIOUS WORK: There have been no California-specific inventory efforts to quantify banks and emissions of high GWP GHGs in non-RAC industrial applications. The U.S. EPA developed a "Vintaging Model" to estimate banks and emissions of high GWP gases on the national level, but this model relies on inputs that are classified as Confidential Business Information by the U.S. EPA and cannot be disclosed to or utilized by ARB. It is therefore necessary to develop a California-specific inventory to quantify emissions rates and banks of high GWP GHGs by application.

OBJECTIVES: The goals of the project will be to quantify emissions rates (during production and use), application growth rates, chemical substitution rates, banks, and end-of-life disposal emissions (if applicable) for each high GWP GHG in each application. Mitigation strategies, such as emissions reductions associated with chemical substitutes, alternatives, or process changes will be examined in terms of costs and benefits as well as life cycle climate performance (LCCP). The cost and benefits of recovery and destruction of high GWP GHGs in each application will be estimated.

DESCRIPTION: A detailed bottom-up inventory for high-GWP GHG in California will be developed. A methodology for generating the inventory that may include data gathering from trade associations as well as surveying the industrial sectors that employ high GWP GHG in various applications will be necessary as part of this project

[1] Numbers from U.S. EPA report "U.S. High GWP Emissions 1990-2010"; distributed to CA by 2005 population fraction, 12.8 percent

The following should be addressed:

- PFC use, banks, and emissions in California (semiconductor manufacturing, aluminum smelters, fire extinguishing, Ozone Depleting Substances (ODS) substitution; PFC/PFPE emissions from solvents)
- Sulfur Hexafluoride (SF_6) use, banks, and emissions in California (semiconductor manufacturing, electric power transmission and distribution, magnesium production and parts casting)
- HFC use, banks, and emissions in California (semiconductor manufacturing, aerosols, fire extinguishing, solvents)
- Nitrogen Trifluoride (NF_3) use, banks, and emissions in California (semiconductor manufacturing)
- HCFC-22 emissions from HFC-23 production
- Hydrofluoroethers (HFE) use, banks, and emissions in California (HFEs have relatively low GWPs, but may be used in large quantities in industrial applications, clothing dry cleaners, and by consumers)
- ODS banks and emissions in California (stockpiles of Class I and II ODS, such CFCs, HCFCs, Halon 1211, 1301, and 2402, carbon tetrachloride, and methyl chloroform, used in the past for solvent cleaning, fire extinguishing and explosion protection [industrial, aviation, military, and other applications])

In terms of overall emissions of high GWP gases (PFCs, HFCs, and SF_6), the most important sector is projected to be semiconductor manufacturing in 2010.[2] All other sectors such as solvents, aerosols, fire extinguishing, HCFC-22 production, magnesium and aluminum production, and electric power transmission/distribution are expected to be similar in magnitude in terms of projected emissions in 2010. Stockpiled Class I and II ODS are not included in estimates of high GWP GHG emissions, and stockpiled quantities of these substances in California are currently unknown, although 1996 national stockpile estimates exist for some chemicals utilized in solvent cleaning applications[2].

BENEFITS: By improving the inventory of high GWP GHGs used in non-RAC industrial applications, it will be possible to identify cost-effective reduction strategies. Some of the benefits of inventory development and high GWP GHG emissions abatement could include:

- Control of high GWP emissions in industrial applications could be a cost-effective way to reduce high GWP gas emissions without having to change consumer behavior.
- Carbon offsets could possibly be given to entities that recover and destroy high GWP GHG.
- Control of high GWP emissions from stockpiles could mitigate impacts on stratospheric ozone depletion as well as global warming.

COST: $200,000

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[2] U.S. EPA, The U.S. Solvent Cleaning Industry and the Transition to Non Ozone Depleting Substances, Prepared by ICF Consulting, 2004.

TITLE: A Spatial Synoptic Classification Approach to Projected Heat Vulnerability in California under Future Climate Change Scenarios

PROBLEM: Excessive heat is the leading cause of weather-related deaths across the United States. In addition to its direct impacts, sustained extreme heat events exacerbate pre-existing cardiovascular, respiratory, and other conditions. During the summer of 1980, as many as 10,000 deaths in the US may have been associated with oppressive heat, while the summer heat wave of 2003 claimed over 15,000 lives in France and 40,000 throughout Europe. In addition, considerable research has shown that the elderly are disproportionately affected by the heat; by 2030 the number of Californians 65 and older is expected to more than double, to over eight million, with those 85 and older increasing to over two million. Atmosphere-ocean general circulation models (AOGCM) projections indicate summer temperatures in California could increase by up to 10 degree Celsius. Such changes are likely to have substantial and perhaps disproportionate effects on extreme heat and related health impacts.

PREVIOUS WORK: Under a range of climate scenarios, heat vulnerability is likely to significantly increase relative to present-day levels. Using statistically downscaled data from two AOGCM for higher and lower emission scenarios, a lengthening in the annual heat wave season across California by up to 9-13 weeks was reported, yielding 6 to 8 times as many oppressively hot days, and, in the absence of acclimatization, leading to up to a tenfold increase in heat-related mortality for Los Angeles by century's end.

OBJECTIVES: The goal of this project is to evaluate the heat vulnerability of the California population in the future, based on the air mass types most closely associated with observed current-day heat-related mortality. To achieve this objective, four main questions need to be answered: 1) How do present heat-health relationships vary with age and other factors? 2) To what degree have large-scale atmospheric circulation patterns and their associated air masses already changed, and are projected to change in the future? 3) What is the projected impact on human health assuming model-simulated temperature increases and changes in air-mass frequency, duration, and timing? 4) What is the expected adaptation potential of the population in each city to changing conditions? These questions will be answered for seven California metropolitan areas: Los Angeles, Sacramento, Fresno, San Bernardino / Riverside, San Diego, San Jose, and San Francisco.

DESCRIPTION: In order to project future heat vulnerability, a thorough reanalysis of the heat-health relationship based on available local historical mortality data for each of the metropolitan areas listed above will be conducted. An analysis will be performed by classifying past days according to the holistic Spatial Synoptic Classification (SSC) air mass that has been incorporated into heat warning system development. Variations of standardized mortality within oppressive air masses will be assessed by developing an algorithm based on supplemental factors. Algorithms will be developed for mortality that account for the three most important variants: the air mass on the particular day, how long the offensive air mass has persisted, and the time of season.

Climate projections for future conditions based on the Intergovernmental Panel on Climate Change, Fourth Assessment Report, Special Report on Emissions Scenarios (SRES) high (A1fi), mid-high (A2), and lower (B1) emission scenarios will be obtained from three of the latest generation of coupled atmospheric/oceanic GCMs (AOGCMs): the NCAR/DOE Parallel Climate Model, the UK Meteorological Office HadCM3 model, and the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory CM2.1 model. Two primary sets of experiments and subsequent diagnostic studies will be conducted to quantify the individual and combined impacts of global climate changes on human health. First, historical simulations will be driven by global climate conditions selected from the period 1957-2000 for the historical GCM simulations as well as the NCEP/DOE reanalysis of observed data. Simulations using the reanalysis will serve as the base for validation, while others will be the baseline reference to determine the individual and combined impacts of global climate change. Second, future projections for the SRES A1fi, A2 and B1 scenarios for each of three general circulation models (PCM, GFDL and HadCM3) will be used to drive altered future conditions, changes in SSC air mass type frequencies and persistence, and the projected change in heat-related human mortality assessed as described next.

Utilizing NCEP ERA-40 reanalysis data, four times-daily gridded 700-hPa geopotential height fields and 850mb temperature and humidity over North America (20°N to 60°N; 60°W to 130°W) for the entire warm-season period of May 1 to September 30 for the years 1957-2003. These gridded data will first be resampled to the same resolution as the AOGCM output. Using principal components analysis and hierarchical cluster analysis (Yarnal 1993), each of these days will be classified into one of several circulation types that represents the large-scale mid-tropospheric flow.

The impact of acclimatization will be assessed by a new acclimatization procedure first utilized in Hayhoe et al. (2004). Rather than using "analog cities" where population characteristics and demographics may be significantly different than the target cities, this new acclimatization procedure assumes that people will most likely respond to heat under climate change conditions as they do today during the very hottest summers.

BENEFITS: Despite any potential future acclimatization, results will show, due to the aging of the US population, a general rise in heat-related mortality; in a warmer world, this vulnerability would increase significantly further. The physically based nature of the modeling system will result in a more complete scientific understanding of the complex interactions among global and regional climate, extreme heat events, and human health, as well as the uncertainties involved.

COST: $175,000

TITLE: The Climate Change Industry in California: An Economic Analysis Assessing the Current Market and Prospects for Growth in the Global Economy

PROBLEM: Government policies relating to air pollution and greenhouse gas emissions in combination with rising oil prices and a strong desire for energy security are creating market drivers of what could be called the climate change industry. Just as the oil and gas industry is one of the world's largest industries today, alternative energy and power sources in a post-petroleum economy will be one of the world's largest industries tomorrow. However, a clear definition and quantification of climate change industry is lacking, along with an idea of where California ranks in the U.S. and global markets in this increasingly important sector.

PREVIOUS WORK: Little has been done to define and quantify the climate change industry in total. Some market analysis has been done in solar energy, wind power, geothermal energy, fuel cells, hydrogen, biofuels, emissions trading and other broad areas like clean energy, but aggregating this information into a clear picture has not been performed.

OBJECTIVE: The goal of this project is to define and quantify the climate change industry, forecast future growth scenarios and characterize California's place in this industry.

DESCRIPTION: Research would involve defining the climate change industry into segments, identifying companies in each segment, and collecting and compiling revenue data on as many companies as possible. Building databases of companies, reviewing existing information, conducting surveys, performing interviews would all be elements of the research. The research project would include data collection, data analysis, and segment and industry modeling.

BENEFITS: There is an emerging and potentially very large industry up for grabs, framing the climate change industry and assessing its potential could be very instrumental in developing state and other programs in support of the industry. In addition, there will likely be considerable resistance to ARB and other agency policies to reduce GHG emissions by the generating community, so a clear argument demonstrating the economic contribution of a climate change industry that would develop would provide a positive counter argument.

COST: $200,000

TITLE: Evaluation of Efficiency Activities in the Industrial Sector Undertaken in Response to Greenhouse Gas Emission Reduction Targets

PROBLEM: In 2005, Governor Schwarzenegger announced greenhouse gas (GHG) emission reduction targets for California which call for reducing emissions to 2000 levels by 2010, to 1990 levels by 2020, and to 80 percent below 1990 levels by 2050. The 2020 targets were included in the California Global Warming Solutions Act of 2006. Meeting these goals will require input from all sectors, including the industrial sector. Many countries around the world have similar national level GHG reduction or energy efficiency targets, and comprehensive programs focused on implementation of energy efficiency and GHG emissions mitigation measures in the industrial sector are essential for achieving their goals. A combination of targets and industry-focused supporting programs has led to significant investments in energy efficiency as well as reductions in GHG emissions within the manufacturing sectors in these countries; information on the successful elements of these programs can help California meet its goals.

PREVIOUS WORK: This research will build on programmatic work that has already been completed in other countries, and will report their successes or failures, evaluating lessons learned and applicable elements for California. For example, many countries have had comprehensive industrial sector energy efficiency programs since the 1990s that actively engage a large portion of the national industrial sector (e.g. 90 percent of industrial energy use is covered by the programs in the Netherlands and the UK) and that have delivered significant energy savings. The UK's Climate Change Agreement program, for example, which includes industries that are important in California such as semiconductors, food processing, and cement manufacturing, has consistently exceeded the program's GHG emissions reduction targets. Lawrence Berkeley National Laboratories (LBNL) researchers previously performed two related studies that were not focused on California: 1) Tax and Fiscal Policies for Promotion of Industrial Energy Efficiency: A Survey of International Experience, and 2) Energy Efficiency Programs and Policies in the Industrial Sector in Industrialized Countries (available at http://industrial-energy.lbl.gov/node/129 and http://industrial-energy.lbl.gov/node/132).

OBJECTIVE: The goal of this research is to identify the characteristics of successful industrial sector greenhouse gas emissions reduction and energy efficiency programs in other countries in order to provide a summary of lessons learned and make recommendations for specific industrial sector program designs that could be implemented in California in support of the 2020 GHG emissions reduction target outlined in the 2006 Global Warming Solutions Act.

DESCRIPTION: This research begins with a characterization of the industrial sector in California, determining which industrial sub-sectors are the top energy consumers and largest CO_2 emitters. Industrial sector energy efficiency and GHG emission reduction programs in other countries (such as Australia, Canada, Denmark, France, Japan, Netherlands, and the UK) that focus on the industrial sub-sectors that are most important in California will then be examined.

For each program identified that addresses industries that are important in California, the general program design will be described along with an assessment of the level of industry participation and the realized energy savings. Program design elements such as information dissemination related to efficiency options, facility auditing, benchmarking, facility-level target-setting, development of implementation plans, energy management programs, monitoring of progress toward targets, and financial incentives will be described. Further, a survey of program managers will be conducted to identify the top barriers faced when initiating the program, both real and perceived by the manufacturers, and to understand how these barriers were addressed. To the extent possible, detailed information on specific GHG emission reduction technologies and measures that were undertaken by facilities participating in national level GHG emission reduction programs in the top GHG emitting sub-sectors in California will be compiled.

The project will conclude with a summary of lessons learned from comprehensive industrial energy efficiency or GHG mitigation programs in other countries and there will be recommendations for specific industrial sector program designs that could be implemented in California in support of the 2020 GHG emissions reduction target outlined in the 2006 Global Warming Solutions Act.

BENEFITS: The industrial sector consumes 25 percent of the energy used in California and emits 28 percent of CO_2 produced in the state. This project will identify program and policies that have effectively targeted this sector in other countries to achieve real energy and CO_2 savings. Increased energy efficiency and reduced GHG emissions can also lead to cost savings and improved competitiveness for industries, reduced emissions of NO_X, SO_X, and particulate matter, reduced water consumption, reduced production of waste, and improved product quality.

COST: $100,000

TITLE: Retail Climate Change Mitigation: Life-Cycle Emission and Energy Efficiency Labels and Standards

PROBLEM: AB 32 established caps on greenhouse gas (GHG) emissions in California. The caps mandate a 25 percent decrease in emissions by the year 2020 and a further 80 percent reduction by 2050. A key obstacle to implementing the law is leakage: as emission levels are restricted in the state, what will prevent businesses from simply moving out of state and exporting their products back into California with their high embedded carbon content?

The Climate Action Team (CAT) report (Cal-EPA 2006)[1] discusses leakage in the context of the market-based cap and trade systems envisioned for California's emission reduction at low cost. The CAT report describes five key elements in a sector-based cap and trade strategy: electricity generation, oil and gas extraction, oil refining, cement production, and landfills. However, these sectors produce only about 30 percent of the state's GHG emissions. Furthermore, the CAT report does not present an emission allowance policy that is relevant to regular product purchases and imports of consumable products and durable equipment other than automobiles. If the climate impacts of regular retail purchases are not apparent in the new emission-cap market, most consumers will be unable to participate in climate change mitigation decisions. Thus, the formulation of a system of embedded GHG emission accounting, pricing, incentives and trading activities remains a fundamental need in the development of comprehensive climate change mitigation markets in the state. Many products such as beef, cheese, milk, and fertilizer can have as much if not more emissions per dollar spent than gasoline.

PREVIOUS WORK: Masanet et al. (2005)[2] devised a method for estimating the life-cycle carbon content of many common retail products as a function of how they are made, used, and disposed of. A labeling and incentive program that allows California consumers to respond to and use this information is the next logical step.

OBJECTIVE: The goal of this project is to develop a framework that allows for the estimation of the potential emissions reductions that could be attained through the funding of incentives, product endorsements, performance labels, or public sector buying programs for low life-cycle GHG emission products.

DESCRIPTION: A labeling and information system framework for embedded life-cycle emission impacts that can be implemented in retail businesses will be developed. The keys to the proposed retail information system are credible default GHG emission intensities for different classes of products and a workable certification scheme wherein product suppliers can document and certify life-cycle GHG emission intensities that

[1] California Environmental Protection Agency (Cal-EPA). 2006. *Climate Action Team Report to Governor Schwarzenegger and the Legislature.* http://www.climatechange.ca.gov/climate_action_team/reports/2006-04-03_FINAL_CAT_REPORT.PDF. Sacramento, California: California Environmental Protection Agency (Cal-EPA).

[2] Masanet, E., L. Price, S. de la Rue du Can, R. Brown, and E. Worrell. 2005. *Optimization of Product Life Cycles to Reduce Greenhouse Gas Emissions in California.* CEC-500-2005-110-F. Sacramento, California: California Energy Commission, PIER Energy-Related Environmental Research.

deviate from the default values. Creating an "opt-in" market for low-carbon-content products will allow businesses to compete actively for "green" consumer demand, and consumers to aid climate change mitigation through "climate-aware" purchase decisions.

The estimation method described in Masanet et al. can be used for estimating the life-cycle GHG emission content of various products. To assess the potential consumer response a model of brand competition in a "carbon-aware" market will be developed. Using elasticities derived for similar type programs or products, such as the U.S. EPA Energy Star program, the market for organic foods or other "green" label products, or through consumer surveys or market experiments, the total possible emissions mitigation attainable through the substitution of high-emission product for lower-emission products will be projected. Finally, several market-enabling policy and program alternatives that could be implemented will be investigated to determine which type of type of program is the most applicable for each product type.

Specifically, this study will be a policy analysis and design effort to examine how to maximize the potential economic demand-side leverage of product life-cycle emission information through labeling and incentive programs in the retail sector. The final output of the research will be a report that includes a list of the products in California that may be the most amenable to life-cycle GHG emissions labeling and/or product standards, an estimate of the GHG emissions reduction potential, and recommendations of how such programs should be enacted in California to maximize emissions reductions.

BENEFITS: This project will result in a method, framework, and potential programs for tracking, reporting, and responding to the life-cycle carbon emission content of a diversity of retail products. As such, it will provide new opportunities for attaining GHG emissions in additional sectors that represent many millions of tons of CO_2-equivalent life-cycle emissions per year. By providing for these new emissions reduction opportunities and mechanisms, this research may provide tens to hundreds of millions of dollars worth of environmental benefits to the state over the long term.

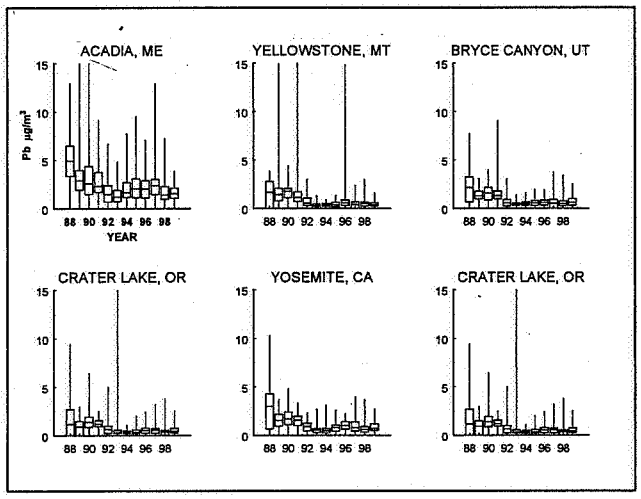
COST: $300,000

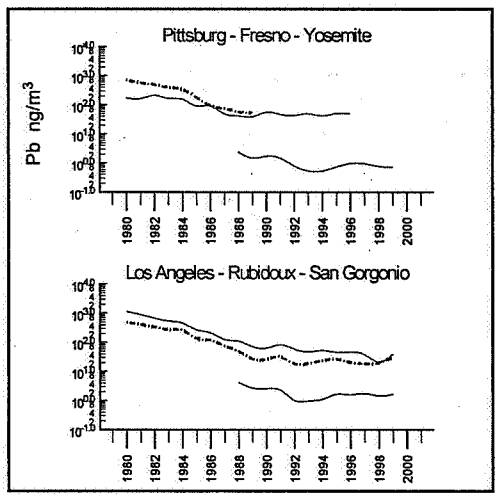
TITLE: Asian Aerosol Impacts in Urban and Interior California

PROBLEM: Global-scale pollutant transport increases the local "background" pollutant burden in California, reducing the amount of local emissions that can be permitted and still attain State and Federal Ambient Air Quality Standards. Asian dust, combustion aerosols, and ozone all contribute to the pollutant burden in the lower free troposphere over California. Future growth of Asian emissions will increase this background burden and may complicate attainment of air quality standards in California.

High altitude monitoring sites have shown that Asian aerosols dominate the mean composition of the lower free troposphere over California, while coastal sites show minimal impact. The degree of mixing of Asian pollutants at low altitudes at inland sites is expected to be greater than at the coast, but there are no published assessments of this impact.

PREVIOUS WORK: Unpublished data (left plot) show that the IMPROVE network captured the last few years of U.S. leaded gasoline use, and that there was a significant





rebound in lead at IMPROVE sites in the years 1995-1998, presumably due to the Asian economic boom of that period. Comparing IMPROVE with ARB lead data (right) shows a weak rebound at Rubidoux, an inland site, and a no clear rebound at Los Angeles North Main, nearer the coast; in central California, Pittsburg, in the Sacramento –San Joaquin Delta, shows a possible rebound, while data from Fresno are incomplete.

OBJECTIVE: The goal of this project is to use a combination of an annualized lead emission inventory for Asia and transport analytical methodologies to assess low altitude Asian pollutant impact to major California air basins (South Coast, San Francisco Bay, San Joaquin, and Sacramento) in the 1990s and to calibrate tropospheric mixing to low altitudes to extrapolate more recent IMPROVE observations to present conditions.

DESCRIPTION: The analysis will consist of five tasks: 1) develop an annually-resolved lead emission inventory for lead in Asia for the 1990s; 2) assess Asian lead transport to

the IMPROVE sites in California by association with Asian soil markers as described in peer-reviewed literature; 3) using the Asian lead emission inventory for the 1990s, develop a statistical relationship between Asian emissions and observed IMPROVE lead concentrations; 4) develop "transfer coefficients" that statistically relate lead concentrations at IMPROVE sites to the low altitude lead data for the period 1995-1998; and 5) combine results to estimate transport efficiency for Asian emissions to low altitude California, and thus predict the impact of Asian emissions growth on California air quality.

BENEFITS: The data from this project will provide a direct estimate of past and present impacts of Asian emissions on air quality in California's most polluted air basins. Constructing quantitative links between Asian lead emissions and California lead concentrations will provide a tool to evaluate the risks to California from current rapid Asian economic growth and consequent expansion of emissions.

COST: $80,000

TITLE: Particulate Matter Measurement for the 21st Century: Implementing a Program to Quantify Internal Combustion Engine PM Using Real-Time Measurement Techniques

PROBLEM: Ultrafine particulate matter (UFPM), especially UFPM from combustion sources, has recently become a heightened concern for the ARB. The ARB faces a situation where both the quantity (i.e., mass) and quality (i.e., composition) of internal combustion engines (ICE) PM emissions are changing, at the same time as the ARB is implementing new or revised methods of measuring PM mass emissions. The modern, low PM-emitting technologies being deployed, concerns regarding UFPM emissions, and the measurement issues and problems being encountered when measuring such low emissions, combined with the advent of real-time PM measurement technologies, suggests that there is now a convergence between PM mass and UFPM number concentration measurements, and that it is time to visit a number of issues. These issues include the viability of the current filter-based methods, making relevant UFPM measurements, and the potential for real-time PM measurement techniques to simultaneously address the issues of measuring PM mass emissions as well as UFPM number concentrations (or some other UFPM metric). Meanwhile, on a separate front, there is an immediate need to reconcile the different PM mass emissions results reported by different currently available PM portable emission measurement systems (PM PEMS). In this way, PM PEMS can be used with confidence for emissions inventory development and other ARB needs.

In essence there are two distinct problems: 1) addressing near-term (immediate) PM PEMS data needs for ongoing and upcoming programs such as emissions inventory and emissions monitoring, and 2) addressing longer-term needs such as measurement issues and methods for late model, very low mass-emitting engines.

PREVIOUS WORK: A large body of work exists regarding both PM mass emissions measurements, as well as UFPM particle characterization. Laboratory, roadside, on-roadway, and atmospheric studies have been, and are being conducted to better understand PM formation, fate, and public exposure.

On a parallel path, a variety of real-time PM measurement instruments have been under development and are being refined. This includes such measurement techniques as laser light scattering, photoacoustic, laser-induced incandescence, quartz crystal microbalance, and taper element oscillating microbalance for mass emissions, and methods using electrical mobility for particle characterizations.

OBJECTIVE: The goal of the project is to implement a comprehensive study for addressing PM measurement issues by using various real-time instruments. The project will include both a near-term and a longer-term study.

DESCRIPTION: The project will be centered on the evaluation of real-time PM measurement instruments and would involve interested stakeholders, including other federal and state government agencies, engine/vehicle manufacturers, instrument

manufacturers, and members from academia. The overall study will include the formation of a "PM measurements panel" under the auspices of the Coordinating Research Council. The PM measurements panel would serve an advisory role on PM measurement research, and would be involved in the organization of a PM measurement workshop. The workshop would establish the best metrics to utilize to fully characterize PM emissions such as mass, number concentrations, surface area, etc., and would provide guidance to instrument manufacturers and to stakeholders planning to sponsor PM measurement-related research projects.

The study will include a near-term element that would address immediate ARB programmatic needs such as emissions inventory and emissions monitoring projects (e.g., the off-road showcase project), and would involve currently commercially available PM PEMS and focus on PM mass emissions measurements. To the extent possible, ARB test facilities would be offered as an in-kind contribution to this program, and similar in-kind (and dollar) contributions would be sought from other stakeholders. The near-term program would be expected to highlight PM measurement issues, and to some extent, serve as a prelude to the longer-term program.

The study will also include a longer-term element. For the longer-term, the objective would be to approach the problem of PM emissions measurement from the scientific perspective of health effects and atmospheric processes, but to culminate in the development of practical engineering solutions to PM emissions measurements. For example, laboratory, wind tunnel, or other methods could be evaluated for their viability to study PM formation and fate under controlled conditions with an eye towards developing test procedures and methods. Other techniques such as using particle number and morphology as a means of quantifying PM mass could also be investigated. In addition to studying real-time PM measurement methods, the viability of continued use of PM mass collected on filter-media as the regulatory 'gold standard' (reference method) would be critically evaluated.

BENEFITS: This project would benefit the ARB by establishing a single PM measurement method (or at least a set of complementary methods) that could span the entire PM mass and size domains. One immediate benefit would be the development and implementation of consistent PM measurement methods across the domain of ARB programs (something that is currently not the case). The methods developed could be used for mass emissions measurements, but could also be utilized in the event that the ARB decides to regulate ultrafine PM emissions from ICEs and other combustion sources.

COST: $500,000

CALIFORNIA AIR RESOURCES BOARD

NOTICE OF PUBLIC MEETING TO CONSIDER THE APPROVAL OF THE 2007 SAN DIEGO 8-HOUR OZONE ATTAINMENT PLAN

The Air Resources Board (the Board or ARB) will conduct a public meeting at the time and place noted below to consider the approval of the 2007 San Diego 8-Hour Ozone Attainment Plan.

DATE: May 24, 2007

TIME: 9:00 a.m.

PLACE: San Diego Marriott Del Mar Hotel
Grand Ballroom
11966 El Camino Real
San Diego, California 92130

This item will be considered at a two-day meeting of the Board, which will commence at 9:00 a.m., Thursday, May 24, 2007 and will continue at 8:30 a.m., Friday, May 25, 2007. This item may not be considered until May 25, 2007. Please consult the agenda for the meeting, which will be available at least 10 days before May 24, 2007, to determine the day on which this item will be considered.

For individuals with sensory disabilities, this document is available in Braille, large print, audiocassette or computer disk. Please contact ARB's Disability Coordinator at 916-323-4916 by voice or through the California Relay Services at 711, to place your request for disability services. If you are a person with limited English and would like to request interpreter services, please contact ARB's Bilingual Manager at 916-323-7053.

Background

The federal Clean Air Act (CAA or the Act) establishes planning requirements for those areas that routinely exceed the health-based National Ambient Air Quality Standards (NAAQS). These nonattainment areas must develop and implement a State Implementation Plan (SIP) that demonstrates how they will attain the standards by specified dates. Federal law holds each state responsible for implementing the provisions of the Act.

In July 1997, the U.S. Environmental Protection Agency (U.S. EPA) promulgated a new 8-hour NAAQS for ozone. U.S. EPA classified the San Diego Air Basin as a "basic" nonattainment area with an attainment date of June 2009. The San Diego Air Pollution Control District (District) developed an attainment plan with input from interested parties. The District's attainment demonstration indicates that the local, State, and

federal controls already in place will reduce emissions sufficiently by 2008 to allow San Diego to attain the ozone standard by the 2009 deadline.

Proposed Action

The District released its draft plan on March 1, 2007 and held a public workshop on April 2, 2007. The District governing board is scheduled to consider approval of the plan at a duly noticed public hearing on May 23, 2007. ARB staff has reviewed the Draft 8-Hour Ozone Attainment Plan for San Diego County and concluded that it meets applicable federal requirements. ARB staff also concluded that the implementation of the April version of the plan would reduce ozone levels throughout San Diego to the benefit of public health and result in attainment of the 8-hour ozone standard by June 2009. ARB staff recommends that the Board approve the San Diego plan as a revision to the California SIP and direct the Executive Officer to submit the plan to U.S. EPA. If the governing board makes changes to the draft plan at its hearing on May 23, ARB staff will consider the changes, and recommend appropriate actions at the ARB meeting.

ARB staff will present a written Staff Report at the meeting. Copies of the report may be obtained from the Board's Public Information Office, 1001 "I" Street, 1st Floor, Environmental Services Center, Sacramento, CA 95814, (916) 322-2990, on May 10, 2007. The report may also be obtained from ARB's internet site at http://www.arb.ca.gov/planning/sip/2007sip/2007sip.htm.

Interested members of the public may also present comments orally or in writing at the meeting, and in writing or by email before the meeting. To be considered by the Board, written comments submissions not physically submitted at the meeting must be received **no later than 12:00 noon, Wednesday, May 23, 2007,** and addressed to the following:

Postal mail: Clerk of the Board, Air Resources Board
1001 I Street, Sacramento, California 95814

Electronic submittal: http://www.arb.ca.gov/lispub/comm/bclist.php

Facsimile submittal: (916) 322-3928

The Board requests, but does not require 30 copies of any written submission. Also, the ARB requests that written and email statements be filed at least 10 days prior to the meeting so that ARB staff and Board members have time to fully consider each

comment. Further inquiries regarding this matter should be directed Ms. Karen Khamou, Air Pollution Specialist, (916) 322-1502, 1001 "I" Street, P.O. Box 2815, Sacramento, California 95812.

CALIFORNIA AIR RESOURCES BOARD

Catherine Witherspoon
Executive Officer

Date: May 8, 2007

The energy challenge facing California is real. Every Californian needs to take immediate action to reduce energy consumption. For a list of simple ways you can reduce demand and cut your energy costs, see our Website at www.arb.ca.gov.

State of California
AIR RESOURCES BOARD

STAFF REPORT

DRAFT ANALYSIS OF SAN DIEGO'S 2007 STATE IMPLEMENTATION PLAN FOR OZONE

Date of Release: May 10, 2007
Scheduled for Consideration: May 24, 2007

This report has been reviewed by the staff of the California Air Resources Board and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Air Resources Board, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

California Environmental Protection Agency
AIR RESOURCES BOARD

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EXECUTIVE SUMMARY

The federal Clean Air Act (the Act) establishes planning requirements for those areas that routinely exceed the health-based National Ambient Air Quality Standards (NAAQS). These nonattainment areas must develop and implement a State Implementation Plan (SIP) that demonstrates how they will attain the standards by specified dates. Federal law holds each state responsible for implementing the provisions of the Act.

In July 1997, U.S. Environmental Protection Agency (U.S. EPA) promulgated a new 8-hour NAAQS for ozone. U.S. EPA classified the San Diego Air Basin as a "basic" nonattainment area with an attainment date of June 2009. The San Diego Air Pollution Control District (District) developed the 8-Hour Ozone Attainment Plan for San Diego County (Plan) with input from interested parties. The District's attainment demonstration indicates that the local, State, and federal controls already in place will reduce emissions sufficiently by 2008 to allow San Diego to attain the ozone standard by the 2009 deadline.

The District staff released a draft plan on March 1, 2007 and held a public workshop on April 2, 2007. The District governing board is scheduled to consider adoption of the draft April 2007 Plan on May 23, 2007. ARB staff has reviewed the Plan and concluded that it meets applicable federal State Implementation Plan (SIP) requirements. ARB staff also concludes that the implementation of the Plan would reduce ozone levels throughout San Diego to the benefit of public health and result in attainment of the 8-hour ozone standard by June 2009. ARB staff recommends that the Board approve the April 2007 version of the Plan as a revision to the California SIP and direct the Executive Officer to submit the plan to U.S. EPA. If the Plan changes at the San Diego Board hearing on May 23, ARB staff will consider and recommend appropriate actions.

I. BACKGROUND

Profile of San Diego

The San Diego federal non-attainment area lies in the southwest corner of California and comprises all of San Diego County. San Diego is 120 miles south of Los Angeles and shares an 80-mile border with Mexico; the City of San Diego is adjacent to the Baja, California city of Tijuana. Its diverse terrain stretches from the Pacific to the Laguna Mountains and includes miles of ocean and bay shoreline, forested hills, fertile valleys, mountains, canyons, and desert. Consequently, San Diego's climate varies from a mild climate on the coast to highly variable temperatures in the desert. September and October often produce the hottest days of the year.

San Diego County covers 4,200 square miles and is home to about eight percent of the State's population. The region's population and emissions are concentrated in the western portion of the county. The city of San Diego, with a population of over 2.9 million, is the second largest city in California. The border region cities of San Diego and Tijuana, Mexico, have a combined population of over 4.8 million.

Air quality in the San Diego air basin is affected by both local emissions and ozone and ozone precursor emissions transported from the South Coast Air Basin. The Air Resources Board's (ARB or Board) ozone transport assessments have also identified Mexico as a contributor to high ozone levels in San Diego.

Health Effects of Ozone

Ozone is a highly reactive gas that forms in the atmosphere through complex reactions between chemicals directly emitted from motor vehicles, industrial plants, consumer products and many other sources. Ozone is a secondary gas, formed in the atmosphere by the interaction of reactive organic compounds (ROG) and oxides of nitrogen (NOx) in the presence of sunlight.

Considerable research conducted over the past 35 years has shown that ozone can lead to inflammation and irritation of the tissues lining human airways. This causes the muscle cells in the airways to spasm and contract, thus reducing the amount of air that can be inhaled. Symptoms and responses to ozone exposure vary widely, even when the amount inhaled and length of exposure is the same. Typical symptoms include cough, chest tightness, and increased asthma symptoms. Ozone in sufficient doses can also increase the permeability ("leakiness") of lung cells, making them more susceptible to damage from environmental toxins and infection.

Medical studies of large populations have found that ozone exposure is associated with an increase in hospital admissions and emergency room visits, particularly for lung problems such as asthma and chronic obstructive pulmonary disease. Several studies have also associated exposure to high ozone levels with increased premature mortality in elderly people with chronic diseases of the lungs and circulatory system.

People who exercise or work outdoors are at greater risk of experiencing adverse health effects from ozone exposure because they inhale more ozone. One study in southern California found that children who participated in more sports activities in high ozone areas were more likely to develop asthma than those who participated in fewer sports. Children and adolescents are at increased risk because they are more likely to spend time outdoors engaged in vigorous activities, and because they inhale more ozone per pound of body weight as compared to adults.

Historical Air Quality

Air quality in San Diego has improved significantly over the last decade as measured by the decline in measured ozone concentrations, and in the number of days over the 8-hour standard of 0.08 parts per million (ppm).

Ozone "design values" are used to characterize a region's air quality for SIP planning purposes. The design value is a three-year average of the annual fourth highest daily maximum 8-hour average ozone concentrations. The use of the 3-year average helps minimize the year to year influence of meteorology. The U.S. Environmental Protection Agency (U.S. EPA) designated San Diego as "nonattainment" based on its 2001-2003 design value. As Figure I shows, San Diego's design value has declined by 15 percent in the past ten years.

The number of days over the standard (exceedance days) is an indication of how frequently the population is exposed to unhealthful air quality. Figure II illustrates the decline in number of days over the standard in San Diego. In the past ten years, the number of days annually in which ozone concentrations in San Diego exceed the national 8-hour standard has declined by 54 percent. The San Diego region has also experienced a shortened ozone season in recent years. Since 2001, the San Diego region has not exceeded the standard before May or after October.

The air quality monitor in Alpine-Victoria has recorded the County's highest ozone levels for all but three of the last 10 years. The monitoring site is located in the foothills east of the City of San Diego and is 2,000 feet above sea level. The site is impacted by emissions from both San Diego and the South Coast Air Basin. San Diego's 2006 design value is 0.088 ppm, which is an increase from the 2005 design value of 0.086 ppm. San Diego, like the rest of California, experienced record high summer temperatures in 2006 that were conducive to ozone formation.

Figure I. San Diego Air Basin
Federal 8-hr Ozone Design Value (1990-2006)

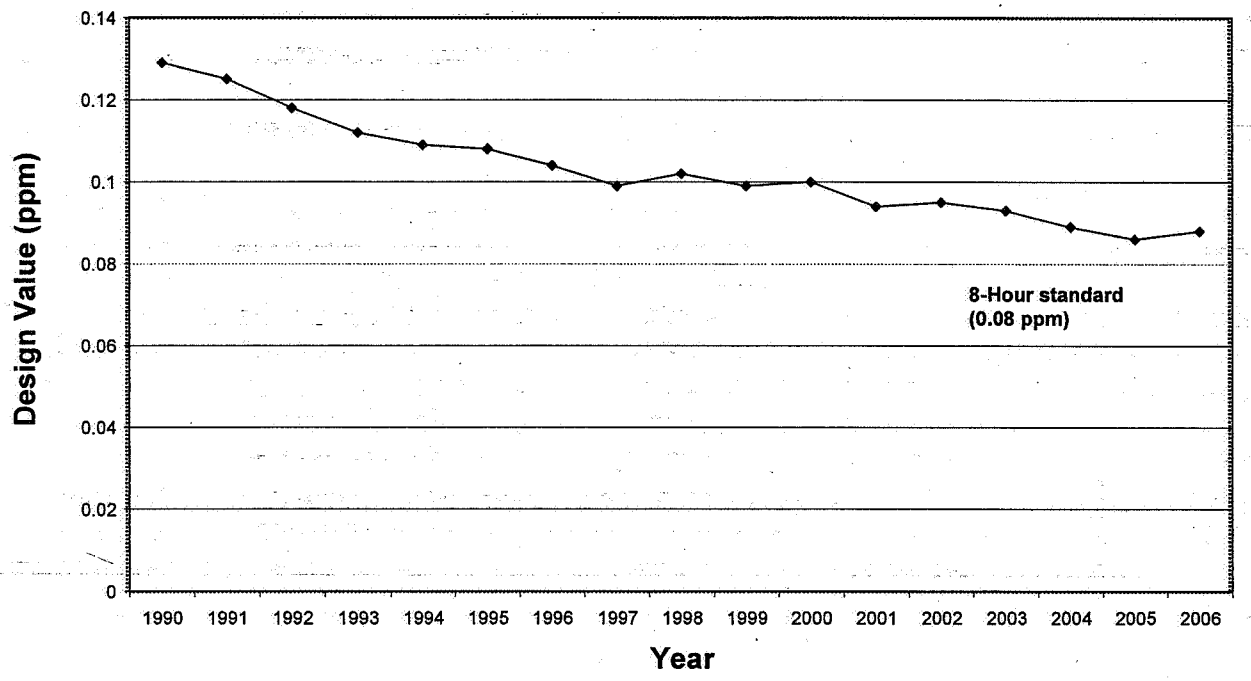
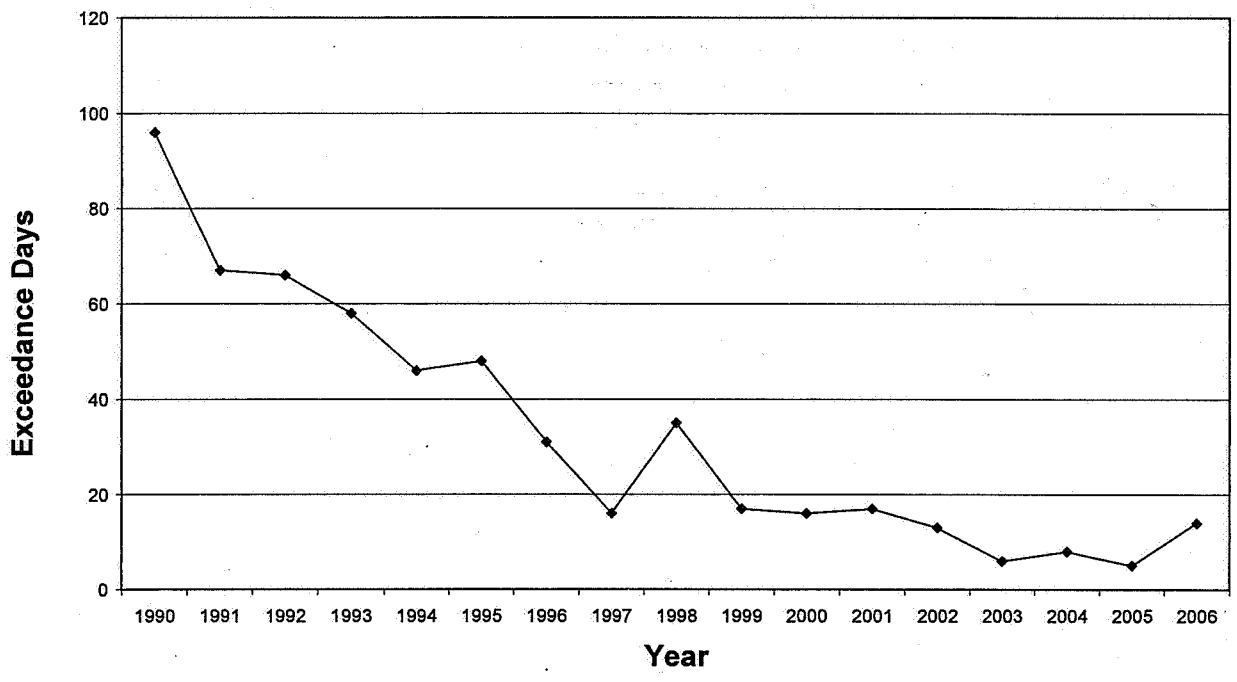


Figure II. San Diego Air Basin
Federal 8-hr Ozone Exceedance Days (1990-2006)



II. AIR QUALITY PLANNING

Air Quality Planning Background

The federal Clean Air Act (the Act) establishes planning requirements for those areas that routinely exceed the health-based National Ambient Air Quality Standards (NAAQS). These nonattainment areas must develop and enact State Implementation Plans (SIPs) that demonstrate how they will attain the standards by specified dates. Federal law holds each state responsible for implementing the provisions of the Act.

State law[1] designates the ARB as the State's air pollution control agency for all purposes set forth in federal law, including the preparation of the SIP. State law further specifies that the ARB must adopt the nonattainment area plan approved by a local air district, unless the ARB finds, after a public hearing, that the locally adopted plan will not meet the requirements of the Act.[2] California SIP revisions must be submitted to U.S. EPA by ARB. The provisions and commitments in a U.S. EPA-approved SIP are federally enforceable. The Act also allows interested parties to sue U.S. EPA, the state, or local agencies to compel implementation of an approved SIP and other provisions of the Act.

Recent Air Quality Planning Activities

The 2007 ozone SIP is the latest step in the air quality planning process that over the years has helped define new actions to improve San Diego's air quality. The District developed the local plan with input from interested parties. The District first published a draft of their 8-hour ozone plan for public review on March 1, 2007. The District held a public workshop on April 2, 2007 to discuss its analysis and 8-Hour Ozone Attainment Plan. The District's Air Pollution Advisory Committee, made up of stakeholders appointed by the District Board, reviewed the plan and recommended that the Board approve it. District staff will present the final draft of the plan to the San Diego APCD Board for consideration at a duly noticed local hearing that is tentatively scheduled for May 23, 2007.

8-hour Ozone Planning Requirements

Ozone Standard

Less than 0.08 parts per million for 8 hours, not to be exceeded, based on the fourth highest concentration averaged over three years.

In July 1997, U.S. EPA promulgated a new NAAQS for ozone that provides additional protection from the harmful health effects of this pollutant. The new ozone standard protects against longer pollutant exposure periods by requiring that ozone concentrations not exceed specified levels over an 8-hour period instead of a 1-hour period. In April 2004, U.S. EPA finalized "Phase 1" of the ozone implementation rule. This rule established the classification scheme for nonattainment areas and identified continuing obligations

[1] California Health and Safety Code (HSC) section 39602.
[2] HSC Section 41650(a).

with respect to the existing 1-hour ozone requirements. The San Diego Air Basin is classified as a basic nonattainment area with an attainment date of June 2009. A basic category refers to an 8-hour ozone nonattainment area whose 1-hour ozone design values meet the now revoked 1-hour ozone NAAQS. San Diego attained the former federal 1-hour standard in 2001. On November 9, 2005, U.S. EPA supplemented its "Phase 1" implementation rule with a "Phase 2" rule. The "Phase 2" rule outlines the emission controls and planning elements that nonattainment areas must address in their implementation plans.

U.S. EPA's "Phase 1" 8-hour ozone implementation rule requires all basic nonattainment areas to meet the general planning and emission control requirements of Subpart 1 (of Part D of Title I) of the Act. Basic nonattainment areas are not subject to the additional, more prescriptive requirements of Subpart 2, which were established for the former 1-hour ozone NAAQS.

SIPs for Subpart 1 areas must include:

- air quality modeling that demonstrates attainment of the 8-hour ozone standard;
- an emissions inventory;
- transportation conformity emission budgets to ensure transportation plans and projects are consistent with, and will not hinder attainment;
- adopted control strategies capable of meeting attainment, and contingency measures in the event the controls fall short of achieving needed reductions; and
- New Source Review rules.

In order to demonstrate attainment of the 8-hour ozone standard by San Diego's June 2009 deadline, the SIP must show that all of the emissions reductions needed for attainment are in place by the beginning of the ozone season in 2008. This is because ozone nonattainment areas are required to model attainment in the full ozone season prior to the area's attainment date[1].

Appeals Court Decision and Implications for Subpart I Areas

In December 2006, a federal Appeals Court vacated U.S. EPA's "Phase 1" 8-hour ozone implementation rule. The Court stated that basic nonattainment areas with 8-hour ozone levels exceeding 0.09 ppm (a level the Court considered to provide equivalent health protection equivalent to the former 1-hour ozone NAAQS of 0.12 ppm) must also be subject to the more prescriptive Subpart 2 requirements. However, U.S. EPA has asked the Court to reconsider its decision. It is not clear if and when U.S. EPA will reclassify Subpart 1 areas.

The District plan indicates that if San Diego is reclassified as a Subpart 2 nonattainment area, the District will revise its SIP to fully address the necessary requirements.

[1] 40 CFR 51.908(d).

III. PLAN EVALUATION

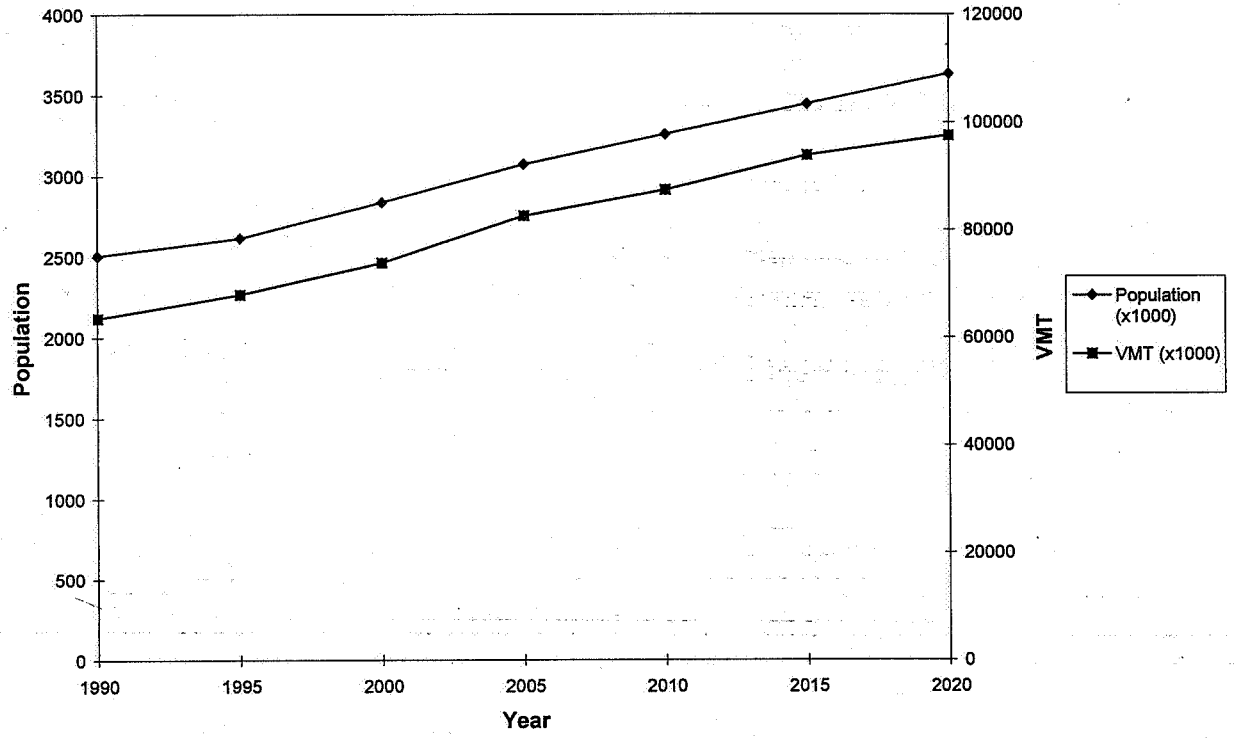
Emissions Inventory

Most of San Diego's population resides in the western, coastal portion of the county. The eastern side of the county is much more rural; it encompasses the 720-square mile Cleveland National Forest and numerous farms. The primary mode of transportation is passenger vehicles, although the downtown area is serviced by light rail and buses.

San Diego's economy has experienced dramatic change since the end of the cold war. Although the United States Navy, Marines, and Coast Guard continue to have a strong presence, San Diego's economy has transformed into a mix of high-technology industries such as telecommunications and biotechnology, international trade operations, and electronics and defense-related manufacturing. San Diego's climate and ocean-front also make it a prime location for recreation and tourism, which ranks as the third largest economic sector, behind manufacturing and military.

San Diego County is experiencing significant growth in population and vehicle use. Population in the region is expected to increase by 16 percent, from 3.1 million today to over 3.6 million in 2020. Vehicle use as measured in vehicle miles traveled (VMT) is projected to increase by 17 percent during this same period, from over 83 million miles per day today to over 97 million miles per day in 2020. San Diego's overall air quality improvement, despite high growth rates, illustrates the benefits of cleaner technologies. Figure III charts San Diego's population and VMT growth from 1990 to 2020.

Figure III. San Diego Air Basin Population and VMT Growth



Baseline Emissions

The main sources of San Diego's NOx emissions are on-road vehicles, ships and commercial boats, and off-road equipment. San Diego's ROG inventory is dominated by passenger cars, consumer products, architectural coatings, recreational boats, and lawn and garden equipment. The inventories reflect the region's urban and suburban population and the strong goods movement sector. The following two tables show the top 25 NOx and ROG emission sources in San Diego's 2006 emissions inventory. The tables indicate that emissions of both precursors will continue to decline into and well beyond the region's 2009 attainment year.

Table I. NOx Emissions
San Diego Air Pollution Control District
2007 SIP Summer Season Emissions Inventory (Tons per Day)

(Prioritized by 2006 emissions)

Source Category	2006	2009	2012
PASSENGER VEHICLES*	44	41	33
HEAVY DUTY DIESEL TRUCKS	51	39	33
SHIPS AND COMMERCIAL BOATS**	31	32	35
OFF-ROAD EQUIPMENT (CONSTRUCTION AND MINING)	26	22	18
OFF-ROAD EQUIPMENT***	13	12	10
GASOLINE-FUELED COMMERCIAL TRUCKS	7	6	5
RECREATIONAL BOATS	6	7	7
AIRCRAFT	5	6	6
FARM EQUIPMENT (COMBINES AND TRACTORS)	4	4	3
COGENERATION (ELECTRICITY GENERATION AND HEAT RECOVERY)	3	3	3
ELECTRIC UTILITIES	2	4	4
PUBIC TRANSIT BUSES	2	2	2
RESIDENTIAL FUEL COMBUSTION	2	2	2
OFF-ROAD EQUIPMENT (LAWN AND GARDEN)	2	1	1
LOCOMOTIVES	1	1	2
OTHER (FUEL COMBUSTION)	1	1	1
MOTOR HOMES	1	1	1
SCHOOL BUSES	1	1	1
MOTORCYCLES	1	1	1
MANUFACTURING AND INDUSTRIAL (BOILERS, IC ENGINES)	1	1	1
SERVICE AND COMMERCIAL (BOILERS, IC ENGINES)	1	1	1
COMMERCIAL TRANSIT BUSES	1	1	1
LANDFILLS (LANDFILL GAS EMISSIONS)	<1	<1	<1
MINERAL PROCESSES (MINING, CEMENT MANUFACTURING)	<1	<1	<1
AGRICULTURAL IRRIGATION PUMPS	<1	<1	<1
All Other Sources	<1	<1	<1
TOTAL	**208**	**189**	**170**

* Includes cars, light and medium duty trucks, minivans, and SUVs.

**Includes emissions out to 100 nautical miles.

***Includes transport refrigeration units, airport ground support equipment, and cargo handling equipment.

Table II. ROG Emissions
San Diego Air Pollution Control District
2007 SIP Summer Season Emissions Inventory (Tons per Day)

(Prioritized by 2006 emissions)

Source Category	2006	2009	2012
PASSENGER VEHICLES*	45	37	30
CONSUMER PRODUCTS	20	19	20
RECREATIONAL BOATS and WATER CRAFT	19	17	16
OFF-ROAD EQUIPMENT (LAWN AND GARDEN)	11	11	10
ARCHITECTURAL COATINGS (PAINTS AND THINNERS)	10	11	11
PETROLEUM MARKETING (GASOLINE EVAPORATIVE LOSSES)	8	9	9
COATINGS (PAINTS AND THINNERS - NON ARCHITECTURAL)	7	7	8
GASOLINE-FUELED COMMERCIAL TRUCKS	5	4	3
OFF-ROAD EQUIPMENT**	5	4	3
MOTORCYCLES	5	4	4
OFF-ROAD EQUIPMENT (CONSTRUCTION AND MINING)	4	4	3
GAS CANS	4	3	2
PRINTING	4	4	4
AIRCRAFT	3	3	3
HEAVY DUTY DIESEL TRUCKS	3	2	2
OFF-ROAD RECREATIONAL VEHICLES	3	3	3
ADHESIVES AND SEALANTS	3	3	2
COOKING	2	2	2
SHIPS AND COMMERCIAL BOATS***	2	2	2
COGENERATION (ELECTRICITY GENERATION AND HEAT RECOVERY)	2	2	2
ASPHALT PAVING / ROOFING	2	2	2
LANDFILLS (LANDFILL GAS EMISSIONS)	2	2	2
DEGREASING	2	2	2
CHEMICAL (PROCESS AND STORAGE LOSSES)	2	2	2
PESTICIDES	1	1	1
All Other Sources	6	6	6
TOTAL	**178**	**164**	**155**

* Includes cars, light and medium duty trucks, minivans, and SUVs.

**Includes transport refrigeration units, airport ground support equipment, and cargo handling equipment.

***Includes emissions out to 100 nautical miles.

Because the ozone attainment deadline falls in the middle of the 2009 ozone season and design values are calculated for calendar years, the SIP must provide for sufficient emission reductions in 2008 in order to demonstrate attainment in 2009. The following table summarizes emission reductions from 2006, the base year for this plan, to 2008, the ozone season that must be modeled to demonstrate attainment by June 2009. ARB staff finds that the emission inventory accurately represents NOx and ROG emissions and reductions over time within San Diego County.

Table III. Baseline Emission Trends with Measures Adopted as of 2006
(San Diego, Summer Planning, in tons per day)

	ROG			NOx		
Source Category	**2006**	**2008**	**% Change**	**2006**	**2008**	**% Change**
Stationary & Area-wide	67.3	68.0	+1.1%	10.7	12.2	+13.3%
On-Road Motor Vehicles	58.5	51.1	-12.6%	108.1	96.8	-10.5%
Off-Road Vehicles and Equipment	52.3	48.5	-7.2%	88.7	85.8	-3.3%
TOTAL	178.1	167.6	-5.9%	207.5	194.8	-6.2%

Emission Reduction Credits

Federal New Source Review (NSR) rules require new and modified major stationary sources that increase emissions in amounts exceeding specified thresholds to provide emission reduction offsets to mitigate the emissions growth. Emission reduction offsets represent either on-site emission reductions or the use of banked emission reduction credits (ERCs). ERCs are voluntary, surplus emission reductions that are registered with the District for future use as offsets.

Table IV. San Diego APCD
Emission Reduction Credit Banking Summary
ERCs Issued 2002 and Earlier
(San Diego, Summer Planning, in tons per year)

Pollutant	ERC Total
NOx	79.2
ROG	230.3

The District added the banked ERC's shown in Table IV into the 2008 emission inventory used in the modeling demonstration of attainment. This ensures that these ERCs, which could be used to enable growth at major sources at any time, are fully accounted for in the inventories used to demonstrate attainment of the 8-hour ozone standard.

Attainment Emission Target

San Diego's attainment demonstration for the national 8-hour ozone standard is summarized in Table V. The District's attainment demonstration is based on photochemical modeling results, augmented with an analysis of the model outputs and local air quality and emissions trends. The attainment demonstration indicates that the local, State, and federal controls already in place will reduce emissions sufficiently by 2008 to allow San Diego to attain the ozone standard by the 2009 deadline. As a result, the 2008 baseline emissions – 194.8 tpd NOx and 167.6 tpd ROG – are also the region's carrying capacity[1] as shown in Table V. The modeling and supplemental analyses are detailed in an appendix of this report.

Table V. Emission Reduction Target for Ozone Attainment

San Diego (2009 attainment deadline) tons per day		
	NOx	**ROG**
2006 Emissions Inventory	207.5	178.1
Projected 2008 Emissions	194.8	167.6
Emission Reduction Target	12.7	10.5
Emission Reductions from Existing Program	12.7	10.5

Control Strategy

Because San Diego was formerly classified as a serious nonattainment area for the national 1-hour ozone standard, it has already enacted a comprehensive control program to address ozone precursors. The combined local, State, and federal emission controls resulted in the District attaining the 1-hour standard in 2001, and also substantially reduced 8-hour average ozone concentrations. Currently adopted controls under district, State, and federal jurisdiction will provide continued reductions in ozone precursors for the 2009 attainment deadline. San Diego's attainment strategy relies on these existing controls and their continued implementation.

Local Strategy

Local air districts are responsible for controlling emissions from most stationary and areawide sources. Such sources include factories, power plants, gas stations, dry cleaners, and residential water heaters. The San Diego District has already adopted rules to control NOx and ROG emissions from almost all stationary and area source categories in San Diego County. Most of these rules were fully implemented by 2002 and are reflected in the base year inventory used to develop this plan. As part of this

[1] Carrying capacity is the pollutant emissions limit that ensures air quality standards are met.

SIP cycle, the District will not adopt additional measures that will be implemented in time for the 2009 deadline, because the existing control strategy is expected to provide for attainment by 2009. However, the District is required to continue to evaluate and update rules to reduce emissions under the California Clean Air Act in order to attain the State ozone standard.

The San Diego District plan also proposes the adoption of a new control measure that will take effect in spring 2008. The measure, which will reduce the ROG content of solvents used in cold solvent cleaning operations by 1 tpd, will replace current District Rule 67.6 (Solvent Cleaning Operations) with two new rules, Rule 67.6.1 (Cold Solvent Cleaning and Stripping Operations) and Rule 67.6.2 (Vapor Degreasing Operations). The rule is being adopted simultaneously with this plan. The emission reductions from this measure are not reflected in the attainment modeling, since the rule will not be fully implemented by January 2008 (the beginning of the first full ozone season prior to the June 15, 2009, attainment deadline). However, this measure will further reduce emissions and help ensure continued attainment, and it will be submitted to ARB as a proposed SIP revision.

State Strategy

ARB is responsible for controlling emissions from mobile sources, consumer products, and fuels. ARB's on-going mobile source control program will provide significant NOx and ROG emission reductions in San Diego. Vehicles and equipment operating in California are subject to the most stringent tailpipe emission standards in the world. Between 2006 and 2008, on-road vehicle emission control programs in San Diego will decrease ROG emissions by 12.6 percent and NOx emissions by 10.5 percent.

ARB has a long history of adopting successful programs to reduce emissions from mobile sources. Regulations already adopted by ARB will continue to reduce emissions as vehicles and equipment meeting the cleanest new emission standards enter into service, as shown previously in Table III. The region will continue to benefit from these regulations as it moves closer to attaining the State ozone standard, and new equipment that conforms to these standards replace older, less controlled engines.

ARB staff is also developing new measures to help the State's nonattainment areas meet U.S. EPA's 8-hour ozone and fine particulate matter (PM2.5) standards. The proposed State Strategy is tentatively scheduled for Board consideration in June 2007. Given San Diego's early attainment date, the proposed State Strategy will not provide new reductions in 2008, and San Diego's plan does not include any reductions from proposed State measures in its attainment demonstration.

Federal Strategy

Under the CAA, U.S. EPA has exclusive authority to establish engine emission standards for a variety of mobile sources including interstate trucks, some farm and construction equipment, locomotives, aircraft, and marine vessels based in the U.S.

San Diego's plan reflects the standards that had been approved by December 1, 2006, but does not reflect any emission reductions from proposed federal actions.

Reasonably Available Control Measures

Stationary Sources

For each nonattainment area required to submit an attainment demonstration, the State must include in its plan a demonstration that it has adopted all Reasonably Available Control Measures (RACM) necessary to demonstrate attainment as expeditiously as practicable. This is different from a Reasonability Available Control Technology (RACT) assessment that pertains to applicable categories of stationary sources of VOC and NOx and is done in a separate SIP. Basic nonattainment areas are not required to make a RACT determination.

San Diego's early projected attainment date, which is based on projected 2008 emission levels with existing controls, eliminates the option of adopting additional measures for earlier attainment. Such measures would have to advance attainment to 2007, the current year.

Nonattainment areas must also meet any reasonable further progress (RFP) requirements. The 2009 attainment date also eliminates the need for a reasonable further progress demonstration in the 2008 milestone year.

Transportation Sources (Transportation Control Measures)

U.S. EPA has identified 16 transportation control measures (TCMs) that must be evaluated as part of a RACM demonstration. TCMs include options for reducing vehicle use, or for reducing conditions that lead to higher vehicle emissions. The draft plan indicates that the District has identified and implemented 13 TCMs as RACM for transportation in San Diego. Since these RACM are already being implemented they do not provide new reductions that would advance the attainment year.

ARB staff concurs with the District's assessment of RACM for stationary and transportation sources.

Contingency Strategy

U.S. EPA requires each plan to identify contingency emission reductions that will take effect should an area fail to attain by the attainment date specified in its SIP. U.S. EPA also requires that the SIP demonstrate that additional contingency emission reductions are available for each milestone year, should they be needed. These reductions must come from measures that will take effect without further action. U.S. EPA has interpreted this to mean that the contingency reductions must come from measures that have already been adopted when the SIP is submitted (or possibly prior to U.S. EPA taking action).

San Diego's plan relies on the existing State mobile source control measures to satisfy contingency requirements. The table below shows mobile source emission reductions over time. The District relies on these measures because they will continue to be implemented, and to reduce motor vehicle emissions, regardless of the air basin's attainment status in 2009.

Table VI. San Diego Air District's Mobile Source Emissions

Source Category	ROG			NOx		
	2009	2010	2011	2009	2010	2011
On-Road Mobile	47.9	44.9	42.5	92.0	87.0	81.5
Off-Road Mobile*	47.0	45.6	44.4	84.3	82.7	82.1
Total	94.9	90.5	86.9	176.3	169.7	163.6

*Off-road emissions extend over the ocean, out to 100 nautical miles.

Attainment Demonstration

San Diego's "basic" nonattainment area classification gives it a June 15, 2009 attainment date. San Diego needs to demonstrate a design value of 0.084 ppm (at most) in 2008 to attain the 8-hour ozone standard. In 2005, the District exceeded the standard on 5 days with an ozone design value of 0.086 ppm, which is approximately two percent over the standard. In 2006, San Diego like much of the rest of California experienced record high summer temperatures. As a result, the district exceeded the standard on 14 days and the design value increased to 0.088 ppm. Existing control programs are expected to reduce the ozone precursors ROG and NOx by about six and seven percent, respectively, by the 2009 deadline. The District's analysis indicates that these programs will be sufficient to attain the 8-hour standard by 2009, despite the impact of the unusually severe 2006 ozone season had on the District's design value. A more detailed description of the modeling analysis is provided in the "Attainment Demonstration" appendix to this report.

Photochemical Modeling

The photochemical modeling used in the San Diego plan was conducted by an air quality expert under contract to the District. The modeler used the EPA-accepted "Comprehensive Air Quality Model with Extensions" (CAMx) modeling system to estimate the emissions reductions needed to achieve the ozone standards. A meteorological model, Mesoscale Model version 5 (MM5), was used to drive the transport and dispersion in the CAMx model. The South Coast Air Quality Management District and ARB are using this same combination for modeling ozone in other parts of Southern California, but the San Diego-specific modeling employed enhanced local meteorological inputs.

San Diego's air quality modeling predicts a 2008 design value of 0.086 ppm, which exceeds the 0.084 ppm attainment standard. U.S. EPA's ozone modeling guidance indicates that when photochemical modeling projects attainment year concentrations of 0.082-0.087 ppm, the State may conduct further analyses of the model outcomes and

consider other evidence such as emissions and air quality trends data. If the weight of this evidence supports a finding that the proposed control program will result in attainment by the statutory deadline, the State may consider this evidence in determining whether the proposed control program will result in attainment. San Diego's plan utilizes such a weight of evidence (WOE) attainment demonstration. The District's modeling approach is summarized in the appendix to this report.

Weight of Evidence Analysis

San Diego's attainment demonstration incorporates a supplementary WOE analysis as allowed under U.S. EPA's April 2007 Final Guidance on the Use of Models and Other Analyses for Attainment of Air Quality Goals for Ozone, PM2.5, and Regional Haze. The District concludes that the evidence indicates that the adopted emission controls will reduce ozone concentrations to the level needed to meet the 8-hour ozone standard by the statutory attainment deadline of June 15, 2009. ARB staff analysis of this plan concurs with the District's conclusion of attainment in 2009.

San Diego's WOE analysis includes additional modeling results, statistical air quality trends analyses, graphical air quality trends analyses, and meteorological analyses. The WOE includes five statistical analyses of 8-hour ozone design values, which together suggest that ozone levels can be expected to be reduced to below 0.085 ppm by 2008. Numerous graphical analyses illustrating the continuing downward trends in ozone and precursor concentrations are also presented, and are summarized in the appendix to this report.

ARB Analysis

ARB staff independently modeled an additional San Diego episode that occurred in July, 2005. ARB's analysis did not include the enhanced local meteorological data used in the District's modeling. This preliminary modeling, using projected 2010 emissions, projected a basin high 8-hour average of 0.085 ppm at the Alpine monitor, without a WOE analysis. Thus, ARB's modeling generally confirms the direction and magnitude of the District's findings.

ARB staff analysis of the District's attainment demonstration concurs with the conclusion of attainment in 2009.

Reasonable Further Progress

The first year the District would be required to show Reasonable Further Progress towards attainment is 2008, the year the District must model attainment for the June 15, 2009 deadline. As a result, the District is not required to include a Reasonable Further Progress demonstration in its Plan.

Transportation Conformity Budgets

San Diego's plan establishes county level on-road motor vehicle emissions transportation conformity budgets for 2008. The emissions budgets reflect the latest planning assumptions and were developed using ARB's latest on-road mobile source emission factor model EMFAC2007.

The new emissions budgets, based on summer planning daily emissions for ROG and NOx, are shown in Table VIII. The budgets were developed from activity data provided by the San Diego Association of Governments (SANDAG), which ARB then incorporated into the EMFAC2007 motor vehicle emission model. The heavy-heavy duty diesel truck vehicle miles traveled (VMT) from 2005 to 2009 were adjusted to match EMFAC2007 VMT estimates with SANDAG estimates. EMFAC outputs were also adjusted to account for baseline emission reductions not reflected in EMFAC2007. These budgets will become applicable when U.S. EPA finds the budgets adequate.

The emission budgets established in this plan fulfill the requirements of the Act and U.S. EPA regulations to ensure that transportation projects will not interfere with progress towards, and attainment of, the national 8-hour ozone standard.

Table VII. On-Road Motor Vehicle Emission Budgets for Ozone
(San Diego, Summer Planning, in tons per day)

Pollutant	2008 and Subsequent Years
ROG	53
NOx	98

IV. ENVIRONMENTAL IMPACTS

The California Environmental Quality Act (CEQA) requires that State and local agency projects be assessed for potential significant environmental impacts. Air quality plans are "projects" that are potentially subject to CEQA requirements. In its Notice of Preparation/Initial Study for this plan, the San Diego APCD found that the plan would not have a significant effect on the environment and prepared a Negative Declaration. ARB staff have reviewed the San Diego 8-Hour Ozone Plan and the Negative Declaration and concur that plan will not have a significant effect on the environment.

V. LEGAL AUTHORITY

The Act requires states to provide for the attainment of national ambient air quality standards. The primary tool to be used in the effort to attain national ambient air quality standards is a plan that any state with one or more nonattainment areas must develop, which provides for implementation, maintenance and enforcement of the standards—the State Implementation Plan (section 110(a)(1)). Section 110(a)(2)(A) of the Act broadly authorizes and directs states to include in their SIPs:

> "...enforceable emission limitations and other control measures, means, or techniques (including economic incentives such as fees, marketable permits, and auctions of emissions rights), as well as schedules and timetables for compliance, as may be necessary or appropriate to meet the applicable requirements of the Act."

State law charges the ARB with coordinating State, regional, and local efforts to attain and maintain both State and national ambient air quality standards. The direct statutory link between ARB and the mandates of the Clean Air Act is found in section 39602 of the Health and Safety Code (HSC). This provision states:

> "The state board is designated the air pollution control agency for all purposes set forth in federal law.
>
> The state board is designated as the state agency responsible for the preparation of the state implementation plan required by the Clean Air Act (42 U.S.C., Sec. 7401, et seq.) and, to this end, shall coordinate the activities of all districts necessary to comply with that act."

State law also limits what the ARB may submit as a SIP revision. HSC section 39602 goes on to state,

> "Notwithstanding any other provision of this division, the state implementation plan shall only include those provisions necessary to meet the requirements of the Clean Air Act."

ARB will exclude any provisions of the San Diego plan that relate solely to the California Clean Air Act requirements from the SIP submittal.

VI. STAFF RECOMMENDATIONS

As described in this report, ARB staff has reviewed the 2007 San Diego Draft 8-Hour Ozone Attainment Plan, and consulted extensively with District staff during this review.

ARB staff finds that the 2007 San Diego Draft 8-Hour Ozone Attainment Plan meets applicable requirements. Staff further concludes that implementation of this plan would reduce ozone levels throughout San Diego, benefit public health, and result in attainment of the 8-hour ozone standard by June, 2009. Therefore, we recommend that the Board take the following actions:

(1) Adopt the 2007 San Diego 8-Hour Ozone Attainment Plan as a revision to the California SIP, including the control strategy, emission inventories, attainment demonstration, and motor vehicle emission budgets.

(2) Direct the Executive Officer to submit the plan to U.S. EPA as a revision to the California SIP.

APPENDIX

SAN DIEGO'S 2007 STATE IMPLEMENTATION PLAN FOR THE 8-HOUR FEDERAL OZONE STANDARD

ATTAINMENT DEMONSTRATION

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Overview

The federal Clean Air Act requires the use of air quality modeling to relate ozone levels to emissions in a region, and to simulate the impact of planned emission reductions on future air quality. Air quality modeling uses day-specific emission inventories, meteorological and air quality measurements, and chemical mechanisms to establish this relationship. U.S. EPA requires the use of air quality modeling in attainment demonstration plans for ozone nonattainment areas classified as "basic" or above.

A regional air quality model cannot capture exactly the nuances of emissions, meteorology, and photochemical reactions that occur in the air. As a result, regional air quality models are best used to describe, in relative terms, how we expect air quality levels to change as emission levels change. An air quality plan, on the other hand, is required to specify the emissions burden that an area can withstand while still attaining the ambient air quality standards. U.S. EPA's modeling guidance recommends the use of supplemental analyses to bridge the gap between modeling uncertainties and planning needs. Where a model predicts attainment year design values that are within a range of allowed uncertainty, U.S. EPA recommends supplemental analyses to demonstrate attainment despite the modeled projections, if the weight of the evidence supports a finding that the proposed strategy will result in attainment.

The San Diego Air Pollution Control District hired Atmospheric Information Systems to conduct the refined regional modeling used in support of San Diego APCD's 2007 Ozone Plan. The modeling and related analyses support a finding that existing controls will bring the San Diego Ozone Nonattainment Area into attainment for national 8-hour ozone standard by the June, 2009 deadline. ARB staff provided gridded emission inventories for this effort, and also conducted preliminary modeling for San Diego using 2010 emission projections. ARB's preliminary modeling supports the District's attainment demonstration.

For a detailed description of the District's modeling and analysis used in the San Diego attainment demonstration, please refer to Attachment H of the San Diego Air Pollution Control District's April, 2007 Eight-Hour Ozone Attainment Plan for San Diego County.

Ozone Episode

An ozone modeling analysis begins with the selection of the episode(s) to be modeled. The episodes are periods of one or more consecutive days of high ozone levels, for which detailed emissions, meteorological conditions, and air quality data have been assembled and studied. U.S. EPA recommends use of 10 or more days for modeling 8-hour ozone design values to develop relative reduction factors (RRFs), but has indicated that it will accept modeling based on five episode days. U.S. EPA further recommends that the calculation of RRFs be based on days for which reference year (2002) predicted concentrations are 85 ppb[1] or higher, although days with at least

[1] U.S. EPA modeling guidance uses parts per billion (ppb) even though the NAAQS is expressed in terms of parts per million (ppm). One thousand (1000) ppb equals 1 ppm. Thus, 86 ppb equals 0.086 ppm.

70 ppb are acceptable. Air quality modeling results are also evaluated based on performance criteria which compare simulated and observed ozone concentrations[1].

The District modeled two episodes chosen from the 1997 Southern California Ozone Study (SCOS97). Comprehensive air quality and meteorological data are available for this study, which covered the entire Southern California region. Although San Diego experienced relatively low ozone during 1997, two episodes included high ozone days in San Diego that met U.S. EPA's modeling criteria. The two modeling episodes chosen for use in this plan were August 4-7, 1997, and September 27-28, 1997. During the August episode, high ozone levels in San Diego were caused by local emissions and air pollution transported from the South Coast Air Basin. The September episode's high ozone levels occurred over a weekend as a result of local emissions[2].

San Diego used a total of six days from the two ozone episodes in the modeled attainment demonstration. The highest measured 8-hour concentration in the August episode was 87 ppb at the Alpine monitoring site. The highest measured 8-hour concentration during the September episode was 83 ppb and also occurred at Alpine.

ARB staff independently modeled a third episode that occurred in July 2005 as part of a Southern California regional analysis. This is not a comprehensive modeling analysis as ARB staff only used one episode. ARB's results from three days of the 5-day episode in July met the U.S. EPA criteria described earlier for San Diego. The highest measured 8-hour concentration during the episode was 81 ppb at the Alpine monitor.

Air Quality Model

The District used the "Comprehensive Air Quality Model with Extensions" (CAMx) with the [California] Statewide Air Pollution Research Center (SAPRC) SAPRC99 chemical mechanism to prepare the 2007 San Diego SIP. The CAMx model has also been selected by the staff of the ARB and the South Coast Air Quality Management District (SCAQMD) for SIP modeling in central and southern California.

The District used the Mesoscale Model version 5 (MM5) prognostic model to generate the meteorological inputs needed for CAMx. Some adjustments to the meteorological model output were done to improve agreement between simulated and measured or expected fields. The use of a prognostic model is consistent with U.S. EPA modeling guidelines[3].

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[1] U.S. EPA (1991). United States Environmental Protection Agency. July 1991. Guideline for Regulatory Application of the Urban Air Shed Model. Office of Air Quality Planning and Standards, Research Triangle Park, NC, EPA-450/4-91-013.

[2] SDCAPCD (2007). San Diego County Air Pollution Control District. Eight-Hour Ozone Attainment Plan for San Diego County. San Diego, CA. April 2007.

[3] U.S. EPA (2006). United States Environmental Protection Agency. April 2007. Guidance on the Use of Models and Other Analyses for Demonstrating Attainment of Air Quality Goals for Ozone, PM2.5, and Regional Haze. Office of Air Quality Planning and Standards, Research Triangle Park, NC.

Emissions Inventory

The District used ARB's emissions inventory, the California Emission Forecasting System (CEFS) version 1.06, with adjustments to reflect State emission control program regulations that will take effect before December 1, 2006 but are not reflected in CEFS v.1.06. The motor vehicle emissions in CEFS v.1.06 are derived from ARB's motor vehicle emissions models, EMFAC2007 and OFFROAD2007. The emissions are gridded for use in the photochemical model to approximate where in the modeling domain they occur. The model also adjusts the inventory to reflect temperature, humidity, and activity level that occurred during the ozone episodes.

In its analysis, the District assumed that currently banked emission reduction credits would be used in the attainment year. The District also modeled the impact of an allowance for increased military activity, through 2015, as requested by the military.

Model Results

The District's analysis of the model outputs includes the use of RRFs as described in U.S. EPA ozone air quality modeling guidance. The RRF approach allows the modelers to project design values from a reference year (in this case 2002) to a future year (2008). The San Diego District's projected 2008 values at the Alpine monitoring site are presented in Table A-I.

San Diego's photochemical air quality modeling predicted a 2008 design value of 86 ppb, which is narrowly higher than the attainment threshold of less than 85 ppb. This concentration is within U.S. EPA uncertainty range for demonstration attainment, provided WOE is also used.

Table A-I. Calculation of Model-Predicted 2008 Design Value at Alpine Monitoring Site (parts per billion)

Date	2002	2008	RRF*	Baseline	2008 Predicted
August 4	75.1	71.4	0.951	92.3	87
August 5	92.5	87.1	0.942	92.3	86
August 6	106.7	100.4	0.941	92.3	86
August 7	91.8	86.2	0.939	92.3	86
September 27	72.8	68.1	0.935	92.3	86
September 28	73.7	68.3	0.927	92.3	85
6-Day Average of Aug 4,5,6,7, and Sept 27,28	85.4	80.3	0.940	92.3	**86**

*RRF = Relative Reduction Factor
Source: San Diego APCD Ozone 8-Hour Attainment Plan, 2007.

ARB modeling supports San Diego's attainment demonstration. As previously mentioned, ARB staff conducted preliminary modeling for San Diego using the 2010 projected inventory without additional controls. ARB's modeling was done for the southern part of the State and focused on refining the analysis for the South Coast region, not San Diego. The model results projected a 2010 design value of 85 ppb at the Alpine monitoring site. Although ARB's analysis cannot be compared directly to the District's modeling, it supports the magnitude of the response to emission reductions demonstrated in the District's modeling, and future values that are amenable to a weight of evidence demonstration.

Weight of Evidence

Due to inherent modeling uncertainties, U.S. EPA guidance states that "for applications in which the modeled attainment test is not passed, a weight of evidence analysis may be used to support a determination that attainment will be achieved, despite the results of the modeled attainment test[1]." The table below provides the guidelines for a Weight of Evidence (WOE) demonstration.

Table A-2. Guidelines for WOE Determinations

Results of Modeled Attainment Test	Supplemental Analyses
Ozone	
Future Design Value <82 ppb, all monitor sites	Basic supplemental analyses should be completed to confirm the outcome of the modeled attainment test
Future Design Value 82-87 ppb, at one or more sites/grid cells	A weight of evidence demonstration should be conducted to determine if aggregate supplemental analyses support the modeled attainment test
Future Design Value greater than or equal to 88 ppb, at one or more sites/grid cells	More qualitative results are less likely to support a conclusion differing from the outcome of the modeled attainment test

San Diego's modeled attainment test resulted in a design value of 86 ppb in 2008. Per U.S. EPA guidance, the San Diego District incorporated a supplementary WOE demonstration. The District provided the following supplemental analyses:

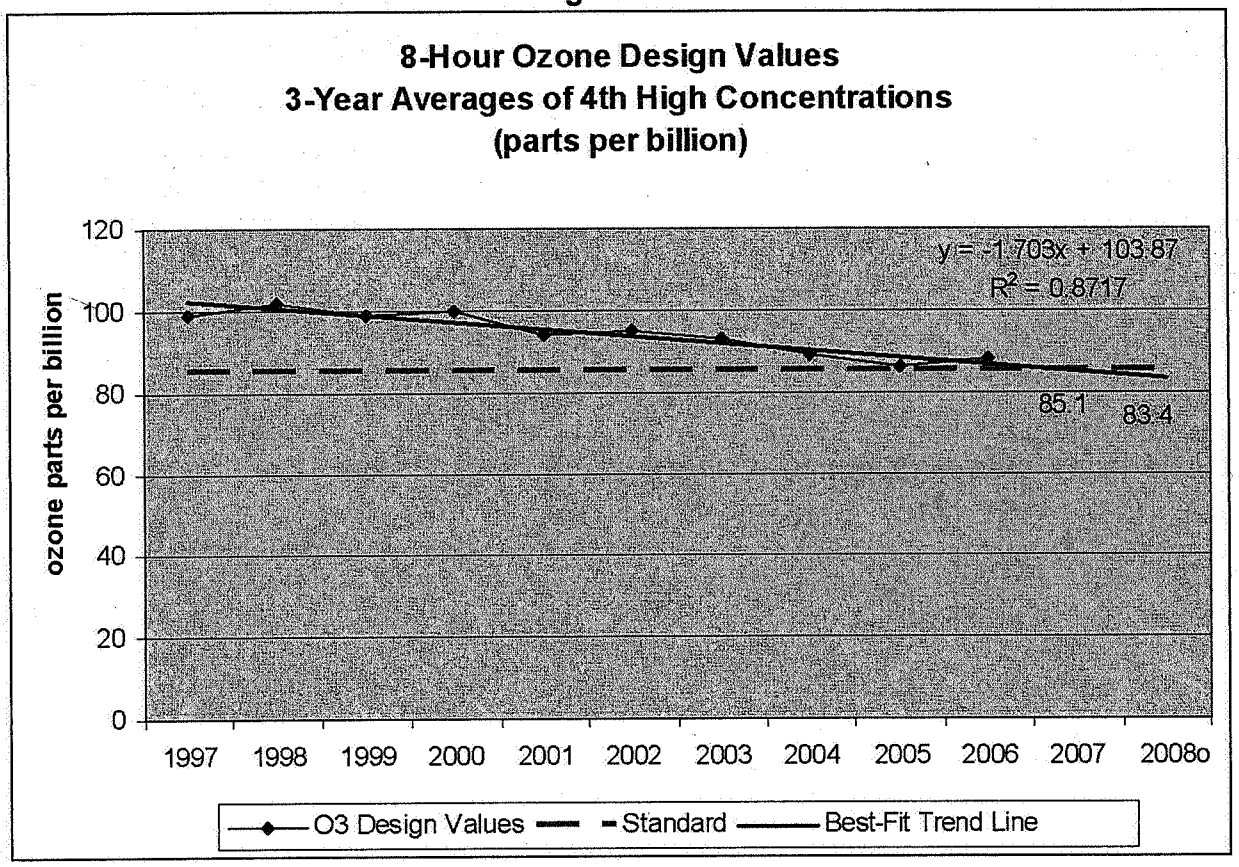
- An analysis of ozone concentrations in unmonitored areas, which indicated that the Alpine monitoring site adequately represents the maximum 8-hour ozone concentrations predicted within San Diego County;
- A modeled ozone exposure reduction metric, which suggested that the modeled values somewhat over-predict future ozone levels in the region and therefore can be considered to be conservative;
- A statistical analysis of 8-hour ozone concentration trends, which suggested that the District would attain by 2008 with its existing strategy;

[1] *Ibid*, U.S. EPA (2007).

- A regression analysis that relates ozone precursor emissions to 8-hour ozone concentrations, which suggested attainment by 2008 with and without emissions transported from the South Coast Air Basin.

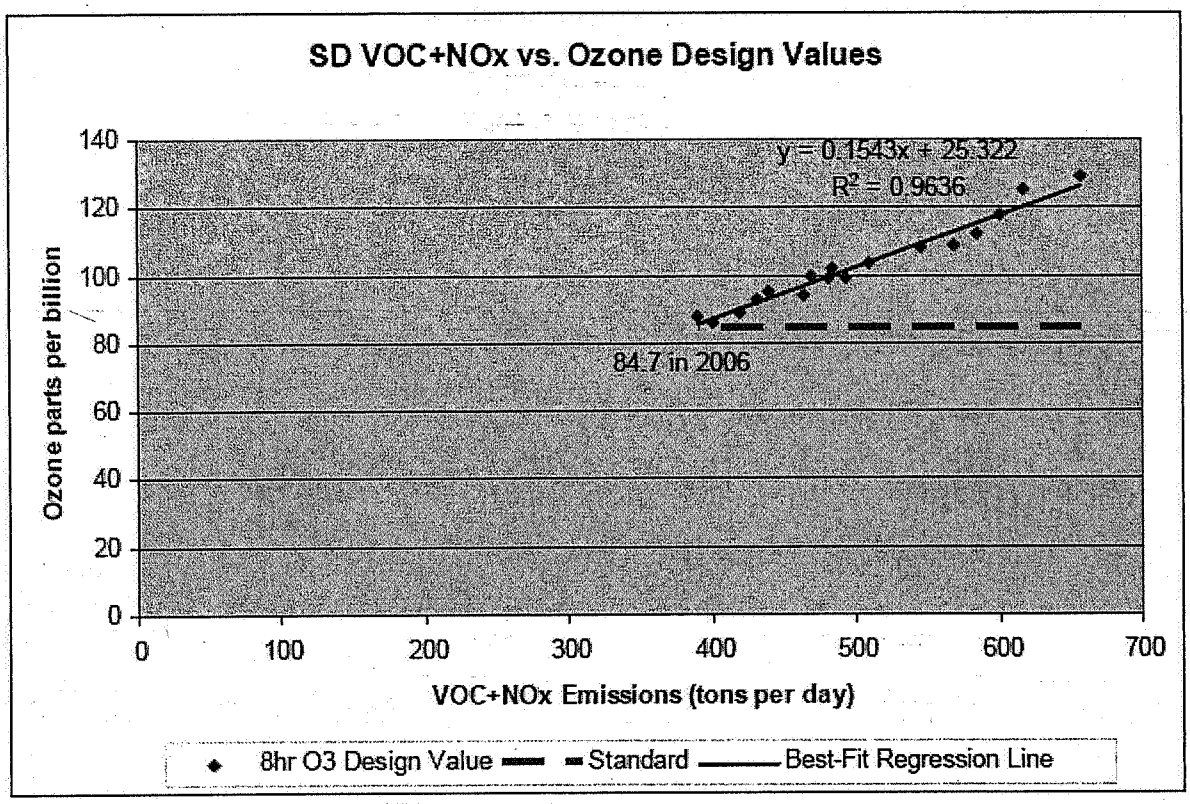
The supplemental analyses provide a comprehensive argument for attainment in 2009. The figure below illustrates the declining trend in measured ozone design values at the Alpine site from 1997 to 2006 (the only site that violates the 8-hour standard). The statistical analysis (best-fit trend line) predicts a design value of 83.4 ppb in 2008, demonstrating attainment.

Figure A-1



The figure below shows a strong statistical association between ozone precursor emissions in San Diego, ROG and NOx, and design values between 1990 and 2006. The best-fit regression illustrates that San Diego would have attained the standard in 2006 with a design value of 84.7 ppb. However, San Diego, along with the rest of California, experienced unusual meteorology in 2006, which was extremely conducive to ozone formation. Nevertheless, San Diego emissions are declining and this graph illustrates how close they are to attainment of the 8-hour standard.

Figure A-2



The weight of the evidence presented in these supplemental analyses supports the District's conclusion that its current strategy will result in attainment by 2008, even though the regional air quality modeling predicts a 2008 8-hour design value of 86 ppb.

CALIFORNIA AIR RESOURCES BOARD

NOTICE OF PUBLIC MEETING TO CONSIDER THE PROPOSED ALLOCATION OF $25 MILLION FOR ALTERNATIVE FUEL INCENTIVES

The Air Resources Board (Board/ARB) will conduct a public meeting at the time and place noted below to present the multi-state agency recommendations to the Board for allocation of $25 million for alternative fuel incentives.

DATE: May 24, 2007

TIME: 9:00 a.m.

PLACE: San Diego Marriott Del Mar Hotel
Grand Ballroom
11966 El Camino Real
San Diego, California 92130

This item will be considered at a two-day meeting of the Board, which will commence at 9:00 a.m., May 24, 2007. Please consult the agenda for the meeting, which will be available at least 10 days before May 24, 2007, to determine the order of agenda items.

For individuals with sensory disabilities, this document is available in Braille, large print, audiocassette or computer disk. Please contact ARB's Disability Coordinator at 916-323-4916 by voice or through the California Relay Services at 711, to place your request for disability services. If you are a person with limited English and would like to request interpreter services, please contact ARB's Bilingual Manager at 916-323-7053.

Pursuant to the 2006 Budget Act (Assembly Bill (AB) 1811), the ARB is required to develop a joint plan with the California Energy Commission (CEC) to spend $25 million to assist in the development of specific measures to reduce air pollution and greenhouse gas emissions through alternative fuel incentives. AB 1811 requires the funds to be encumbered by June 30, 2007, and fully expended by June 30, 2009.

There are a number of recent State policy directives that call for substantial expansion of the use and production of alternative fuels made from biomass and to reduce dependence on petroleum-based fuels. These include the Governor's Executive Order on biofuels (S-06-06), the Bioenergy Action Plan for California, and the Climate Action Plan. The ARB and CEC, with assistance from other State agencies, designed the Alternative Fuels Incentives Program to be consistent with the State policies on alternative fuels and the AB 1811 provisions.

ARB and CEC staff will present the multi-state agency recommendations for allocation of the $25 million for the Alternative Fuel Incentives Program (AB 1811). ARB staff has prepared a summary with a brief description for each of the proposed projects. This

summary will be available at least 10 days before the Board meeting at the following ARB website:

http://www.arb.ca.gov/fuels/altfuels/incentives/incentives.htm

Interested members of the public may also present comments orally or in writing at the meeting, and in writing or by email before the meeting. To be considered by the Board, written comments and email submissions not physically submitted at the meeting must be received **no later than 12:00 noon, May 23, 2007**, and addressed to the following:

Postal mail: Clerk of the Board
Air Resources Board
1001 I Street
Sacramento, California 95814

Electronic submittal: http://www.arb.ca.gov/lispub/comm/bclist.php

Facsimile submittal: (916) 322-3928

The Board requests, but does not require 30 copies of any written submission. Also, the ARB requests that written and email statements be filed at least 10 days prior to the meeting so that ARB staff and Board members have time to fully consider each comment. Further inquiries regarding this matter should be directed to Dean C. Simeroth, Branch Chief, Criteria Pollutants Branch, at (916) 322-6020 or dsimerot@arb.ca.gov.

CALIFORNIA AIR RESOURCES BOARD

Catherine Witherspoon
Executive Officer

Date: May 9, 2007

CALIFORNIA AIR RESOURCES BOARD

NOTICE OF PUBLIC MEETING TO CONSIDER A STATUS REPORT ON THE ZERO EMISSION VEHICLE (ZEV) PROGRAM

The Air Resources Board (ARB or the Board) will conduct a public meeting at the time and place noted below to consider a status report on the Zero Emission Vehicle (ZEV) Program as directed by the Board at its April 2003 meeting. As part of this review, the Board directed that an independent panel of experts (Panel) be established to report on the status of advanced technologies and the readiness of various technologies for commercialization. The Panel's findings will be presented as part of ARB staff's report to the Board. The Board will not make any changes to the ZEV Program at this time, but could direct the staff to return later this year with proposed changes.

DATE: May 24-25, 2007

TIME: 9:00 a.m.

PLACE: San Diego Marriott Del Mar
Grand Ballroom
11966 El Camino Real
San Diego, California 92130

The item will be considered at a two-day meeting of the Board, which will commence at 9:00 a.m., May 24, 2007, and adjourn at 6:00 p.m. The meeting will then continue at 8:00 a.m., May 25, 2007. Please note that this item may not be considered until May 25, 2007. Please consult the agenda for the meeting, which will be available at least 10 days before May 24, 2007, to determine the day on which this item will be considered.

For individuals with sensory disabilities, this document is available in Braille, large print, audiocassette or computer disk. Please contact ARB's Disability Coordinator at (916) 323-4916 by voice or through the California Relay Services at 711, to place your request for disability services. If you are a person with limited English and would like to request interpreter services, please contact ARB's Bilingual Manager at (916) 323-7053.

BACKGROUND

In September 1990, ARB adopted a low-emission vehicle regulation whose aim has been to drastically reduce pollution from passenger cars and light-duty trucks. As part of the newly created program, the Board included a goal of requiring large automakers to commercialize vehicles with no direct emissions, known as zero emission vehicles or ZEVs, beginning with 1998 model-year vehicles. This ZEV requirement was included to catalyze efforts to commercialize sustainable transportation. The ZEV Program

anticipated the added benefit of prompting automakers to develop extremely clean conventional and alternative fuel and hybrid electric vehicles.

Because of the long-term, technology-forcing nature of the ZEV Program, the Board directed staff to provide regular updates on the progress being made in meeting the requirements. Earlier updates have given the Board the information necessary to amend the ZEV Program to respond to new developments in vehicle technology and to the experiences gained by industry. The May 2007 status report will update the Board on the advances in vehicle technology that have occurred since the Board's consideration of the ZEV Program in 2003.

As part of the regulatory changes made in 2003, the Board directed that an independent expert panel be established to provide a thorough and accurate assessment of the current worldwide status of ZEV technologies and the prospects for technology advancement in both the near- and long-term. Of particular concern were the fuel cell vehicle requirements that begin in 2009 and the extent to which the development and production of advanced technology partial ZEVs have contributed toward commercialization of fuel cell vehicles and whether economies of scale have largely been achieved. The information gathered by the Panel and ARB staff will be used to assist the Board in determining if adjustments to the program are needed later this year.

AVAILABILITY OF DOCUMENTS AND AGENCY CONTACT PERSON

A summary of the written report updating the Board on the progress of the ZEV Program will be presented by ARB staff at the meeting. A summary of the Panel's written report regarding technology development will be presented by Panel members. Copies of both reports may be obtained from the Board's Public Information Office, Air Resources Board, 1001 I Street, 1st Floor, Environmental Services Center, Sacramento, CA 95814, (916) 322-2990, prior to the scheduled meeting. The reports will also be available electronically on ARB's website at http://www.arb.ca.gov/msprog/zevprog/zevprog.htm. Further inquiries regarding this matter should be directed to Tony Andreoni, Manager, ZEV Implementation Section, at (916) 324-6021, or by email tandreon@arb.ca.gov.

SUBMITTAL OF COMMENTS

Interested members of the public may also present comments orally or in writing at the meeting, and in writing or by email before the meeting. Written and oral comments become part of the public record of the meeting. To be considered by the Board, written comments submissions not physically submitted at the meeting must be received **no later than 12:00 noon, May 23, 2007** and addressed to the following:

Postal mail: Clerk of the Board, Air Resources Board
1001 I Street, Sacramento, California 95814

Electronic submittal: http://www.arb.ca.gov/lispub/comm/bclist.php

Facsimile submittal: (916) 322-3928

Please note that under the California Public Records Act (Govt. Code Section 6250 et seq.), your written and oral comments, attachments, and associated contact information (e.g. your address, phone, email, etc.) become part of the public record and can be released to the public upon request. Additionally, this information may become available via Google, Yahoo, and any other search engines.

The Board requests but does not require 30 copies of any written submission. Also, ARB requests that written and email statements be filed at least ten days prior to the meeting so that ARB staff and Board Members have time to fully consider each comment. ARB encourages members of the public to bring to the attention of staff in advance of the meeting any suggestions or comments.

CALIFORNIA AIR RESOURCES BOARD

Catherine Witherspoon
Executive Officer

Date: April 23, 2007

The energy challenge facing California is real. Every Californian needs to take immediate action to reduce energy consumption. For a list of simple ways you can reduce demand and cut your energy costs, see our Web-site at www.arb.ca.gov

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY
AIR RESOURCES BOARD

STATUS REPORT ON THE CALIFORNIA AIR RESOURCES BOARD'S ZERO EMISSION VEHICLE PROGRAM



This report has been reviewed by the staff of the California Air Resources Board and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Air Resources Board, nor does the mention of trade names or commercial products constitute endorsement or recommendation for use.

Date of Release: April 20, 2007
Scheduled for Consideration: May 24 and 25, 2007

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Appendix B: California Hydrogen Highway Network Year End Progress Report to the Legislature, December 2006

1.0 Introduction

The goal of the Air Resources Board's (ARB or the Board) Zero Emission Vehicle (ZEV) program is to evolve the California passenger car fleet to vehicles with no direct emissions. Since its inception in 1990, the program has been modified on several occasions to better reflect the pace of technological development, costs and realities of the marketplace. The ZEV program continues to push the development of clean vehicles and supports the vision needed to meet California's longer-term environmental goals.

This report has been prepared in response to the Board's direction to staff at its April 2003 Board hearing. As described in Resolution 03-4, the Board directed that an independent panel of experts be appointed to report on the status of ZEV technologies and on the readiness of various technologies for market and consumer acceptance. The Independent Expert Panel's (Panel's) Report is attached as Appendix A. In addition to the information gathered by the Panel, data presented at an ARB ZEV Technology Symposium and other information collected by ARB staff are being made available to assist the Board in determining if further adjustments to the program are warranted.

To provide an understanding of the program's effectiveness in pushing research and development and the commercial potential of advanced vehicles, this report examines the key findings of the Panel, industry-wide compliance status, and the development of infrastructure necessary for vehicles in the ZEV program.

2.0 Background

In September 1990, ARB adopted a low-emission vehicle regulation whose aim is to drastically reduce pollution from passenger cars and light-duty trucks. As part of the newly created program, the Board included a goal of requiring large auto manufacturers to commercialize vehicles with zero emissions, beginning with 1998 model-year vehicles. This ZEV requirement was included to catalyze efforts to commercialize sustainable transportation. The program would ultimately have the added benefit of prompting manufacturers to develop extremely clean conventional and alternative fuel and hybrid electric vehicles.

Because of the long-term, technology-forcing nature of the ZEV regulation, the Board directed that staff provide regular updates on the progress being made in meeting the requirements. Doing so has given the Board the information necessary to amend the program to respond to new developments in vehicle technology and to the experiences gained by industry.

2.1 Current Program

The original ZEV program required that 10 percent of new vehicle sales by large manufacturers have zero emissions, starting with 1998 models. The Board modified the program in 1998 and 2001 to allow up to 60 percent of the requirement to be met with vehicles having extremely low emissions and specific attributes, as shown in Table 2.1. In 2009 up to 85 percent of the requirements may be met with these vehicles. Vehicles meeting these standards are referred to as "partial zero emission vehicles" (PZEV) and "advanced technology partial zero emission vehicles" (AT PZEV). Staff refer to the categories of vehicles used to meet the ZEV regulation as gold (ZEV), silver (AT PZEV) and bronze (PZEV) to simplify discussion. PZEVs and AT PZEVs have achieved commercial success and are responsible for significant emissions reductions due to the large numbers of vehicles sold. Examples of a PZEV are the Ford Focus and BMW 325. An example of an AT PZEV is the Toyota Prius hybrid electric vehicle.

Table 2.1
ZEV Program Requirements
2009 Model Year - Base Path

Certification Standards				
% Requirement	% of Total Vehicle Sales[1]	Vehicle Type	Category	Technical Description
2.5%	< 1%	Zero Emission Vehicle (ZEV)	Gold	Zero tailpipe emissions: battery electric vehicles, and hydrogen fuel cells.
2.5%	5%	Advanced Technology (AT PZEV)	Silver	Vehicles certified to PZEV standards and employing ZEV-enabling technologies: e.g. hybrids or compressed natural gas vehicles.
6%	30%	Partial Zero Emission Vehicle (PZEV)	Bronze	Conventional vehicles certified to the most stringent tailpipe emission standards, zero evaporative emissions, and extended warranty.
11%	Total ZEV Requirement			

1. Percent of total California sales differs from percentage requirement because credits per vehicle type vary.

The Board's most recent amendments to the ZEV program in 2003 revised the percentage of ZEVs required to 11 percent starting in 2009, increasing to 16 percent in 2018. Large volume manufacturers are allowed to comply with either the base compliance path using the percentage ZEV requirements shown in Table

2.1, or with an alternative path, shown in Table 2.2 below. The Alternative Path is designed to advance the commercialization of fuel cell vehicles[1]. It allows AT PZEVs to be used to meet both the gold and silver obligations, provided that the manufacturer meets the requirements specified below.

Table 2.2
Alternative Compliance Path Fuel Cell Requirements

Phase	During Model Years	Manufacturer's Market Share of:
I	2005 to 2008	250 fuel cell vehicles
II	2009 to 2011	2,500 fuel cell vehicles
III	2012 to 2014	25,000 fuel cell vehicles
IV	2015 to 2017	50,000 fuel cell vehicles

As illustrated in Table 2.2, the requirement for fuel cell vehicles increases by a factor of ten for Phase II and III and then doubles for Phase IV, reflecting a transition from demonstration to full commercialization. Phases I and II reflect that fuel cell vehicles are still early in the development process, with further technological changes expected prior to ramp-up toward commercialization. Phases III and IV are designed to establish new commercial markets for the technology in California. A central task assigned to the Panel was to determine if the Alternative Path is technologically feasible and appropriate to achieve successful fuel cell commercialization.

2.2 Manufacturer Actions and Compliance

Manufacturers originally planned to meet the ZEV requirements with battery electric vehicles. In 1996, due to cost and performance issues, the ARB eliminated the early (1998) requirements to allow additional time for battery research and development. To ensure a significant market for advanced battery manufacturers, the ARB entered into agreements with manufacturers to place in California roughly 1,800 advanced-battery electric vehicles between 1998 and 2000. The agreements were designed to provide battery developers with the necessary initial production volumes to meet the cost and performance goals needed for commercial production. Contrary to expectations, the cost for advanced batteries remained too high for commercial viability. In 2003, the Board found that nickel metal hydride battery packs for full function electric vehicles would cost approximately $7,000 to $9,000 each at production levels exceeding 100,000 battery packs per year, and would cost two times more at lower production levels. Notwithstanding these costs, several manufacturers continued

[1] The Alternative Path requires use of Type III ZEVs. Type III ZEVs are defined as ZEVs with driving range greater than 100 miles and the ability to refuel in 10 minutes or less. This requirement is currently demonstrated by fuel cell vehicles, therefore, when referring to the regulation requirements related to Type III ZEVs, staff refers to fuel cell vehicles.

to place a modest number of battery electric vehicles beyond the memorandum of agreement volumes. These vehicles earned ZEV credits that have been used for compliance with the regulation.

Manufacturers began to look seriously at hydrogen fuel cell vehicles in the late 1990's as an alternative to battery electric vehicles. This interest led to cooperative efforts among the ARB, industry and other governmental agencies to create the California Fuel Cell Partnership (Partnership) in 1999. The goals of the Partnership are to demonstrate vehicle technology and the viability of hydrogen fuel infrastructure technology, explore paths to commercialization, and increase public awareness and enhance opinion about fuel cell electric vehicles. Manufacturers continue to aggressively pursue the development of fuel cell vehicles.

There are currently twenty-one auto manufacturers subject to the ZEV regulation. Six are defined as large volume manufacturers: General Motors, Toyota, Ford, Honda, DaimlerChrysler and Nissan. The remaining 15 are intermediate volume manufacturers. Intermediate manufacturers can meet the regulation entirely with PZEVs.

All manufacturers are currently in compliance with the ZEV regulation. Most manufacturers have enough banked credits from zero emission vehicles already placed to comply with the regulation through approximately 2009. One manufacturer has produced more fuel cell vehicles than required to meet their Alternative Path obligation for 2005 to 2008. The remaining manufacturers have, on average, completed about half their production obligation. It should be noted however, that while all of the large manufacturers have active fuel cell vehicle demonstrations, some of these manufacturers may chose to comply using the Base Path and would not need to produce any additional fuel cell vehicles between now and the end of 2008.

To meet the AT PZEV requirement, some large manufacturers are producing AT PZEVs (primarily hybrid electric vehicles) and some large manufacturers are using previously produced neighborhood electric vehicle credits. Four of the six large manufacturers have AT PZEVs in the market; two of these manufacturers, Toyota and Honda, dominate the volumes produced to date. Most of the large manufacturers have sufficient banked credit to more than meet the AT PZEV requirement for several years to come. Regardless of the method with which manufacturers are meeting the AT PZEV requirement, the number of AT PZEVs produced to date is beyond what is required by the ZEV regulation. For example, in 2005, twice as many AT PZEVs were produced than required to meet AT PZEV requirements. That will change towards 2009, when the required volume of AT PZEVs increases to 8 percent of the total fleet. The Panel was asked whether the required volumes of AT PZEVs are in line with ARB's ZEV deployment strategy.

Table 2.3 presents the approximate total number of gold, silver and bronze vehicles placed as of model-year 2005. Manufacturers have been producing PZEVs at a rate greater than their obligation in aggregate. For example, in 2005, manufacturers on the whole produced 40 percent more PZEVs than the industry wide PZEV requirement.

Table 2.3
Vehicle Placements by Type
(Through 2005)

Vehicle Type		Quantity[1]
ZEV	Fuel cell	130
ZEV	Battery electric	4,400
ZEV	Neighborhood electric	26,000
AT PZEV	Hybrid/Compressed Natural Gas	70,000
PZEV	Conventional	507,000

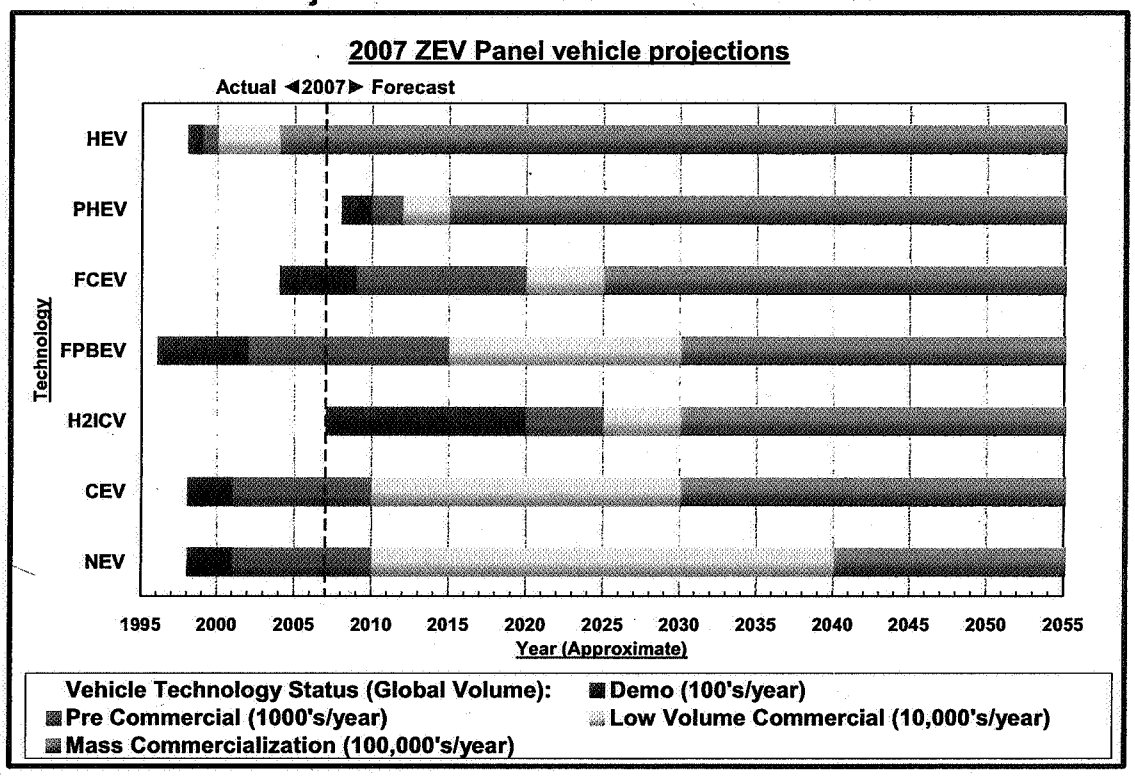
1 Estimates of total vehicle placements from 1994 through 2005

3.0 Summary of Expert Review Panel Findings

The Expert Review Panel was asked to provide a thorough and accurate assessment of the current worldwide status of zero emission vehicle technologies and the prospects for technology advancement in both the near- and long-term. In addition, the Panel was asked to project mass marketability of vehicles using these technologies. Finally, the Panel was also asked to evaluate the synergy between the AT PZEV requirements and the development of ZEV technologies.

The Panel spent much of 2006 gathering technical information, cost data, and expert opinions from leading developers of components and major manufacturers through correspondence and site visits. The information was then critically assessed by the Panel to project the current status and prospects for commercialization of each of the technologies evaluated. Figure 3.1 below illustrates the Panel's projections of when various ZEV technologies will be ready for demonstration and increased volumes along the path to commercialization.

Figure 3.1
Projected Achievement of Global Volumes



1. "HEV" means hybrid electric vehicle; "PHEV" means plug-in hybrid vehicle; "FCEV" means fuel cell electric vehicle; "FPBEV" means full performance battery electric vehicle; "H2ICV" means hydrogen internal combustion vehicle; "CEV" means city battery electric vehicle; "NEV" means neighborhood battery electric vehicle.

Following are summaries of the Panel's findings by technology type.

3.1 Fuel Cell Electric Vehicles

As shown in Figure 3.1 above, the Fuel Cell Electric Vehicle (FCEV) bar lines up fairly closely to the Alternative Path volumes listed in Table 2.2 for the start of Phase II. However, the Panel's estimate for transition to 10,000s of vehicles is 2020, compared to the current ZEV Alternative Path Phase III date of 2012.

The Panel found that FCEVs are considered by several manufacturers to be the ultimate solution to reducing both criteria pollutant and climate change emissions. Most major manufacturers have made significant investments in research, development, and demonstration of the technology. While substantial progress has been made, simultaneously achieving performance, durability and cost objectives continues to be a difficult challenge. In addition, the cost, weight, and volume of adequate on-vehicle hydrogen storage and availability of hydrogen

production and infrastructure remain major barriers to commercialization. Table 6.1 in Section 6 of this report summarizes the Panel's key technology and cost projections.

The Panel concluded that while these challenges are not trivial, the past rate of success and the massive intellectual and financial resources being devoted to fuel cell vehicle technology, ensures that FCEVs remain a promising candidate for a future mass market true ZEV.

3.2 Battery Electric Vehicles

The Panel found that previous efforts to commercialize battery electric vehicles prompted by the ZEV program were unsuccessful due to cost and lack of mass market customer acceptance. They also found that in other countries where fuel prices and driving conditions provide lower barriers to commercialization, a few manufacturers are now developing smaller vehicles using lithium-based batteries. However, the Panel concluded that in California, full-sized battery electric vehicles are still not likely to be a mass market technology in the foreseeable future due to high cost of the batteries, and limited customer acceptance. The Panel concluded that city electric vehicles are more likely to become future mass market ZEVs in Japan and Europe than in the United States due to performance limitations and vehicle safety requirements.

3.3 Plug-in Hybrid Electric Vehicles

The Panel found that plug-in hybrid electric vehicles offer direct societal benefits to the consumer and are likely to become commercially available in the near future. The incremental cost of the small battery pack should be offset by the lower operating cost of the technology. The major technical issue with PHEVs is the ability of the energy battery to endure the large number of deep cycles the battery must deliver over the life of the vehicle. The number of deep cycles is substantially higher for PHEVs than FPBEVs and thus represents a new dimension in deep cycling requirements. Battery cycle life for PHEVs is not completely know at this time. The Panel also found that test procedures to accurately determine emissions and efficiency do not exist and need to be developed. Also, the cost impact of greater electric range is not well understood and could have a significant impact on consumer acceptance. The Panel concludes that commercialization of plug-in hybrid electric vehicles will stimulate battery development and help consumers become comfortable with plugging in a vehicle.

3.4 Hydrogen Internal Combustion Engines

The Panel found that manufacturer interest in the use of hydrogen internal combustion engines is not widespread. While developing conversions of conventional powertrains is far easier than fuel cell vehicles, issues regarding hydrogen storage and infrastructure are the same or worse than those facing fuel cell vehicles.

The Panel found that while the technology is not true zero emissions, prototype vehicles have demonstrated very low emissions. The technology also provides minor benefits to future mass market ZEVs by increasing demand for a refueling infrastructure and fuel supply.

3.5 Advanced Technology Partial Zero Emission Vehicles

The Panel found that the ZEV program requirements for AT PZEVs, particularly hybrids, help to develop pure ZEV technologies by accelerating the development and deployment of advanced ZEV technologies. In particular, key systems contained within the hybrid systems are directly comparable to key ZEV fuel cell systems. These include efficient electric drive motors, high power electronics, and computer control systems which incorporate regenerative braking. Promoting the widespread adoption of these technologies in AT PZEVs will lead to performance improvements and cost reductions that are necessary for ZEVs to become mass-market vehicles in the future.

The Panel also found that the research and development work on hybrid batteries by manufacturers, battery suppliers, and material developers worldwide, continues to improve the key characteristics of batteries used in hybrid applications. The Panel concluded that this in turn will improve the batteries needed in future pure ZEV technologies, including fuel cell vehicles and battery electric vehicles.

The Panel found that hybrid technology appeals to the mass market customer willing to pay a premium. The Panel concluded that production of hybrid electric vehicles (HEV) continues to reduce the cost of electric drive components and systems - but cost is still an issue and future market success and volume of HEVs is largely dependent on the price of gasoline – making future growth uncertain.

3.6 Neighborhood Electric Vehicles

The Panel found that over the last several years, a limited market for neighborhood electric vehicles appears to have had some commercial success. However, they concluded that the mature market potential for the technology is relatively small due to limited applicability. Neighborhood electric vehicles

represent a very simple technology and have little synergy with larger battery electric vehicles. As such, the Panel concluded that neighborhood electric vehicles provide no significant benefits to future mass market ZEVs due to simple technology and performance limitations. On the positive side, NEVs serve a particular market quite well and there are no barriers to deployment.

4.0 ZEV Technology Symposium

In September 2006, the ARB staff held a 2 ½ day ZEV Technology Symposium to gather additional information from industry, academia, and the public. Sessions included:

- Background information on the ZEV regulation
- Updates from the auto manufacturers
- Hydrogen technology
- Battery technologies
- Battery electric and plug-in hybrid electric vehicle demonstrations

An open comment session allowed the public to provide additional presentations and perspectives.

Symposium session information provided staff with useful technology updates. The hydrogen technology session covered current hydrogen storage capability (liquid versus gaseous hydrogen), fuel cell technology developments, hydrogen powered combustion engine development, and hydrogen infrastructure requirements. New small volume vehicle manufacturers provided information on their development of battery electric vehicles while battery developers provided an update on lithium ion technology and testing methods. Large volume manufacturers provided an update on upcoming vehicle platforms, while supporters of electric and plug in hybrid electric vehicles provided their perspective on new emerging technologies.

The following general findings were gleaned from the Symposium presentations:

- Fuel cell development is progressing with newer generations of technology, but higher pressure hydrogen storage systems are needed to increase vehicle range, and overall system cost is still a concern.
- Lithium ion battery technology is showing promising development results for plug-in hybrid electric vehicles and extended all-electric driving range, but further material and battery production research is still needed.
- Further testing results on battery durability and cycle life are also needed.
- Low volume battery electric vehicle manufactures' will begin production in the near term, helping to push new battery electric vehicle technologies into the California market.

5.0 Fueling Infrastructure Status

An important part of successful commercialization of ZEVs is refueling infrastructure. The staff did not ask the Panel to report on infrastructure readiness in light the California Hydrogen Highway Network's Blueprint Plan for implementation of hydrogen refueling stations. The findings of the Blueprint Plan and an update on implementation are presented below.

Concerning battery electric vehicles, significant public infrastructure was installed to recharge these vehicles over the last 15 years. Any future production of battery electric vehicles will benefit from the lessons learned and the infrastructure to recharge the vehicles will be much easier to establish.

5.1 California Hydrogen Highway Blueprint Plan

The Blueprint Plan for the establishment of a Hydrogen Highway Network was created at the direction of the Governor in Executive Order S-7-04. The Executive Order directed state agencies to work with industry and academic partners to agree on the best way forward to create the infrastructure necessary to support introduction and broad commercialization of hydrogen vehicles. The Blueprint Plan was developed with the help of over 200 industry, academic and government experts over the course of a year. In May of 2005, the Blueprint Plan was released with the following findings:

- The number and location of stations should closely match deployment of vehicles to avoid under utilization of stations or stranded vehicle demonstrations. In particular, the largest urban areas of the State were selected as target locations for early mini networks; Los Angeles, San Diego, San Francisco and Sacramento. The Blueprint Plan suggested that 50 to 100 stations in 2010 could support at least 2,000 hydrogen vehicles.
- Environmental goals for well-to-wheel performance of hydrogen vehicles are important. The Blueprint plan recommended that emissions of greenhouse gases be reduced 30 percent and that criteria pollutants and toxic emissions not be increased compared to conventional vehicles. The Blueprint Plan also recommended that hydrogen be produced from a minimum of 20 percent renewable resources.
- Industry, academia and government need to share the risk. It is appropriate for all sectors to partner to coordinate implementation and to share the development and financial burdens of creating the hydrogen refueling network. Accordingly, the Blueprint Plan recommendation that the State co-fund placement of hydrogen stations and provide subsidies for hydrogen vehicles.

5.2 Implementation Status

Attached as Appendix B is the California Hydrogen Highway Network's Year End Progress Report to the Legislature summarizing the progress of infrastructure development in California. Currently, there are 24 hydrogen fueling stations operating in California and 11 more in the planning or development stages. Of the 24 existing stations, 15 are "publicly" accessible. The other nine stations are private, serving a restricted fleet of vehicles. The existing hydrogen stations have been developed and funded through a variety of collaborative, public-private partnerships that include the U. S. Department of Energy, local air quality districts and State government.

Manufacturers are still concerned that infrastructure will be insufficient in the short term to meet the needs of their next generation vehicle placements. While approximately five new hydrogen stations will come on line over the next year, and six additional stations are planned, California is far shy of the 50 to 100 station goal recommended in the Hydrogen Blueprint Plan for 2010. Co-funding and other incentives, in addition to mitigating liability and solving codes and standards issues, will be critical priorities to continue the development of a hydrogen refueling network.

6.0 Program Policy Implications

The Panel was not asked to make recommendations regarding the ZEV regulation. They were asked only to provide the technical basis for the Board to assess the progress and potential for success of the ZEV technologies. In the following section, staff reviews fundamental issues and questions relevant to implementation of the ZEV program, and identifies where changes to the program may be needed.

6.1 Fuel Cells

Issue: In 2003 it was clear that the Board wanted to accelerate development and commercialization of fuel cell vehicles. Creating the Alternative Path provided an incentive to manufacturers to aggressively demonstrate fuel cell vehicles in California in phases designed to lead to mass commercialization. However, when the Board approved the ramp up schedule for the Alternative Path there was a wide divergence of opinion about how and when a commercialization ramp up would take place. This was one of the primary reasons the Board asked the staff to convene an Independent Expert Panel. The Board wanted to know, once initial demonstrations were launched, what the prospects for volume growth would be.

Current Treatment in the Regulation: Table 2.2 of this report shows the ramp up schedule for fuel cell vehicles in the Alternative Path, with a ten times increase in

volume for each phase of implementation until Phase IV when it doubles. Based on discussions with manufacturers and looking at the U. S. Department of Energy's (U.S. DOE's) estimates of anticipated technology development and introduction, this approach appeared reasonable in 2003.

Panel Findings: "The intense effort on FCEVs will result in technically capable vehicles by the 2015 to 2020 timeframe, but successful commercialization is dependent on meeting challenging cost goals and the availability of an adequate hydrogen infrastructure." Table 6.1 below taken from the Panel report summarizes the technical and cost status of fuel cell vehicles compared to the U.S. DOE's FreedomCar targets for commercialization.

Table 6.1
Derived from Table 6-10 from Panel Report
U.S. DOE's FreedomCAR Fuel Cell Power System1 Goals and Status

		Panel's Assessment of	
Fuel Cell Power System Parameter[1]	**FreedomCAR Goals** 2010/2015[2]	**Present Status**	**Forecasted 2015 Status**
Life (years)	15	2 – 3	10 – 13
Peak Efficiency (%)	60	50 – 60	60
Gravimetric Power Density[3] (W/kg)	325	300 – 500	700 – 1100
Volumetric Power Density[3] (W/l)	220	n/a	n/a
Cost[4] ($/kW)	$45 (2010) $30 (2015)	$75 – 600	$30 – 75

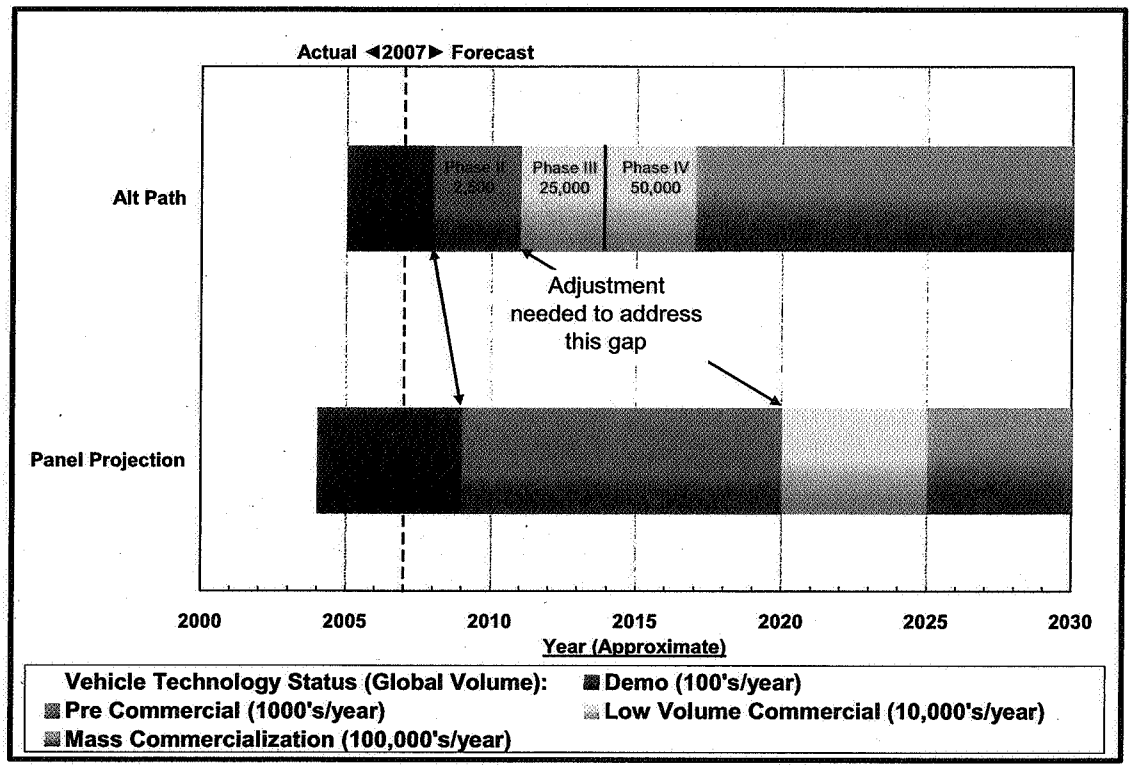
1. Consists of the fuel cell stack, the fuel cell stack auxiliary sub-systems (e.g., sub-systems for air supply, fuel supply, thermal management, and any other necessary functions, such as water management), the hydrogen storage system, the high voltage energy storage system (if used), and all enclosures and connections.
2. Source: Figure 3 (page 10), Technology-Specific 2010 and 2015 Research Goals, FreedomCAR and Fuel Partnership Plan, U.S. Department of Energy, March 2006, http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/fc_fuel_partnership_plan.pdf
3. Excluding hydrogen storage.
4. Direct material/labor and production facility costs. Indirect costs, marketing and profit not included. Design level assuming 250,000 units per year.

As Table 6.1 shows, a number of targets are far from realization. In particular, the fuel cell life and cost remain far from targets that are necessary to achieve volume ramp-up. The Panel also identified hydrogen storage as a significant challenge to fuel cell vehicle commercialization for primarily cost reasons, and hydrogen infrastructure as perhaps the most significant barrier on the vehicle placement side of the equation.

Staff findings and recommendations: The fuel cell life issue alone points to the need for additional generations of fuel cell vehicles in limited numbers before ramping up to production volumes. Coupled with high per vehicle costs the need for further demonstration is undeniable. Staff, therefore, recommends that the Board adjust the Alternative Path phases to allow further demonstrations for continued progress towards the fuel cell stack life and cost goals.

The Panel projects that 1,000s of fuel cell vehicles per year globally are achievable in the next five years given the pace of efforts underway by manufacturers and suppliers. Staff concludes that the Phase II volumes, therefore, are appropriate (2,500 over three years, 2009 through 2011). Maintaining Phase II is especially important as manufacturers struggle to engage hydrogen fueling partners to seriously respond to the need for infrastructure (more utilization of stations catalyzes fuel provider investment). Where the Alternative Path deviates from the Panel's projections for commercialization is in Phase III, as illustrated in figure 6.1 below.

Figure 6.1
Fuel Cell Commercialization Forecast Compared to Alternative Path



As shown in this chart, the Panel's findings suggest that the transition from Phase II to Phase III is the area where adjustments are most needed. Such changes could range from repeating the volumes required in Phase II through addition of a Phase that would create an intermediate step between 2,500 and 25,000 vehicles.

Another approach could be to lengthen phases. An important consideration will be what volumes are necessary to cause investment in continuous manufacturing process development, a necessary step toward cost reduction.

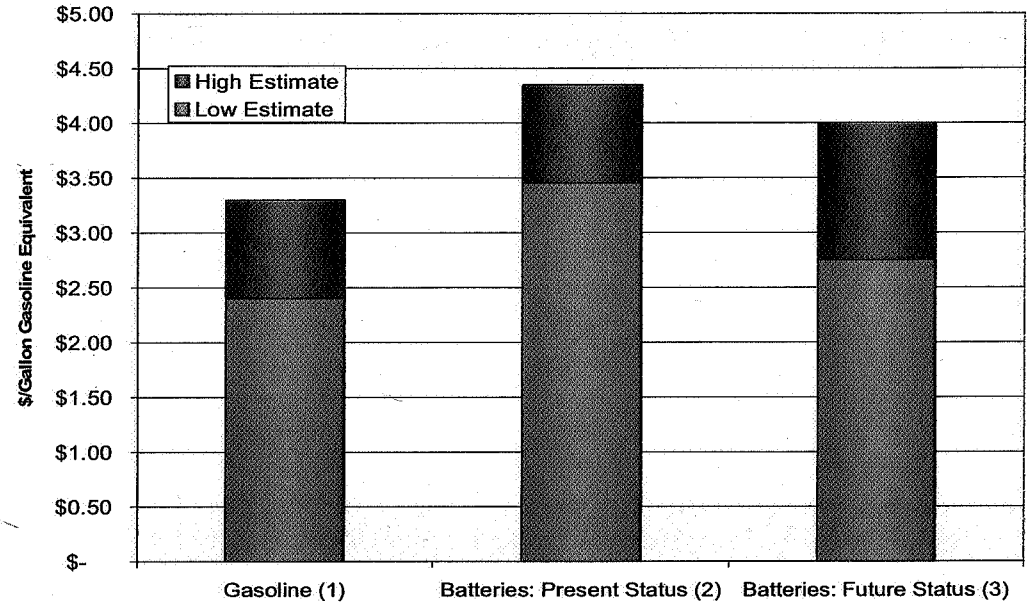
6.2 Battery Electric Vehicles

Issue: Battery electric vehicles (BEV) were the primary compliance strategy of manufacturers in the early years of the ZEV regulation's history. In 2003 however, the technical findings on cost and durability pointed to a limited opportunity to make BEVs mainstream. In an effort to refocus the regulation towards a technology with mass market commercial potential, the Board shifted the regulation towards acceleration of fuel cell vehicle technology. However, ARB's interest in BEV technology remains strong and staff is optimistic that BEV technology will play a significant role in California's future fleets.

Current Treatment in the Regulation: Battery electric vehicles can be used to meet the gold obligation in the ZEV regulation. The credit earned by a BEV depends on its driving range. However, because they cost much less than fuel cell vehicles (about 10^{th}), BEVs may only be used to meet up to half of the Alternative Path obligation and they may substitute for a fuel cell vehicle at a rate of ten to one (assuming full function BEV).

Panel Findings: The Panel found that progress has been made in batteries that could be used for BEVs. Both Nickel Metal Hydride (NiMH) and Lithium Ion (Li Ion) battery chemistries appear to provide performance and life cycle performance necessary for customers. However cost remains an issue. Figure 6.2, derived from the Panel's Table 6-4 illustrates one way of looking at the cost of the battery pack as a consumer might see it.

Figure 6.2
Comparison of Gasoline Price and Battery Cost



(1) Retail gasoline price estimates are high and low for California from April 2006 through April 2007 according to California Energy Commission's website: http://www.energy.ca.gov/gasoline/graphs/diesel_images/image_grabber.php?link=Gas_Retail.gif

(2) Battery cost comparison assumptions: 10 year life, 12,000 miles/year, 27.5 mpg (combined) ICE vehicle, 0.300 kWh/mile AC basis for full function BEVs; costs not included: scheduled maintenance, battery markup and warranty cost not recovered by OEM, time value of money, inflation, value of vehicle at end of 10 years. 2006 average U.S. residential electricity rate of $0.0973/kwh. Battery pack cost source: Table 6-3 (U.S. Advanced Battery Consortium Goals for Electric Vehicle Batteries, 2005 Annual Progress Report, Energy Storage Research and Development, FreedomCAR and Vehicle Technologies Program, U.S. Department of Energy, January 2006).

(3) Future Status derived from Table 3-13 of Panel Report, assumes Lithium Ion batteries at 20,000 to 100,000 full-function BEV packs per year.

Figure 6.2 shows only what the cost of gasoline would need to be to make the incremental cost of the battery for a BEV cost comparable for the owner. This comparison assumes that the only difference in cost between a gasoline car and the BEV is the battery pack and it assumes that the owner is driving the vehicle 12,000 miles per year (which could be considered aggressive for a BEV).

The Panel also laid out information about several independent manufacturers with plans to market full function BEVs as well as the plans of several large and intermediate manufacturers to produce smaller city type BEVs for international markets where fuel costs and driving conditions support such urban commute vehicles.

Staff findings and recommendations: Battery electric vehicles have received renewed interest since 2003. Announcements by several new companies and improvements in battery chemistry have raised new optimism that the technology

may be viable in the mid-term. Although the Panel notes that cost and utility are still significant barriers to full commercialization, staff recommends that the Board examine more even treatment of BEVs in the regulation as compared to FCEVs. For example, BEVs and FCEVs could offered equal credit before 2012. By returning to technology neutrality and considering BEVs and fuel cell vehicles similarly, the ARB might induce some manufacturers to choose to pursue battery electric vehicle development instead of fuel cell vehicle development. The outcome would be that overall ZEV production could be greater, but fewer fuel cell vehicles may be produced.

6.3 Plug-In Hybrid Electric Vehicles

Issue: The question of how to treat plug-in hybrid electric vehicles (PHEVs) was a controversial topic during the 2003 amendments and remains so today. The Board was asked to classify PHEVs as "gold" as they appeared to have greater chance for near term commercial viability considering the smaller battery pack, unlimited range and limited infrastructure needs. However, the Board said no, gold means zero emissions. Instead, the Board directed staff to create sufficient regulatory incentive outside of the gold category to encourage introduction of PHEVs. One of the toughest questions the Board asked the manufacturers as they testified at the 2003 hearings was "why don't you produce a plug-in hybrid vehicle?" Coming into this technology review, with still no PHEV from a major manufacturer, staff asked the Panel to help staff to assess what more could be done to further support PHEV.

Current Treatment in the Regulation: PHEVs earn silver credit that ranges from 10.8 to 18 depending on the amount of all electric range. This compares to a conventional hybrid that earns a credit of up to 0.7. PHEVs produced after 2009 may earn up to 4 credits each and after 2012 three credits each. Certification test procedures for PHEVs need revisions to better reflect current design approaches to PHEVs. When the initial certification procedures were adopted staff anticipated that PHEVs would be designed to operate in an all electric mode until the battery pack was exhausted. Instead, manufacturers are designing fully integrated PHEVs where the battery and gasoline engine operate intermittently or simultaneously (blended) throughout typical driving. Currently, the regulation invites manufacturers to present an alternative certification calculation method for approval of their PHEV system.

Panel Findings: The Expert Panel concludes that PHEVs have the potential to provide significant direct benefits and to foster future mass market ZEVs by stimulating battery development and conditioning mass market customers to accept plugging in. Several major manufacturers are showing a new interest in the technology and have recently announced PHEV development activities and timeframes for selling them to the public. PHEVs have the potential to achieve significant electric drive use. The technology may be very close to technical and

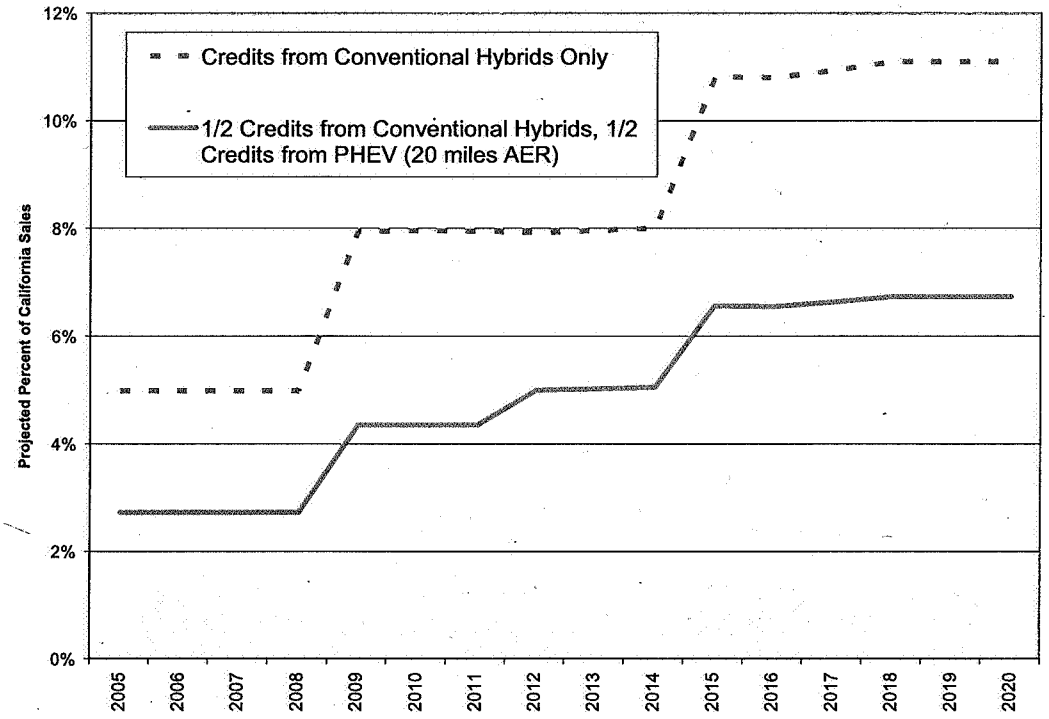
economic feasibility and ready for mass market introduction by 2015. The Panel concluded that the significant issue that must be addressed before commercialization can take place is the cycle life of batteries used in PHEVs which may experience more deep cycles than full function BEVs.

Staff findings and recommendations: While interest in and technical promise for PHEVs is at an all time high, the fundamental question remains; should PHEVs count toward meeting pure ZEV requirements? Staff recommends against allowing PHEVs to be used in the gold category. This recommendation is based on the original concern that PHEVs are not zero emission. Additionally, uncertainty exists regarding how PHEVs will be used (will they be plugged in consistently and throughout their life? Will all electric range be maximized under a wide variety of driving cycles? etc.).

As examples of PHEVs are demonstrated it is clear that multiple approaches are under development that could have very different impacts on air quality. Traditionally, we have thought of plug-in hybrids as range extended battery electric vehicles or electric vehicles with an engine that could recharge the battery if/when needed. However, PHEVs being discussed today have more of a blended approach to using the battery pack. Like a conventional hybrid, the battery is used off and on throughout the driving cycle to assist the engine or drive in an all electric mode. Staff needs to learn more about how these blended PHEV strategies would be implemented and how they might impact air quality before recommending how they be treated in the ZEV regulation. For these reasons, staff does not recommend opening up the pure ZEV category as an incentive to bring PHEVs to market.

Staff does believe, however, that there are good reasons why manufacturers will produce PHEVs and there are adjustments to the regulation that could be explored that would facilitate this. The gold category is challenging for manufacturers, but as the percentage of the overall obligation that can be met by silver category vehicles increases, significant pressure builds on manufacturers to produce large numbers of "conventional" AT PZEVs. This pressure would make production of a high scoring silver vehicle increasingly attractive. Figure 6.3 illustrates an example of how use of PHEVs with 20 miles all-electric range to meet one half of the credits from the AT PZEV category can significantly reduce the overall number of AT PZEVs needed while creating a market for PHEVs.

Figure 6.3
Example PHEV use in AT PZEV Obligation
(Alternative Path example presented)

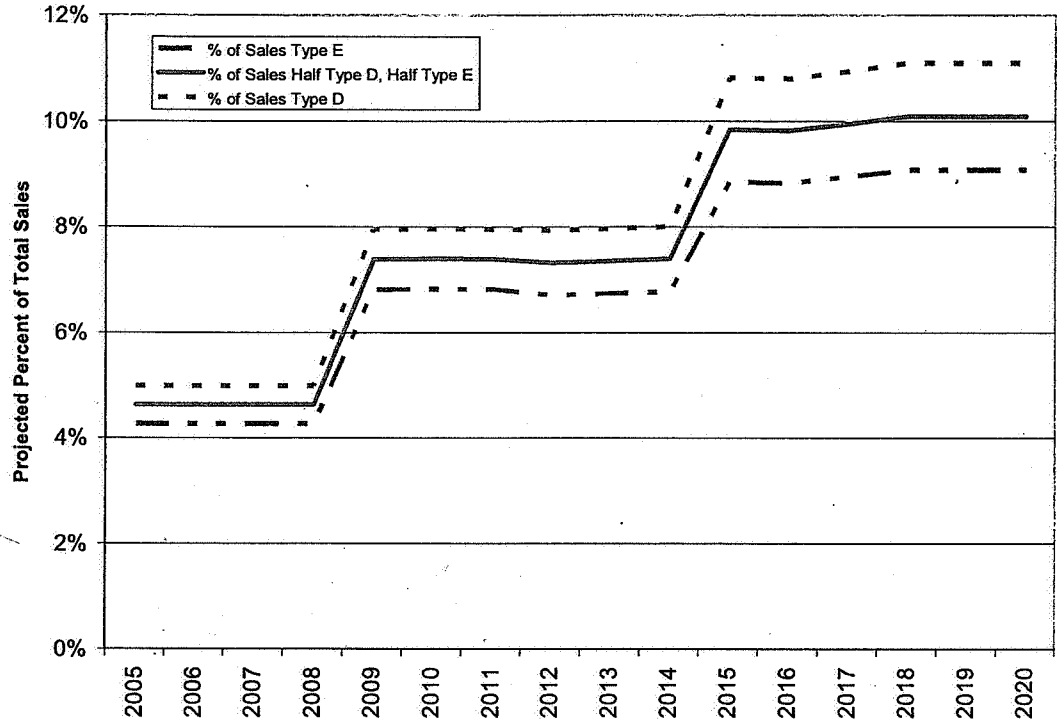


As figure 6.3 demonstrates, the percentage of vehicles that would be produced using only conventional hybrids reaches 11 percent of overall sales. However, meeting half of the silver category with PHEVs with all electric range of 20 miles reduces the obligation by about 40 percent with a maximum silver category volume reaching 7 percent of total sales. This pressure relief offered by PHEVs is significant and may be adequate incentive for their market introduction.

6.4 Advanced Technology Partial ZEV (AT PZEV) Volumes

Issue: The AT PZEV category was created to promote early commercialization of vehicle components that are instrumental to the success of zero emission vehicles, such as batteries, electric drive systems and hydrogen storage tanks. The way in which the regulation ramps up vehicle requirements over the years leads to relatively high volumes of AT PZEVs. Figure 6.4 illustrates how the volume of AT PZEVs grows if only conventional hybrids are used to comply with the AT PZEV category. Three cases are presented using different hybrid types; strong hybrids (Type E), moderate hybrids (Type D) and a mix of the two types.

Figure 6.4
AT PZEV Volumes Compared to All California Sales
(Alternative Path Example)



At the peak of implementation, AT PZEVs could account for 11 percent of projected total annual California vehicle sales. Manufacturers have argued that such volumes of AT PZEV technologies are not valuable to commercialization of ZEV components and that market acceptance of that volume of vehicles will be challenging. The Board directed that the Panel examine the value of high AT PZEV volumes to the development and commercialization of ZEVs.

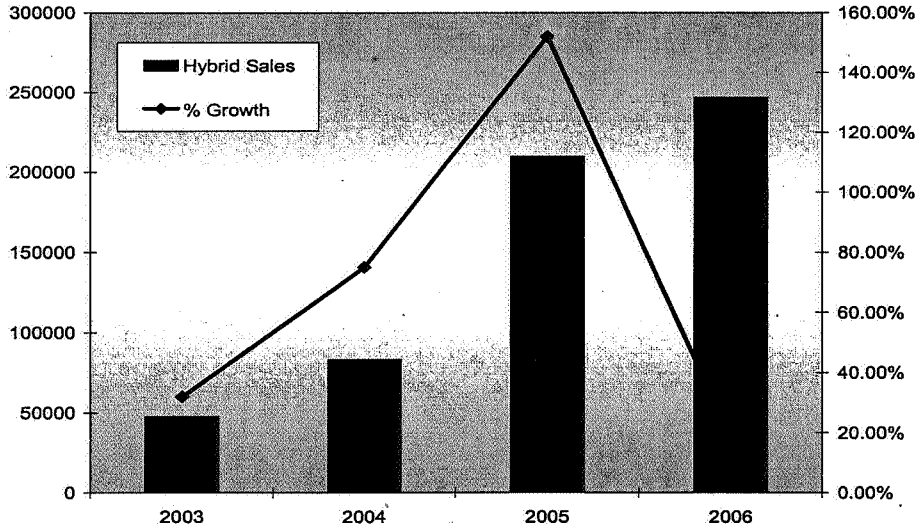
Current Treatment in the Regulation: AT PZEVs earn a range of credits depending on the characteristics of the vehicle that make it ZEV enabling. Examples include electric drive components, batteries, compressed gas fuel tanks, and all electric range. Table 6.2, below, illustrates the variety of vehicle types and credits that may be earned by AT PZEVs.

Table 6.2
Example AT PZEV Credits Per Vehicle

Vehicle Type	Total Credit Per Vehicle		
	2009-2011	2012-2014	2015+
Type C Hybrid (Mild)	0.4	0.2	0.2
Type D Hybrid (Moderate, e.g. Honda Civic)	0.6	0.55	0.45
Type E Hybrid (Strong, e.g. Toyota Prius)	0.7	0.65	0.55
Compressed Natural Gas Vehicle	0.7	0.7	0.7
PHEV with 20 Miles All Electric Range	4.0	2.1	2.1
PHEV with 60 Miles All Electric Range	4.0	2.7	2.7
Hydrogen Internal Combustion Engine Vehicle	4.0	2.2	2.2

Panel Findings: The Panel concluded that AT PZEVs, hybrid electric vehicles in particular, are providing major support to future mass market ZEVs by stimulating advances in electric drive systems, electric accessories, and battery technologies. Additionally, the growing public awareness of electric drive technology was identified as a benefit. The Panel provided the data for Figure 6.5 showing the growth in national sales of hybrid electric vehicles. Rapid growth in sales occurred in initial years, likely fueled by various incentives and rising gasoline prices. The Panel linked continued market penetration to both meeting improved cost targets and market factors such as gasoline prices and available incentives.

Figure 6.5
National Annual Hybrid Sales



Staff findings and recommendations: Hybrid sales in 2007 are increasing dramatically as gasoline prices have again topped $3 per gallon, with projections for continued high prices. With this trend in sales and with the projection for gasoline prices, staff expects sales of hybrid AT PZEVs to remain healthy. Staff

expects manufacturers to begin using a variety of AT PZEV types (like PHEVs) which provides flexibility in meeting the requirements. Therefore, staff does not recommend any changes to the AT PZEV portion of the regulation.

6.5 Hydrogen Internal Combustion Vehicles

Issue: The topic of how hydrogen internal combustion engine vehicles (H2ICEs) are valued in the ZEV regulation was raised in the 2003 amendments. The Board was asked to consider allowing H2ICEs to be used in the gold category as they appeared to have a chance for near-term commercial viability, had demonstrated extremely low emission levels, and would help expand the hydrogen refueling infrastructure. The Board decided at the time that H2ICEs were not truly zero emission vehicles. Instead the Board directed staff to create sufficient regulatory incentive outside of the gold category to encourage introduction of H2ICEs. One major manufacturer still considers this technology as zero emitting and since 2003, has added exhaust after treatment to make its H2ICE vehicle virtually emission free. Staff asked the Panel to explore this technology further.

Current Treatment in the Regulation: H2ICEs earn a silver credit of 13.8 through 2008. H2ICEs produced between 2009 and 2011 earn 6.9 credits per vehicle and 2.2 credits per vehicle in 2012 and beyond (see Table 6.2). They are not considered "pure" zero emission vehicles within the regulation because they emit small amounts of oxides of nitrogen.

Panel Findings: The Expert Panel's opinion is that H2ICEs could provide minor benefits to future mass market ZEVs (for fuel cell vehicles), limited to advancing onboard vehicle hydrogen storage and hydrogen infrastructure. Further, they caution that if the relative incentives change, it could cause a shift in resources away from fuel cell vehicle development to fund H2ICEs. Currently, H2ICE technology is being pursued by only two manufacturers.

Staff findings and recommendations: While at least one manufacturer recognizes technical promise for H2ICEs, the question remains; should H2ICEs count toward meeting the pure ZEV requirements? Staff recommends against allowing H2ICEs to be used in the gold category. This recommendation is based on the original concern that H2ICEs are not zero emission. Even with sophisticated after treatment manufacturers cannot guarantee that H2ICE vehicles will stay emission free throughout their useful lives. For this reason, staff does not recommend opening up the pure ZEV category as an incentive to bring H2ICEs to market.

Staff believes, however, that there is sufficient credit for H2ICEs in the silver category should a manufacturer decide to produce H2ICEs for AT PZEV credit.

6.6 Neighborhood Electric Vehicles

Issue: Prior to 2003, neighborhood electric vehicles could be used to meet ZEV obligations, earning relatively high credit levels with fairly low cost. A few manufacturers took advantage of this compliance path and delivered a large number of NEVs to California. The resulting glut of credits created a challenge for implementation of the ZEV regulation and the Board reacted in 2001 by drastically reducing the credits earned per vehicle and limiting the amount of banked NEV credits that could be applied towards compliance in a given year. The question has been raised to the Board since then, did we overreact? NEVs are after all zero emission vehicles, displacing daily driving and avoiding emissions from cold starts. Staff committed to return to the Board with an assessment of the air quality benefits of NEVs based on data from real world operation, and a reassessment of the appropriate credit levels.

Current Treatment in the Regulation: The credit earned by NEVs is outlined below:

Table 6.3
NEV Credits

2003	2004-2005	2006 +
1.25	0.625	0.15

Panel Findings: The Panel found that NEVs do not contribute to the advancement of technology used in full performance ZEVs. The batteries, drive systems, brakes, etc. are not compatible with full size vehicles. However, they agreed that NEVs are helpful in solving emissions, greenhouse gas and energy independence issues and they are commercially viable.

Staff findings and recommendations: Staff has been presented with extensive data tracking the daily use of NEVs, demonstrating the emissions benefit of NEVs. User surveys indicated NEVs were used for two out of every three trips and the length of trips was sufficient to offset the emissions of a cold start of a conventional vehicle. Given the air quality data benefits presented, it would appear appropriate to consider an increased credit value for NEVs. The staff recommends the Board direct staff to adjust the credit value appropriately to reflect the value of NEVs for emission reduction.

7.0 Additional Issues

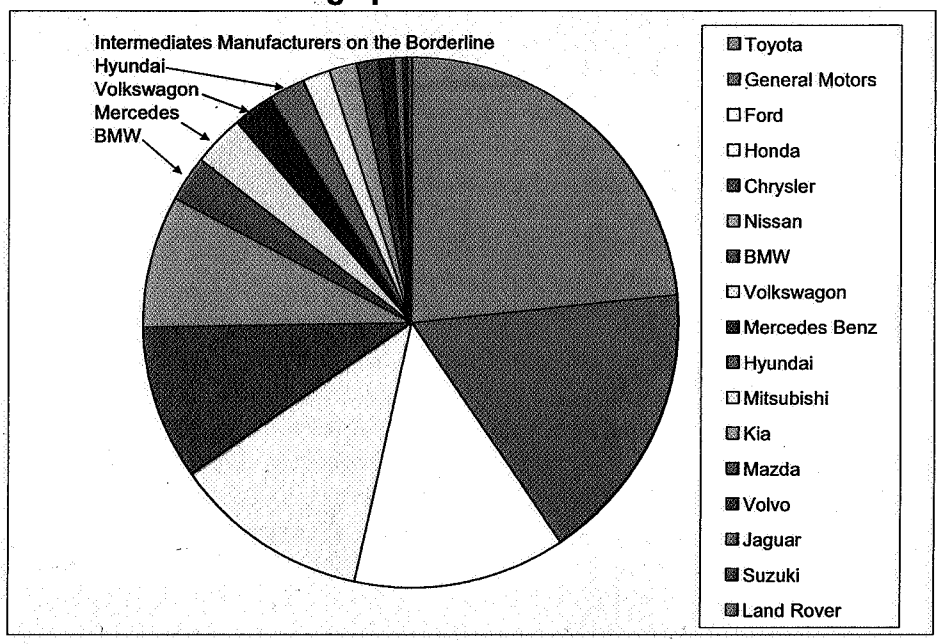
As implementation of the ZEV regulation proceeds staff has identified several issues that the Board should be aware of and that may need adjustment. These include the definition of intermediate volume manufacturers, the "travel" provisions allowing fuel cell vehicles placed in any state that has adopted the ZEV regulations to count towards compliance in California, and regulatory incentives for even cleaner conventional vehicles.

7.1 Intermediate Volume Manufacturers

The ZEV regulation defines an intermediate manufacturer as a company having annual California sales between 3,001 and 60,000 vehicles. The Board established this definition so that smaller manufacturers would not have to invest in development of pure ZEVs. At the time this definition was created, the break between intermediate and large was established at 60,000 vehicles because there was clear distinction in the market place between companies above that threshold and those below.

At this time there are several manufacturers that are approaching or have passed the 60,000 vehicles per year threshold and will become subject to the full ZEV obligation after a period of time established in the regulation (six-year lead time). These are companies that are now complying with the ZEV program using a higher percentage of PZEVs. However, as illustrated in Figure 7.1, below, a significant gap still exists in the market place between large manufacturers and the next group of manufacturers traditionally thought of as intermediate.

Figure 7.1
Market Share of Manufacturers in California
Average production 2003 - 2005



For this reason, staff intends to examine the implications of adjusting the intermediate volume manufacturer definition. This examination is not trivial. There are issues surrounding product development, compliance strategies and impacts to large manufacturer obligations in coming phases that would be affected by a change to the definition.

7.2 Section 177 State "Travel Provisions"

In 2003, the manufacturers expressed concern about the multiplicative effects of California's ZEV regulations across the country as other states adopted and implemented the State's ZEV regulations as allowed by section 177 of the federal Clean Air Act amendments of 1990. These states, referred to as Section 177 states, would cause the ZEV requirement to effectively double. While the Board was determining if the Alternative Path volumes for fuel cells were reasonable and appropriate, the manufacturers were calculating what the requirements would mean for them nationwide, and expressed concerned that these volumes were not necessary to support ZEV technology development and would be unreasonably costly.

The compromise, based on the notion that early demonstrations are best accomplished with small numbers of vehicles, was to allow fuel cell vehicles placed in California (or in other Section 177 states) to count towards compliance in all states (referred to as the travel provision). While the Board was concerned that

this might mean that California would loose fuel cell vehicle volume, there was some confidence that California would attract the majority of vehicles because of the California Fuel Cell Partnership effort, developing infrastructure and existing program momentum. Since implementation began, more than 90 percent of all fuel cell vehicles placed to meet the ZEV requirements have been placed in California. Clearly the "leakage" of fuel cell vehicle demonstrations has not been wide-spread. This travel provision no longer applies after model year 2011 vehicles.

While the travel provision is working well in the current phase, issues have been raised about implementation of the provision in later phases, especially with regard to how the vehicle obligations are calculated for states other than California. The travel provision will be an area of the regulation that will need to be reexamined as other parts of the regulation are adjusted.

7.3 Extremely Clean Vehicles

Staff has had recent discussions with industry regarding treatment of conventional vehicles with direct emissions substantially lower than PZEVs. While staff does not believe that vehicles with direct emissions, however low, should receive pure ZEV credit, further investigation is needed to determine how best to encourage the commercialization of such vehicles.

8.0 Summary and Conclusions

The Independent Expert Panel's review of technologies used to comply with the ZEV regulation has provided a variety of useful measuring sticks by which to determine if the ZEV regulation is on track for the successful mass commercialization of zero emission vehicles. It is clear that progress has been made in many areas and that much work remains before the goal will be met. It is also apparent that there is no single winner among the technologies: many hold promise; all have challenges and benefits. For these reasons, staff concludes the ZEV program is still a critical part of the Air Resources Board's efforts to attain health based air quality standards and contributes towards meeting the State's policies on climate change and fuel diversity. Although it is apparent that some changes are needed to the regulation, on the whole, it remains effective and useful.

Status and Prospects for Zero Emissions Vehicle Technology

Report of the ARB Independent Expert Panel 2007 Executive Summary Only

Prepared for
State of California Air Resources Board
Sacramento, California

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April 13, 2007

EXECUTIVE SUMMARY

1. Introduction

At the 2003 Zero Emission Vehicle (ZEV) Regulation hearings, the California Air Resources Board (ARB) directed staff to establish an independent expert review panel (Panel) to examine the status of ZEV technologies and to advise the Board. The Panel was constituted in early 2006 and carried out its work between May 2006 and March 2007. The overall objective of the Panel was to provide a thorough and accurate portrayal of the current status of sustainable zero emission vehicle technologies and the prospects for ZEV technology advancement in both the near-and long-term.

The Panel's work consisted primarily of extensive data collection followed by a critical assessment. Summaries of the data and the Panel's assessment are contained in this Final Report.

Starting in early May, the Panel engaged in an intensive effort to gather information on ZEV technology status, key technical issues, current and prospective materials and manufacturing costs and plans for evaluation/demonstration and commercialization of various ZEV and ZEV enabling technologies. This information was collected by soliciting responses to a series of questionnaires that were developed by the Panel, and through visits with key sources, including the leading developers of ZEV enabling technologies and the major automobile manufacturers.

The information collected by the Panel members underwent a thorough, critical assessment by the entire Panel in an effort to fully understand and accurately portray the current and likely near and medium term state of the art. Information from the various sources was compared and contrasted and, where gaps or discrepancies were identified, was followed up with selected sources in an effort to reconcile the information.

The Panel organized its efforts around three main ZEV enabling technologies –energy storage, hydrogen storage and fuel cells. Then, building on current status and prospects for further advances of these technologies and their integration into vehicles, the Panel attempted to forecast the prospects of zero and near-zero emission vehicles.

The Panel's key findings and conclusions are summarized below.

2. Vehicle Energy Storage Systems

The Panel's investigation focused on advanced battery technologies with potential to be fully developed and available for use in Hybrid Electric Vehicles (HEVs), Full Performance Battery Electric Vehicles (FPBEVs) and Plug in Hybrid Electric Vehicles (PHEVs) within the next 5-10 years. The principal findings and conclusions for the main candidate technologies are summarized below, followed by some observations on battery strategy and availability from the Panel's discussions with battery and automobile manufacturers.

A. Nickel Metal Hydride Batteries (NiMH)

High power NiMH technology for HEVs is now mature and mass manufactured in Japan in plants with capacities up to 500,000 systems annually. It is the conclusion of the Panel that high cost remains the greatest challenge for battery and HEV manufacturers, with an estimated cost (price to Original Equipment Manufacturers [OEMs]) of $2,000 for compact and $4,000 for a midsize HEV battery produced at a rate of 100,000 systems per year. These costs appear to account for much of the current price difference between hybrid and conventional vehicles. At a production rate of 1 million systems, battery costs are projected to drop to $1,300 and $2,500, respectively. Competition is expanding but market entry requires large investments for the required fully automated battery manufacturing plants.

Medium power/medium energy NiMH technology has promise to meet the technical requirements for PHEVs with relatively short (e.g., 10-20 miles) nominal electric range. It is the conclusion of the Panel that in mass production, medium power/medium energy NiMH technology's incremental cost over that of HEV batteries, estimated to be about $800-1,200, is probably less than the difference in lifetime fuel costs. However, no substantial efforts to develop or capabilities to fabricate medium power NiMH technology appear to exist.

High energy NiMH technology is still used successfully in FPBEVs manufactured by major automobile manufacturers under the ZEV program. It is the conclusion of the Panel, however, that energy density is fundamentally limited and marginal for FPBEV applications, and costs remain as high as or higher than in 2000 and are unlikely to decline. High energy NiMH technology for possible FPBEV applications has not advanced in recent years.

B. Lithium Ion Batteries (Li Ion)

Li Ion batteries are making impressive technical progress worldwide especially with regard to calendar and cycle life and safety, the areas of special concern for automotive applications. Promising new materials and chemistries are expanding the capabilities and prospects of all Li Ion technologies.

High power Li Ion technology for HEVs appears close to commercialization in the view of the Panel. A variety of materials, manufacturing techniques and companies are competing to achieve the performance and cost goals for this established battery application which increases the probability of technical and market success. Importantly, for HEV applications Li Ion batteries have potentially lower cost than NiMH because they promise to deliver the required power with smaller capacities and lower specific cost.

Medium energy/power Li Ion technology has sufficient performance for PHEVS and small FPBEVs, and it can be expected to meet the life requirements for FPBEVs, in the view of the Panel. Recent test results indicate good potential to also deliver the very demanding cycle life for PHEVs. The projected costs for shorter range PHEV Li Ion batteries are about $3500-4000 in mass production; this is generally less than the fuel cost savings expected over the life of the vehicle. Low volume cell production and prototype battery fabrication is underway in Asia and Europe, and limited fleet demonstrations are underway or planned.

High energy Li Ion technology has sufficient performance for small FPBEVs, and good potential to meet all performance requirements also of midsize and larger FPBEVs with batteries of modest weight (e.g., less than 250-300kg). Cell and battery technology designed for these applications are likely to also meet cycle life goals. It is the conclusion of the Panel, however, that battery cost remains high even in mass production, (probably near the levels projected in

2000), well in excess of expected lifetime fuel cost savings. While high energy Li Ion technology probably will benefit from general progress in Li Ion technology, no efforts seem underway to advance technology designed for FPBEV applications.

Batteries assembled from large numbers (typically, 5,000 or more) of small, high energy Li Ion cells mass-manufactured for laptop computers and other electronic applications are now being used in FPBEVs (and PHEVs) fabricated on a small scale. It is the conclusion of the Panel, however, that such small-cell batteries, although providing early opportunities to demonstrate the technical capabilities of PHEV conversions and modern FPBEVs, have inherently high costs and uncertain calendar and cycle life.

C. ZEBRA Batteries

The ZEBRA (sodium-nickel chloride) battery technology has insufficient power density for HEV and PHEV applications but meets the technical requirements for small FPBEVs. The batteries have been successfully demonstrated in small European FPBEVs, heavy duty vehicles and hybrid buses. The ZEBRA battery is likely to remain the lowest-cost advanced battery because of low materials costs and can be ordered now from its Swiss manufacturer in quantities of 1000s, with rapid expansion of production possible if demand develops. However, the Panel has not seen any automobile manufacturer interest in the battery, probably due to a combination of limited power density and the implications of high temperature operation.

D. Industry Strategies and Perspectives

Battery manufacturers' positions depend on their current technology capabilities and market positions. Mass-manufacturers of NiMH high power cells and modules for HEV batteries are focused on technology cost reduction and involved in capital-intensive production capacity expansions that assume increasingly competitive HEV mass markets exceeding 1 million vehicles by 2010. FPBEVs are not a target of their NiMH battery technology development efforts, and they consider PHEV battery requirements insufficiently defined to permit an assessment of NiMH technology and market prospects for this new application. No development activities appear underway to explore whether NiMH has technical potential for PHEVs.

Mass-manufacturers of Li Ion cells for consumer products are now engaged in the development of established Li Ion chemistries for HEV applications, with commercialization possible as early as 2008, and a vigorous market competition of technologies and manufacturers is likely to emerge. They do not appear to be pursuing development of Li Ion batteries for FPBEVs or for PHEVs. Li Ion battery costs are considered too high for FPBEVs and government financial incentives are thought unlikely to induce a large number of customers to buy vehicles of limited range. The major impediment to engagement in developing Li Ion batteries for PHEVs appears to be that the PHEV battery requirements are insufficiently defined at this time. GM's apparent interest in PHEVs (tied to Li ion availability) might stimulate efforts to develop Li Ion technology for PHEV applications. The Panel found no major battery manufacturer interest in high energy Li Ion batteries for FPBEV applications.

Several smaller companies in Europe and Japan have been developing medium and high energy Li Ion technologies, some of them based on advanced materials, chemistries and/or manufacturing techniques. Their strategy is pursuit of limited-volume applications and markets that may be emerging, especially in small Battery Electric Vehicles (BEVs) (including FPBEVs) and more recently also in PHEVs. Several of these companies hold the view that Li Ion-powered PHEVs and small BEVs will be able to attain life cycle cost competitiveness with conventional

vehicles in urban fleet applications, and a few have established cell production capacities for hundreds to a few thousands of 10-25kWh batteries per year, sufficient for demonstration fleets. Most of these organizations are owned by large companies but the resources being invested in development and demonstration of batteries are still very modest. While the commercial prospects of BEV- and PHEV-design Li Ion technologies still seem unclear to them, several of these manufacturers noted that development of such technologies was likely to benefit from supported demonstration programs and/or financial incentives.

Automobile manufacturers' positions regarding batteries are determined largely by their extensive efforts to evaluate and advance the HEV-design Li Ion battery system technologies likely to be commercialized within the next few years. Confidence in the readiness of Li Ion batteries for deployment in mass-produced vehicles is growing but some concerns about life and safety remain. Based on their experience with the FPBEVs under the California ZEV initiative, most automobile manufacturers continue to hold the view that FPBEVs will remain niche vehicles, and no efforts to advance battery technologies for FPBEV applications are being supported by them at present. It remains to be seen whether recent announcements by Mitsubishi and Nissan of plans for introduction of BEVs are going to stimulate efforts to develop Li Ion batteries that meet the requirements of these vehicles.

The prospects of PHEVs also were judged negatively by most major automobile manufactures until recently. However, several manufacturers are now active in modeling, designing and evaluating various PHEV architectures and technologies, with consequent attention to candidate battery technologies and their prospects. In the U.S., an effort sponsored by DOE and supported by USABC is now underway with automobile industry expert participation to establish PHEV battery performance, life and cost targets for a planned Research and Development (R&D) program. In Japan the New Energy and Industrial Technology Development Organization (NEDO) is launching an initiative to develop PHEV batteries with the involvement of leading Li Ion battery developers. These initiatives and automobile manufacturers' initiatives such as GM's recently announced plans to offer a PHEV version of the Saturn VUE HEV and to launch the "Volt" PHEV if suitable Li Ion batteries become available are the signals needed by the major battery manufacturers to become engaged with their own resources in the development and manufacture of batteries for PHEVs.

3. Hydrogen Storage Systems

Storing sufficient hydrogen on a vehicle to power it for adequate distance, safely, and at reasonable cost, without an excessive weight penalty has been and remains a serious challenge for the automobile industry and its suppliers. All of the major potential manufacturers of fuel cell vehicles interviewed by the Panel highlighted hydrogen storage to be among the two or three areas of greatest concern, including all of the other cost and technology challenges associated with developing fuel cell systems for consumer vehicles; one manufacturer identified it as the single greatest challenge.

Unlike other major technologies being pursued in support of ZEVs, hydrogen storage technologies have advanced relatively little in recent years. The primary system advancements have been in the area of improving compressed gaseous hydrogen storage and, to some extent, improving liquid hydrogen storage. However, in the last 3 to 4 years, as it became apparent that on vehicle fuel reformers for generation of hydrogen from carbon based liquid fuels were not a viable option, many alternative storage concepts have begun to receive significant research attention. A few concepts (e.g., metal hydrides and carbon nanotubes) that have been

investigated at relatively low levels of effort for many years are now receiving increased attention. However, these efforts are fairly young and it is still too early to determine if they will result in technically and economically realistic hydrogen storage system alternatives.

A. Near Term Outlook

In the near term, the dominant form of storing hydrogen onboard light vehicles will continue to be compressed hydrogen gas. With the exception of BMW, every other OEM contacted indicated that this was the only realistic short term choice available and only Honda indicated that they intend to limit the storage pressure to 350 bar. All the other OEMs preferred 700 bar, which will provide storage of over 50% more fuel in the same space envelope and correspondingly provide almost 50% more range. Using 700 bar storage pressure is not, however, without problems. The volumetric density (kWh/L) will be higher but unit energy cost ($/kWh) is also expected to be higher and the gravimetric energy density (kWh/kg) about the same. It may also require either reduced fill rates or pre-cooling of the hydrogen prior to transferring into the vehicle tank to avoid overheating the tank structural materials.

Liquid hydrogen storage is being demonstrated as workable but with limitations. It provides both higher gravimetric and volumetric density advantages over compressed gas storage but has issues with boil off and dealing with cryogenic liquids. It is not likely to be widely accepted by automobile OEMs in the judgment of the Panel.

An important issue with any of the short term hydrogen storage options is the need for widely accepted codes and standards for permanent storage, onboard storage, and all aspects of transferring and transporting hydrogen.

Cost is another important issue, especially for the short term since none of the storage systems are produced in sufficient volumes to allow significant production economies of scale. While none of the OEMs gave specific current or near-term costs for the essentially one-of-a-kind hydrogen storage systems, the Panel estimates them to cost $10,000 or more each for both liquid and compressed gas storage.

B. Longer Term Outlook

For the longer term, some of the alternative storage technologies being researched may prove to be effective. Both solid and liquid carriers are being researched with hydrogen "recharging" being carried out both onboard and off of the vehicle. There don't appear to be any clear winners at the present among these alternatives and, in fact, none of the researchers who responded to the hydrogen storage questionnaire provided projections for complete system performance or costs. It appears to be too early to make reasonably accurate projections.

C. Conclusions of the Panel

It is the conclusion of the Panel that on-board hydrogen storage is a major challenge for hydrogen fuel cell vehicles. At present, the only technology being demonstrated by the OEMs, with the exception of BMW, is compressed hydrogen gas storage which has problems providing sufficient vehicle range without excessive volume, weight, and cost.

The volume issue can be partially resolved by using 700 bar storage (thus a smaller required volume) and by innovative vehicle design or design modification. Such innovations might include utilization of a long, small-diameter tank running longitudinally where the center "tunnel"

is located and/or replacing rear coil springs with leaf springs to increase space available for hydrogen tanks. Thus, depending on the type of vehicle and system efficiency, it seems likely that sufficient compressed hydrogen could be stored on a vehicle to provide a range in excess of 200 miles, perhaps reaching 300 miles or more.

Liquid hydrogen storage technology appears to have advanced sufficiently that, within certain constraints, it could be utilized. The advantages of liquid hydrogen, higher storage density and low pressure, suggest that it also could provide an adequate range.

However, it seems unlikely that either compressed or liquid hydrogen storage systems can meet weight or cost targets, especially for 2015. Using the TIAX estimates for mass-manufactured tanks, the system cost would be about $10 to $12 per kWh for 350 bar systems and $13 to $15 per kWh for 700 bar systems compared to DOE targets of $4 per kWh for 2010 and $2 per kWh for 2015. Assuming that at least 5 kg (165 KWh) of hydrogen will be needed to provide sufficient vehicle range, the cost would be $1650 even with the lowest TIAX tank cost estimate. For liquid storage, the cost would be even higher. There is little expectation that the cost of either of these systems will go much lower even with higher volumes.

The weight outlook is better than the cost outlook. The TIAX projections for weight fraction are slightly over 6% for both 350 bar and 700 bar systems, compared to the DOE targets of 6% for 2010 and 9% for 2015. The pressure tank manufacturers have also indicated that 6%, and perhaps a bit higher weight fraction is within reach. For a 6% weight fraction system to contain 5 kg of hydrogen, the system would weigh about 83 kg (about 183 lb). Neither TIAX nor the tank manufacturers project that the 2015 target of 9% can be met with pressurized hydrogen tanks.

There are many alternative hydrogen storage systems under investigation. Some of the absorption materials being investigated are relatively inexpensive and have shown, at least in the research phases, the capacity to contain well over 6% hydrogen. However, the remainder of the support system could have a huge effect on both cost and weight fraction.

4. Automotive Fuel Cell Systems

Automotive fuel cell technology continues to make substantial progress but is not yet proven to be commercially viable. Technological and engineering advancements have improved, simplified and even eliminated components of the fuel cell system. Progress made since the 1998 ARB fuel cell report include major improvements in the membrane electrode assembly (MEA) and fuel cell stack technologies. The Balance of Plant has a reduced number of components and now uses some parts that are of automotive quality and cost. The fuel cell system has a reduced start time and in-vehicle start-up from a frozen condition has been demonstrated. Great strides have been made in the science of materials, and operating characteristics of fuel cells. This increase in fundamental understanding shows promise for solving life, abuse and durability issues for fuel cell systems.

The consensus among the majority of fuel cell system developers is that in order to achieve commercialization there are simultaneous requirements for:

1) Higher MEA power per unit area of fuel cell electrodes (goal of 0.8 to 1.0 W/cm^2)
2) Reduced MEA catalyst cost (goal of total MEA catalyst loading <0.1 to 0.5 mg Pt/cm^2)
3) Longer fuel cell system operating life and increased durability (goal of >5000 hours of

customer use)

4) Proton Exchange Membrane (PEM) materials that are stable and can operate at a higher temperature (above 100°C)
5) Engineering advances

An increase in MEA specific power allows a given fuel cell stack to produce more power and thus achieve a lower $/kW. Nearly every stack cost factor, at a given voltage, decreases in inverse proportion to MEA specific power. The MEA catalyst cost is directly related to the price of platinum. The price of this noble metal is rising due to world wide demand exceeding supply and at current levels it represents a significant barrier to automotive fuel cell commercialization. The life and durability of fuel cells in automotive applications is not yet proven. A life of 5000 + hours in a light duty vehicle type load cycle has not been demonstrated at the cell or stack level. The development of high temperature membranes can potentially reduce the size and complexity of the Fuel Cell Electric Vehicle (FCEV) thermal system and may possibly eliminate the need for stack humidification. Engineering advances and innovation are focused on materials, stack design, and balance of plant to reduce cost and increase life.

Overall, the Panel concludes that at this time no fuel cell developer has achieved the necessary requirements for automotive fuel cell commercialization. The developers are relying on future technological improvements to meet both cost and life goals. Achieving these goals creates some contradictory requirements for the fuel cell system. The Panel believes that these requirements are difficult to achieve separately and because they are interrelated, even more difficult to solve simultaneously. These technological improvements include the development of MEAs that use significantly less catalyst material and that operate at higher specific power and temperature over a longer system life. To simultaneously increase performance, extend life and reduce cost will likely take ingenuity and invention.

Each of the developers believes that the simultaneous requirements can be met but on different time schedules. For example, one major developer's objective is to compete with the "upper" segment of internal combustion engine (ICE) vehicles in the year 2020 at volumes of 100,000 units per year. Another major developer's assessment is that a commercially viable fuel cell system would be available in 2010, if a production rate of 500,000 units per year could be realized.

At this time, large conventional suppliers to the automotive industry are not active in fuel cell development and are taking a wait and see attitude. If the market develops, it is conceivable that they will rapidly acquire the technology.

The Panel remains cautiously optimistic regarding the prospects for fuel cell system commercialization. There are still large technical barriers to be solved but these might well be overcome over the next 5-10 years through massive efforts underway at the major fuel cell and automobile manufacturers. However, there are other issues that are beyond the control of any single manufacturer. Wide spread deployment of FCEVs will require continuous strong support and a long term commitment from government agencies in resolving there issues. These include timely availability of adequate and affordable hydrogen refueling, as well as need for a host of sustainable financial incentives to help minimize the capitalization risks of all key stakeholders during the early years of initial commercialization of hydrogen powered FCEVs.

5. Vehicle Integration – Automotive Manufacturers

The status and prospects of vehicle integration of zero emission vehicles (ZEVs) by ten major original equipment automotive manufacturers (OEMs), as well as their advanced technology vehicles (ATVs) that could have synergistic benefits supportive to the introduction of ZEVs, are summarized below. In addition to vehicle technical considerations, vehicle business considerations (e.g., manufacturing cost, capital investment, marketability, etc.) also are addressed, in order to forecast the future prospects, introduction timing, and volume milestones of the ZEV and ATV technologies.

A. Full Performance Battery Electric Vehicles (FPBEVs)

Full Performance Battery Electric Vehicles are defined in this report as BEVs fully capable of high speed U.S. urban/suburban freeway driving.

Despite substantial technology progress, prior efforts to introduce FPBEVs were unsuccessful due to high manufacturing cost (primarily the battery) and limited mass market customer acceptance due to limited range and long recharge time, and there has been little progress since. Specifically, the large batteries required to provide the necessary driving range, as well as an acceptable "cushion", remain very expensive.

Higher fuel prices and less demanding driving conditions in Japan and Europe provide lower barriers to success and as a result a few OEMs are developing small FPBEVs with Li Ion batteries for these markets, and they may bring them to the U.S. as niche vehicles.

It is the Panel's opinion that FPBEVs are not likely to become mass market ZEVs in the foreseeable future due to the high cost for the battery not being recoverable with fuel cost savings and limited customer acceptance due to range and recharge time issues.

B. City Electric Vehicles (CEVs)

City Electric Vehicles are defined in this report as BEVs with limited acceleration and top speed (e.g. 50/60 mph) and thus not suitable for high speed U.S. urban/suburban freeway driving, although at present they must meet all Federal Motor Vehicle Safety Standards (FMVSS) requirements. These performance limitations allow a smaller size battery and lower power electric drive system, so that the vehicle can have a lower manufacturing cost and thus be made more affordable to the customer.

Prior efforts to produce CEVs were unsuccessful due to high cost and limited mass market customer acceptance and there has been little progress since. A special CEV FMVSS similar in concept to FMVSS 500 (e.g., restrict CEVs from freeway driving, etc.) may help stimulate development in the U.S.

It is the Panel's opinion that CEVs are more likely to become future mass market ZEVs in Japan and Europe than in the U.S. due to performance limitations.

C. Neighborhood Electric Vehicles (NEVs)

Neighborhood Electric Vehicles are defined in this report as BEVs capable of top speeds between 20 and 25 mph that meet FMVSS 500 and are limited to roads with posted speeds of

35 mph or less.

NEV technology appears to be commercially successful but has low volume potential due to limited applicability. Also, because they use very simple technology, NEVs have very little synergy with larger BEVs.

It is the Panel's opinion that NEVs provide no significant technical benefits to future mass market ZEVs due to their simple technology and performance limitations.

D. Hybrid Electric Vehicles (HEVs)

HEVs have no customer compromises and therefore appeal to mass market customers willing to pay a premium. While producers are driving down the costs of electric drive components and systems, high manufacturing cost is still an issue. However, OEMs are introducing many new entries, despite the cost issue, mostly for competitive reasons. Overall, HEV sales volume rises and falls with the price of gasoline – making future growth forecasts uncertain.

It is the Panel's opinion that HEVs, due to their success, are providing major support to future mass market ZEVs by continuing to stimulate advances in electric drive systems, electric accessories, and battery technologies. Also, they are increasing customer awareness of electric drive technology and the associated benefits.

E. Plug-in Hybrid Electric Vehicles (PHEVs)

PHEVs have no expected customer compromises while promising several benefits to customers and society. The relatively small battery capacity can be fully used daily for maximum customer fuel savings payback of the initial vehicle premium.

Recently, some OEMs have become interested in PHEVs, and GM and Ford have shown concept PHEVs at recent auto shows and other events – which is attracting major media attention and establishing high consumer expectations.

However, definitions and fuel economy/emissions testing standards do not yet exist and need to be agreed upon. Also, All Electric Range (AER) could have a major impact on manufacturing cost, as well as capital investment requirements if unique and more powerful electric drive systems are necessary, and therefore AER could have a significant impact on the early success of the technology.

Despite the fact that recent auto show PHEVs appeared to require new platforms, it may be more likely that OEMs will want to derive early PHEVs from existing HEVs in order to minimize capital investment and the associated business risk. For the same reason, blended AER, as opposed to EV mode, may be more likely in early products.

It is the Panel's opinion that PHEVs have the potential to provide significant direct societal benefits and are likely to become available in the near future. They may foster future mass market BEVs by stimulating energy battery development and conditioning mass market customers to accept plugging in.

F. Fuel Cell Electric Vehicles (FCEVs)

FCEVs are considered the ultimate solution by several OEMs with massive R&D efforts

underway. However, simultaneously achieving performance, durability and cost objectives with FCEVs continues to be very difficult.

The cost, weight, and volume of adequate vehicle hydrogen storage and availability of a hydrogen infrastructure are major issues.

Plug-in series hybrid FCEVs operating "steady state" have potential to simultaneously achieve performance, durability and cost objectives.

It is the Panel's opinion that with the past rate of success and the massive intellectual and financial resources being devoted to this technology, FCEVs continue to be a promising candidate for a future mass market true ZEV.

G. Hydrogen Internal Combustion Vehicles (H2ICVs)

H2ICV technology is not widespread and is only being pursued by two OEMs – BMW and Ford. This technology entails fairly simple conversions of conventional powertrains, with relatively low manufacturing costs and capital investment requirements. However, the hydrogen issues are the same for infrastructure and worse for onboard storage than for FCEVs. Also, while they have very low emissions, H2ICVs are not true ZEVs.

It is the Panel's opinion that H2ICVs could provide minor benefits to future mass market ZEVs (FCEVs), limited to onboard vehicle hydrogen storage and hydrogen infrastructure, but the Panel also cautions that if the relative incentives change there could be a shift in resources away from FCEV development to fund H2ICVs.

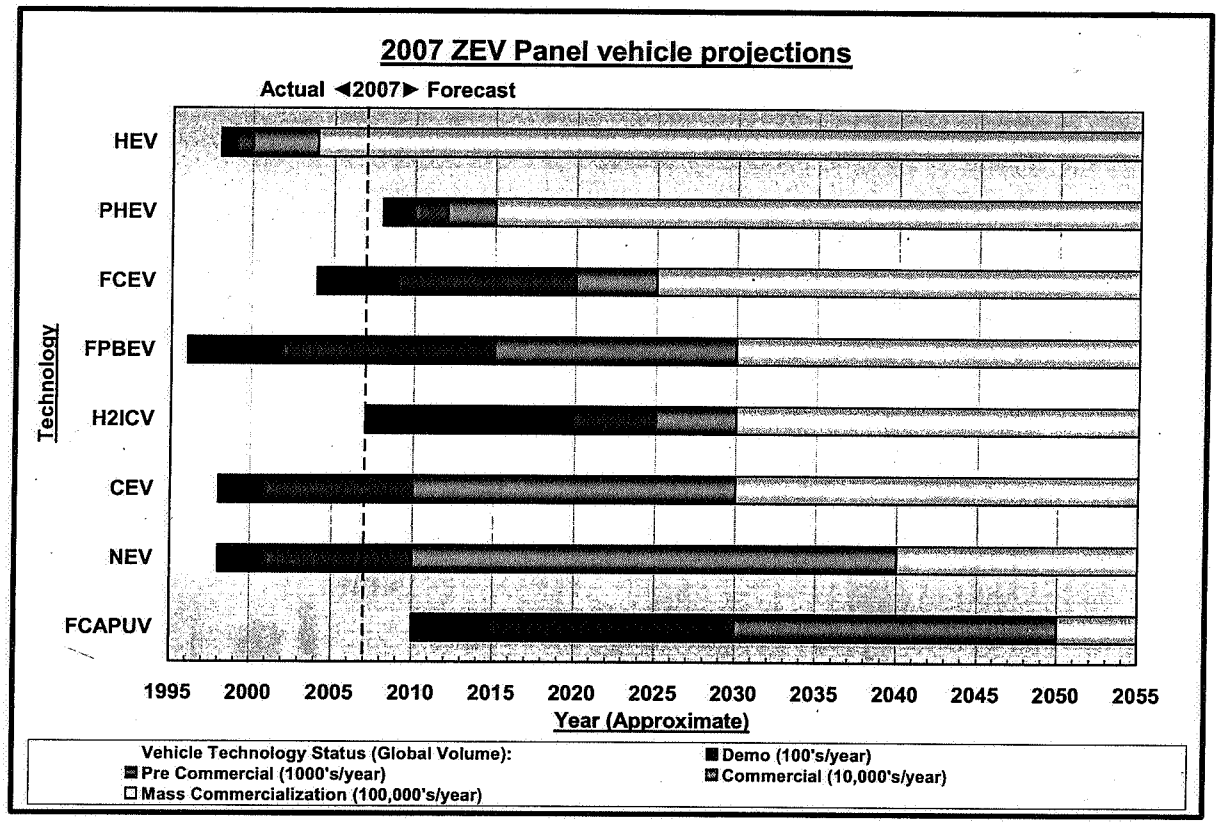
H. Fuel Cell Auxiliary Power Unit Vehicles (FCAPUVs)

FCAPUV technology is not widespread and is only being pursued by one OEM – BMW. The Hydrogen Proton Exchange Membrane (PEM) system in a H2ICV is the most likely application but this is operationally different from a FCEV.

It is the Panel's opinion that FCAPUVs are unlikely to provide any significant benefits to future mass market ZEVs.

6. Overall Conclusions: The Prospects of ZEVs

The bottom line question posed to the Panel by the ARB was "what is the approximate timeframe in which the Panel expects the various ZEV and ZEV enabling technologies to achieve the Demonstration stage (100s of vehicles per year), Pre-Commercialization (1000s of vehicles per year), Early Commercialization (10,000s of vehicles per year) and finally Mass Commercialization (100,000's of vehicle per year). Of course, a precise answer to this question is very difficult as it depends upon many factors which are impossible to foresee at this time. The chart below reflects the Panel's consensus projection on global volumes, based on today's automotive environment, including the present ZEV regulations, and barring any sudden and unanticipated major trigger events (e.g., scientific breakthroughs, trends and actions such as further major increases in gasoline taxes (U.S.) and/or reduced gasoline availability driven by major disruptions in petroleum supply, increasingly dramatic evidence of climate change, war, terrorism, etc.):



The Panel suggests that these time projections while necessarily uncertain regarding the exact years of implementation carry somewhat greater confidence in the relative timing of these technologies for the reasons outlined in this report and briefly summarized here:

> *The Panel's projection is that PHEVs with modest energy storage capacity will be derived from HEVs and will proliferate rapidly, stimulating further development and cost reduction of energy batteries and leading to commercially viable PHEVs and, in the longer term, FPBEVs. While PHEVs will continue to grow rapidly, as they have no functional limitations, FPBEVs will grow more slowly due to customer acceptance of limited range and long recharge time. NEVs are commercially viable now and will continue to grow, but will grow slowly due to limited functionality. CEVs will become commercially viable in Japan and Europe in the not too distant future due to lower hurdles for BEVs to overcome. CEVs may be offered in the U.S. as energy batteries continue to mature, but growth will be slow due to functional limitations of BEVs in general, and the specific limitations of CEVs, especially urban freeway driving. The intense effort on FCEVs will result in technically capable vehicles by the 2015 to 2020 time frame, but successful commercialization is dependent on meeting challenging cost goals and the availability of an adequate hydrogen infrastructure. If that happens, FCEVs will grow rapidly, followed by some H2ICVs, and some H2ICVs with FCAPUs.*

As a long term ZEV outcome, the Panel can envision plug-in hybrid FCEVs, powered by sustainable electricity for shorter trips and sustainable hydrogen for longer trips.

Glossary of Terms, Abbreviations and Symbols:

APU	auxiliary power unit
ARB	Air Resources Board (California, CARB)
ATPZEV	Advanced Technology Partial Zero Emission Vehicle
BEV	battery electric vehicle
CEV	city electric vehicle
CH2	compressed hydrogen
CNG	compressed natural gas
CO	carbon monoxide (contributor to air pollution)
CO2	carbon dioxide (greenhouse gas)
Cold FTP	driving schedule conducted in 20°F ambient temperature (part of fuel economy label value for 2008 MY vehicles)
Combined	vehicle fuel economy – prior to 2008 MY: harmonic average of FTP and HFET weighted 55/45% respectively; can be applied to adjusted values or unadjusted values ("C-H", "M-H")
Consumption	vehicle fuel consumption – quantity of fuel or energy consumed divided by distance traveled (e.g., litres/100 kilometers, Wh/mile)
CVT	continuously variable transmission
CY	calendar year
DOD	depth of discharge (battery)
DOE	United States Department of Energy
DOT	United States Department of Transportation
Economy	vehicle fuel economy – distance traveled divided by quantity of fuel or energy consumed (e.g., miles/gallon, miles/kWh)
EDF	Electricitè de France
Efficiency	output energy divided by input energy, expressed as a percentage
EPA	United States Environmental Protection Agency
EPRI	Electric Power Research Institute
ETS[1]	electrical traction system (direct current to torque out)
EV	electric vehicle
FC	fuel cell
FCAPU	fuel cell auxiliary power unit
FCAPUV	fuel cell auxiliary power unit vehicle
FCEV	fuel cell electric vehicle
FCPS[1]	fuel cell propulsion system (hydrogen fuel in to torque out)
FCS[1]	fuel cell system (fuel cell stack + balance of plant for H2, air, coolant supply)
FPBEV	full performance battery electric vehicle
FMVSS	Federal Motor Vehicle Safety Standards
FTP	Federal Test Procedure; UDDS followed by first 505 seconds of UDDS ("FTP75", "EPA75")
GVWR	gross vehicle weight rating
H2	hydrogen
H2ICV	hydrogen internal combustion vehicle
HC	hydrocarbons (contributors to air pollution)
HEV	hybrid electric vehicle
HSS[1]	hydrogen storage system
HFET	Highway Fuel Economy Test (dynamometer driving schedule)
ICE	internal combustion engine

ISO	International Organization for Standardization
Label	vehicle fuel economy – prior to 2008 MY: city label = FTP x 0.9; highway label = HFET x 0.78 ("window sticker")
LEV	low emission vehicle
LH2	liquid hydrogen
LHV	lower heating value (for calculating energy content of fuels used in vehicles)
Li Ion	lithium ion (battery)
Mass-Market	buyers that make up the majority of the (automotive) customer base, primarily interested in price/value/convenience, not hobbyists/enthusiasts
METI	Japanese Ministry of Economy, Trade and Industry
MY	model year
n/a or n.a.	not available (at publication of report)
NEV	neighborhood electric vehicle
NHTSA	National Highway Traffic Safety Administration (part of DOT)
NiMH	nickel-metal hydride (battery)
NOx	oxides of nitrogen (contributors to air pollution)
NREL	National Renewable Energy Laboratory (part of DOE)
OEM	original equipment automotive manufacturer
Panel	2006-2007 ZEV Technology Review Expert Panel (contractors to ARB)
PEM	polymer electrolyte membrane, or proton exchange membrane (fuel cell)
PbA	lead-acid (battery)
PHEV	plug-in hybrid electric vehicle
RESS[1]	rechargeable energy storage system (battery, ultra capacitor, flywheel, hydraulic)
SAE	Society of Automotive Engineers
SC03	driving schedule with air conditioning operating and 95°F ambient temperature (part of fuel economy label value for 2008 MY vehicles)
SMUD	Sacramento Municipal Utility District
SOC	state of charge (battery)
SULEV	super ultra low emission vehicle
TBD	to be determined (before finalizing report)
UDDS	Urban Dynamometer Driving Schedule ("LA4", "city test")
UEV	utility electric vehicle
ULEV	ultra low emission vehicle
US06	driving schedule containing aggressive acceleration and high speeds (part of fuel economy label value for 2008 MY vehicles)
USABC	United States Advanced Battery Consortium
USCAR	United States Council for Automotive Research
VESS	vehicle energy storage system (section 3)
VFCS	vehicle fuel cell system (section 4)
VHSS	vehicle hydrogen storage system (section 5)
V2G	vehicle to grid (discharging electric vehicle battery energy into electric grid)
VOC	volatile organic compound (contributor to air pollution)
ZEV	zero emission vehicle

1. ISO term (electric vehicles)

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MAIN REPORT

1. Introduction

At the 2003 Zero Emission Vehicle (ZEV) Regulation hearings, the California Air Resources Board (ARB) directed staff to establish an independent expert review panel (Panel) to examine the status of ZEV technologies and to advise the Board. The Panel was constituted in early 2006 and began work in May 2006. The overall objective of the Panel is to provide a thorough and accurate portrayal of the current status of sustainable zero emission vehicle technologies and the prospects for ZEV technology advancement in both the near-and long-term. The Expert Panel is not considering specific changes to the ARB ZEV Regulation but rather is focused on providing independent advice on the status of technologies.

2. Work Program and Process

In many ways the Panel is similar to previous panels which have been asked to provide independent expert advice to the Board (Kalhammer 1995, Kalhammer 1998, Kalhammer 1999, Anderman 2000) but with a notable distinction regarding the breadth of the scope of the study. Rather than focusing on one technology, i.e., fuels cells or batteries, this study broadly reviews all ZEV, near ZEV and partial ZEV technologies.

Special emphasis in this review is on timing and cost projections from the technology developers and OEMs. In particular, the Panel was asked to address the following questions:

- When will ZEVs achieve a level of automotive-industry technical maturity necessary for deployment at the following U.S. industry-wide production levels:
  - 100's (demonstration),
  - 1,000's (pre-commercialization),
  - 10,000's (early commercialization), and
  - 100,000's (commercialization)?
- What are the projected manufacturing costs at each of the above production levels?
- Does the deployment of ZEV technologies in Advanced Technology (AT) non-ZEVs accelerate the development and affordability of these components so that ZEVs can be deployed sooner? At what sales volumes does each of these AT "bridge" technology vehicles continue to provide significant improvement in the performance and affordability of components needed for ZEVs?

The Panel's work was organized into four key tasks:

A. Acquisition of information

From early May into December, the Panel was engaged in an intensive effort to gather information on ZEV technology status, key technical issues, current and prospective materials and manufacturing costs and plans for evaluation/demonstration and commercialization of various ZEV technologies. ZEV technology topics which the Panel emphasized included:

- On-vehicle hydrogen storage technologies

- Automotive Fuel cell technologies (both vehicle & vehicle APU) and including balance of plant (BOP) components.
- Batteries (both power and energy)
- Electric drive systems, and
- Automotive platform issues:
  - Transition from low volumes to mid-high production volumes
  - Ground-up VS conversion ZEV design considerations,

For application in:

- Fuel Cell Vehicles (FCVs),
- Battery Electric Vehicles (BEVs), and
- Advanced Technology non-ZEVs, including:
  - Plug-in hybrids, &
  - Hydrogen combustion engine vehicles

This information was collected by soliciting responses to a series of questionnaires that were developed by the Panel (See Appendices A, B, C, D and E) and through visits with all of the key sources, including the leading developers of the components as well as the major OEMs. A listing of companies or organizations visited is contained in Appendix F. Multiple site visits took place with some companies and many companies and organizations were asked follow up questions after the visits were completed.

B. Critical assessment

The information collected by the Committee members underwent a thorough, careful and critical assessment in an effort to fully understand and accurately portray the current and likely near term state of the art. Information from the various sources was compared and contrasted and where gaps or discrepancies were identified was followed up in an effort to reconcile the information.

It is important to note, however, that at the end of the day the assessment relied as it had to on the data provided. While a great deal of new (at least to the Panel) and valuable information was provided, some questions and requests for information remained unanswered in spite of numerous requests. Where possible, the Panel provided interpretation and in some cases extrapolation from the information it received to support its projections and assessments.

C. Reports at Public Meetings

The Panel presenting a status report of the panel's work at ARB's ZEV Technology Symposium in September of 2006 and is preparing to provide the Panel's conclusions directly to the Board at a 2007 hearing.

D. Final Report

The Panel's key findings and conclusions are documented in this Final Report. Sections of this report were circulated in draft form to most information sources to assure accuracy and to prevent the inadvertent inclusion of information given to the Committee in confidence.

3. Vehicle Energy Storage Systems

A. Background and Scope

Energy storage is fundamental to electric, hybrid electric and plug-in hybrid electric vehicle operation, and it has proven instrumental to achieving efficient practical operation of fuel cell vehicles. The prospects for large-scale introduction of these vehicles and realization of their zero/near-zero emission benefits are tied closely to the availability of energy storage systems that provide high performance, are durable and safe, and meet severe cost constraints.

Systematic efforts to meet these demanding requirements through development of improved batteries have been undertaken repeatedly for more than thirty years. Since the early 1990s, the United States Advanced Battery Consortium (USABC) has led a large cooperative government-industry program to develop more advanced battery technology, first for electric vehicle applications and since the mid-1990s for hybrid electric vehicles. In 2000, the Battery Technical Advisory Panel (BTAP 2000) chartered by the California Air Resources Board reviewed progress and assessed the status of nickel metal hydride (NiMH) and lithium ion (Li Ion) batteries, the two energy storage technologies that had received much of the USABC development support and were considered the most promising choices for full performance battery electric vehicle (FPBEV) and hybrid electric vehicle (HEV) applications.

The BTAP 2000 panel concluded (Anderman, 2000) that NiMH batteries were likely to meet the power and endurance requirements for FPBEVs. However, batteries limited to an acceptable fraction of EV total weight would limit FPBEV range on a single battery charge to approximately 75 to 100 miles in real world driving. The cost of such a battery was estimated to exceed approximately $10,000 if produced at the level of 10-20k battery systems per year, $7,000 in mass production (100k or more systems per year). Li Ion batteries were seen to meet power requirements at reduced weight and thus to offer promise for increased FPBEV range. However, Li Ion technology appeared handicapped by inadequate calendar life (typically only 2-4 years) and by sensitivities to abuse tests intended to simulate battery safety behavior. Moreover, Li Ion battery cost was projected to be even higher than that of NiMH batteries; at least until substantially less expensive battery materials and mass production were achieved.

The BTAP 2000 panel also observed that leading advanced battery developers were achieving rapid progress in developing high power NiMH battery technologies for the hybrid electric vehicles under development at several OEMs. HEV battery technology advancement was seen to benefit directly from the years of FPBEV battery development. Conversely, the successful commercialization of HEVs was expected to lead to continued improvements of advanced battery technologies, including technologies for possible future FPBEV applications.

Six years later, high power NiMH batteries are commercially produced in Japan on a large scale for the rapidly growing numbers and types of HEVs, and high power Li Ion battery technologies of much improved endurance are emerging from companies in Japan, Europe and North America. Several of these are being considered for commercial introduction in HEVs possibly beginning in 2008, and advances in battery chemistry and technology are rekindling interest in Li Ion batteries for BEV propulsion. At the same time, the emergence of the plug-in hybrid electric vehicle (PHEV) as a partial ZEV option and possible bridge to more competitive BEVs and fuel cell-electric vehicles (FCEVs) is creating substantial interest in batteries with energy and power characteristics intermediate to those of FPBEV and HEV batteries.

Because these positive developments bear directly on the prospects of ZEV and near (including partial) ZEV technologies, an assessment of battery status and prospects is one of the key tasks established for this Panel by the California Air Resources Board. The Panel decided to center its assessment of vehicle energy storage systems on lithium ion batteries that promise to meet the energy storage requirements of FPBEVs, PHEVs and FCEVs. Nickel metal hydride battery progress and prospects for PHEV applications also were assessed, as were a limited number of battery technologies with significant near- and/or longer-term promise to meet ZEV requirements.

Among candidate technologies, the emphasis was on those now in low volume production or, at least, available from laboratory pilot facilities and tested in prototype or experimental vehicles. In the Panel's view, advanced batteries that have not reached this stage are unlikely to be available in commercial quantities in the nearer term.(e.g., within the next 3-5 years), However, information is presented on one battery type that is in an earlier state of development but might have longer term potential especially for FPBEV applications if successfully developed.

To the extent possible, up to date technical information and cost projections were obtained from manufacturers and developers of candidate battery technologies. This information base was supplemented with pertinent information obtained from expert individuals and groups at OEMs, National Laboratories and private organizations active in advanced battery testing and evaluation.

The Panel's review of vehicle energy storage systems is organized in four main subsections. In Section 3.B, the energy storage functions, technical requirements and cost constraints for electric and hybrid (including fuel cell hybrid and plug-in hybrid) electric vehicles are discussed to provide context for the subsequent review and assessment of candidate battery technologies. Section 3.C summarizes the battery technical information collected by the Panel. Prospective costs of candidate batteries are discussed in Section 3.D, and Section E reviews candidate manufacturers and the availability from them of batteries for ZEV, near-ZEV and partial ZEV applications. Finally, Section 3.F summarizes the Panel's overall assessment of ZEV and near-ZEV battery status and prospects, and it presents information on the strategies and views of battery and OEMs pertinent to the prospects of ZEV and near-ZEV batteries.

B. Vehicle Energy Storage Requirements

The primary functions and capabilities provided by the storage systems of electric vehicles and the main types of hybrid electric vehicles are summarized in Table 3-1.

Table 3-1: Vehicle Functional Capabilities Provided by Energy Storage

Vehicle Type	Functional Capabilities
Micro HEV	Automatic start and stop *plus* regenerative braking
Mild HEV	Micro HEV capabilities *plus* power assist to vehicle IC engine
Full HEV	Mild HEV capabilities *plus* electric launch
Plug-in HEV	Full HEV capabilities *plus* electric range with grid-charged electricity
FPBEV	Exclusively electric propulsion power *and* energy (grid-charged)

With increasing vehicle functional capabilities the vehicle energy storage system needs to deliver increasing amounts of electric power and energy. These increases are determined almost entirely by the vehicles' *incremental* capabilities (see Table 3-1), as shown in recent analyses of mid-size HEV architectures (Deiml, 2005) and PHEV designs (Duvall, 2001).The

energy storage system of fuel cell hybrid electric vehicles provides additional functions but the performance requirements are generally similar to those of full HEVs.

The following discussion of energy storage requirements is limited to full (fuel cell) HEVs, FPBEVs and PHEVs, the vehicle types that operate as ZEVs all or part of the time.

1. Performance

Table 3-2 summarizes the energy storage power and energy requirements derived from the analyses of, Deiml and Duvall, respectively, with the assumptions given in the footnotes and discussed below. They are generally consistent with the goals established by the United States Advanced Battery Consortium (USABC) and by the FreedomCar Program for FPBEV and HEV batteries, respectively, see also Section 6.A.i (2) further below.

Table 3-2: Vehicle Energy Storage System Performance Requirements

EDV Type	Weight (max. kg)	Peak Power (min. kW)	Power Density (min. W/kg)	ES Capacity (min. kWh)	Energy Density (min. Wh/kg)
Full HEV	50[1]	40[1]-60	800-1200	1.5-3 [0.7][2]	30-60
Plug-in HEV[3]	120	65[4]; 50[5]	540[4]; 400[5]	6[4]; 12[5]	50[4]; 75[5]
FPBEV	250	50[6]; 100[7]	200[6]; 400[7]	25[6]; 40[7]	100[6]; 160[7]

[1] Data taken from Deiml (2005)
[2] Minimum energy required to perform the electric launch function
[3] PHEV data derived from Duvall (2001) are considered preliminary
[4, 5] Requirements for midsize passenger PHEVs with nominal electric ranges of 20 and 40 miles, respectively
[6, 7] Requirements for small and midsize FPBEVs, respectively, with weight, performance and accommodations comparable to similar size ICEVs

For full HEVs, battery capacities need to be several times larger (see Table 3-2) than the minimum energy required for vehicle electric launch because energy must be delivered at high power that reduces available energy. Also, on occasion the battery must provide energy repeatedly within relatively short periods during which insufficient battery charge is restored by the engine and regenerative braking.

For PHEVs, the required battery capacities are substantially larger than for full HEVs; actual capacity will be determined by the specified nominal electric ranges. During normal PHEV operation the battery is being discharged continuously until its state of charge (SoC) has declined to a predetermined level. When that level is reached, the PHEV control system switches vehicle and battery operation to the HEV ("charge-sustaining") mode. In that mode, the PHEV battery is subject to small swings in SoC, generally less than 50Wh, or less than 1% of capacity even for a 6kWh PHEV battery (Table 3-2). PHEV batteries must meet peak power requirements even at the lowest SoC they experience, often set at 20% SoC to prevent excessively deep discharges that could compromise battery life.

FPBEVs need much larger battery storage capacities for practical driving ranges, and the highest practical gravimetric and volumetric energy densities are desired for acceptable battery weight and volume. Because of the larger weight of FPBEV batteries, gravimetric power densities can be lower than for other advanced technology vehicle batteries yet still enable sufficient battery peak power. However, as with PHEV batteries peak power must be sufficient to meet vehicle minimum power requirements down to low SoCs (e.g., 20%). Another key requirement for all advanced-technology vehicle applications is that batteries meet peak power and storage capacity requirements at the lowest operating temperatures they experience in practical applications.

Table 3-2 makes clear that full HEV applications pose the most demanding requirements for high *power* density of batteries while FPBEVs demand the highest possible *energy* density. Battery designs for different PHEVs must be optimized for intermediate but different levels of power and energy. The common driver for these requirements is the desire to minimize battery weight, volume and cost.

2. Life

a) Cycle Life

Batteries deteriorate in operation due to the cumulative changes of the structure and composition of key battery *cell* components caused by charge-discharge cycling. Battery cycle life – the number of cycles before battery performance has degraded to a predetermined level – is a measure of a battery's ability to withstand these changes. The key requirement for the cycle life of HEV, BEV and PHEV batteries is that they retain a high fraction (often taken as 80%) of their original power and energy delivery capabilities over the life of the vehicle. In the past, a nominal vehicle life of 10 years was used to set battery cycle life requirements. More recently, USABC has adopted a 15-year life goal for its battery development program, consistent with the 15-year life requirement established by the California Air Resources Board for ZEV technologies.

Batteries for HEV applications must tolerate a large number of shallow charge-discharge cycles because of the numerous power assist, braking and recharge events that occur over the vehicle life. BEV batteries, on the other hand, must be able deliver a large number of deep discharge-full recharge cycles to maximize the vehicle miles delivered by the battery over its lifetime. In addition, they must tolerate the many recharges imposed by regenerative breaking, but because individual recharges are very small (typically less than 0.2% of capacity) for a single braking event, their effect on battery life can normally be neglected.

PHEV batteries are deep-discharged like BEV batteries, but they are expected to experience a larger number of deep cycles because their smaller capacity is likely to be used more often. PHEV batteries must be able to sustain a large number of shallow charge-discharge cycles although fewer than HEV batteries, but only a fraction of these cycles occur at low SoC (e.g., 20%), and SoC swings will be less than 1% of capacity. The stresses imposed by these cycles (and those at higher SoCs) are much less than those on HEV batteries and thus are unlikely to limit PHEV battery life.

Table 3-3 summarizes approximate cycle life requirements for HEV, PHEV and FPBEV batteries.

Table 3-3: Battery Cycle Life Requirements[1]

Vehicle Type	Deep Cycles		Shallow Cycles
	Energy[2] (MWh)	Number[3] @80%DoD	Number[4] @ 50Wh[5]
Full HEV	n.a.	n.a.	200k [300k]
PHEV-20	~12 [~17]	2400 [3500]	fewer than full HEV
PHEV-40	~17 [~25]	2300 [3400]	fewer than full HEV
Battery EV	~32[6]	1000 [1500]	fewer than full HEV

[1] for battery operation over a 10-year life [15-year life and total energy delivery requirements in brackets]
[2] energy delivered by battery over its life time in form of deep discharges

[3] number of equivalent 80% DoD cycles to be delivered by battery over its life time
[4] number of shallow cycles to be delivered by battery over its life time
[5] maximum energy to be delivered by battery in single pulse
[6] for mid-size FPBEV with 40kWh battery discharged to 20%SoC

The cycle life requirements for HEV and FPBEV batteries were developed by USABC from analyses of representative vehicle driving patterns. The PHEV battery deep cycling requirements shown in Table 3-3 were derived (Duvall 2001) from the statistical distribution of the daily distances driven by U.S. automobiles, under the assumptions that PHEVs are operated to maximize daily use of propulsion energy from the battery, and that PHEV batteries are fully recharged after each day of operation. From these inputs, the total DC electric energy delivered by the batteries over a 10 year (respectively 15 year) period shown in Table 3-3 can be determined. Dividing these totals by the maximum battery capacities used (80% of 6kW and 12 kWh, respectively) results in the equivalent numbers of 80% depth-of-discharge cycles to be delivered by the batteries over their service life, see Table 3-3.

PHEV can also be operated in the so-called "blended" (EV-HEV) mode where the internal combustion engine is allowed to turn on in response to power demand above a preset level while the battery continues to be discharged until 20% SoC is reached. In the blended mode, the battery will experience fewer deep cycles over 10 and 15 years than in the strategy to maximize use of electricity. Thus, the deep cycling requirements shown in Table 3-3 for PHEV batteries are conservative, even more so because batteries are unlikely to be discharged to 20% SoC every day, and the amount of energy delivered by a battery over its life increases as the depth of discharge decreases.. As discussed in the Battery Technologies subsection below, this effect is observed with both Li Ion and NiMH batteries and can benefit the cycle life of both, PHEV and FPBEV batteries.

b) Calendar Life

Batteries also can deteriorate through undesirable chemical reactions between battery cell materials, whether the battery is being cycled or not. The general effect of these reactions is to degrade one or more of the cell's functional components and thereby the battery's energy storage and/or peak power performance. Battery degradation processes are specific to the type of battery and the materials used in it. They tend to be complex and their control through choice of appropriate designs, materials and operation is almost always difficult. The challenges and prospects of achieving the 10-15 year calendar life essential for cost/economic viability is discussed in Section 3.3, with emphasis on the life prospects of lithium ion batteries.

3. Safety

Batteries present potential hazards if the energy they store and the chemicals they contain are released rapidly and in an uncontrolled way outside the battery containment. Depending on the specific battery chemistry, such releases can be caused by shorting, sustained and/or rapid overcharging or excessive heating of batteries. These abuses can occur only if the generally hierarchical electric, thermal and mechanical controls used to assure the safety of batteries in BEV, HEV or PHEV applications fail.

The maximum amount of energy dissipated as heat in a battery by a short circuit is determined by the maximum (electrochemical) energy storage capacities required for the specific application, independent of technology. These capacities range from about 1 kWh for a partially charged HEV battery to about 40kWh for a fully charged FPBEV battery. The corresponding

energies are the equivalent of approximately 1/40 to at most 1 gallon of gasoline. As long as there is no rupture of battery cells by the heat generated in a short circuit or no propagation of cell rupture through the battery, shorting is not normally a truly hazardous abuse of batteries although it can damage the battery.

Excessive overcharging of most types of batteries can result in gas evolution within battery cells, rupture of pressure release devices and release of gases, some of them flammable. For some battery types, overcharging can cause progressive heating and a thermal "runaway" condition of continued heat evolution even after the triggering event is terminated. However, if the battery materials react only with each other inside the battery enclosure, heat release is limited to the amount above.

The maximum amount of heat that can be released by a battery is given by the total heat of combustion of all battery components. That heat is different for different battery types but generally exceeds the electrochemical energy content of a battery several times. However, this heat is released only through exposure of all battery materials to air and their subsequent complete combustion, an event that is exceedingly unlikely unless the entire battery is immersed in a hot fire. Even in that event, combustion and heat release would likely be gradual rather than explosive because of the gradual penetration of air and propagation of combustion into the densely packed battery cells.

Different battery technologies differ substantially in the mechanisms, materials and energy amounts involved in uncontrolled releases of energy and chemicals. Specific considerations pertaining to safety of the battery technologies reviewed by the Panel are presented in Section 3.C further below.

4. Costs

The high costs of batteries have been one major impediment to the introduction of electric vehicles. Even the far smaller batteries of commercially available hybrid electric vehicles contribute substantially to their cost increment over conventional vehicles. High battery costs also are among the chief concerns surrounding the prospects of plug-in hybrid electric vehicles. Cost constraints are, therefore, a central consideration in the assessment of candidate battery technologies, and they continue to be key drivers in the development and commercialization of advanced batteries for ZEV and near-ZEV applications.

Table 3-4 summarizes cost goals established by USABC and the FreedomCAR program for the development of advanced FPBEV and HEV batteries, respectively. The table also includes a preliminary cost goal that is currently being discussed for PHEV batteries.

Table 3-4. Battery Cost[1] Goals

Vehicle Type	Battery Rating	Production Rate (Batteries/year)	Specific Capacity Cost[2] ($/kWh)	Specific Power Cost [3] ($/kW)
FPBEV	40 kWh	25k	<150 [< $6,000]	n.a.
HEV	25--40 kW	100k	n.a.	<20 [< $500 – $800]
PHEV	(10 kWh)	(100k)	(<300) [< $3000]	n.a.

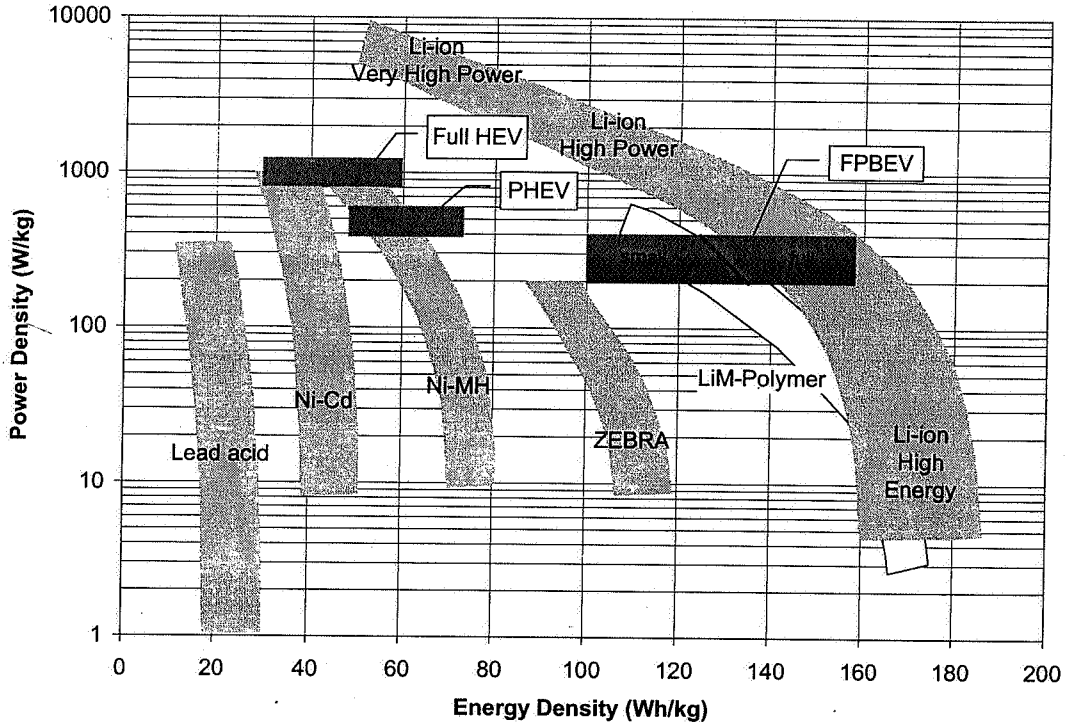
[1] selling Price to OEMs
[2] in brackets: cost goals for complete batteries of rated energy storage capacity
[3] in brackets: cost goals for complete batteries of rated peak power capability

No detailed derivation of the battery cost goals shown in the table has been published. However, the assumption underlying the goals of USABC and the FreedomCar program is that, if achieved, battery costs would permit market introduction of FPBEVs and HEVs.

C. Battery Technologies: Status and Prospects

Only a few battery types have the potential to meet the combination of power and energy density requirements for full HEVs, PHEVs and FPBEVs, as illustrated in Figure 3-1.

Figure 3-1: Potential of Battery Technologies for HEV, PHEV and EV Applications



The figure shows (as rectangular domains) the approximate ranges of energy and power densities required for the batteries of the various advanced-technology vehicles, see Table 3-2. It also includes the general relationship between gravimetric power and energy densities for the battery types used or being considered for automotive applications. These so-called Ragone plots show that, for each type, batteries designed for high power densities have substantially lower energy densities than batteries optimized for high energy (FPBEV designs).

Whenever the performance domain for a specific vehicle type is below and to the left of the "Ragone" performance characteristic for a particular battery type in Figure 3-1, properly engineered versions of that battery type can be expected to meet vehicle power and energy requirements. The figure indicates that only lithium ion batteries can be designed to meet the performance requirements of small and midsize FPBEVs, all types of PHEVs, and full HEVs. As discussed further below, all other battery types either have restrictions with respect to their ZEV and partial ZEV applicability, or they require compromises with respect to battery weight and vehicle performance.

1. Lithium Ion Batteries: Characteristics

a) Cell Chemistry and Composition

As the lightest metal and most electronegative element, lithium is the most attractive negative electrode (anode) material for high energy batteries. However, high reactivity with water and with the solvents used in organic battery electrolytes prevented the use of lithium in rechargeable batteries until two important discoveries were made about 15 years ago: lithium can be inserted ("intercalated") electrochemically in carbon "host" materials, and a protective layer forms at the interface of the lithium-containing carbon with the organic electrolyte solvent when a cell is charged for the first time. Remarkably, this complex solid-electrolyte interface (SEI) layer prevents further attack of the electrolyte by lithium but allows passage of lithium ions during charge-discharge cycling. The host material forming the negative electrode in Li Ion cells is made from special grades of graphite and/or coke. Mixed with binders, these carbons are deposited on thin copper sheets that serve as conducting supports.

A variety of materials can be paired with carbon-based negatives in battery cells using organic electrolytes. Mixed with carbon for increased conductivity and with binders, these materials are deposited on thin aluminum sheets as conducting supports. Currently established positive electrode materials are listed in Table 3-5 and reviewed below in the context of current Li Ion battery technology.

Active Material Chemical Formula (discharged state)	Storage Capacity (mAh/g)	Nominal Voltage (Volt)	Stability at High T and SoC	Stability against Dissolution	Active Material Cost Range ($/kg)	($/kWh)
$LiCoO_2$	145	3.6	fair-good	very good	30-40	57-75
$Li(Ni_{0.85}Co_{0.1}Al_{0.05})O_2$	160	3.6	fair-good	very good	28-30	~50
$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$	120 (200)	3.6 (3.9)	good	good[1]	22-25	~55 (~30)
$LiMnO_2$	100	3.9	very good	fair	8-10	~25
$LiFePO_4$	150	3.3	very good	very good[1]	16-20	~35

[1] when chemically stabilized

$LiCoO_2$. Lithiated cobalt oxide is the main component of the positive electrodes in Li Ion cells produced on a very large scale for consumer product applications. It has good storage capacity for lithium ions, adequate chemical stability and good electrochemical reversibility but is relatively more expensive per kWh of storage capacity than other oxides and thus not a good candidate for automotive applications of Li Ion batteries that are under severe cost constraints.

Li $(Ni_{0.85}Co_{0.1}Al_{0.05})_2$. Commonly termed NCA, this lithiated mixed oxide of nickel, cobalt and aluminum has become accepted for prototypical HEV, FPBEV and PHEV batteries. It approaches the favorable characteristics of $LiCoO_2$ at lower per-kWh costs.

Li $(Ni_{1/3}Co_{1/3}Mn_{1/3})$ O_2. Often termed NCM, this lithiated mixed oxide of nickel, cobalt and manganese is potentially less expensive than NCA. It can be charged to two cell voltage levels. At the higher voltage (e.g., 4.1-4.2 Volts), NCM yields excellent storage capacity and relatively low per-kWh cost but tends to degrade through dissolution of manganese; at lower voltage, capacity is substantially less and per-kWh cost is higher but stability appears adequate.

$LiMnO_2$. Lithium manganese spinel (denoted LMS in the following) is more stable than cobalt oxide and nickel oxide-based positives in Li Ion cells because the spinel crystal structure is inherently more stable and has no or little excess lithium ions in the fully charged state. Thus, it provides very little lithium for undesirable lithium metal deposition on the negative electrode in

overcharge. Also, the threshold of thermal decomposition of the charged (lithium-depleted) material is at a considerably higher temperature than that of other positive electrode materials. Despite its lower specific capacity, the expected substantially lower per-kWh cost will make LMS attractive if the efforts to stabilize the material against electrochemical dissolution of its manganese content are successful.

$LiFePO_4$. Lithiated iron phosphate (olivine), denoted LFP in the following, is now being used successfully as a potentially lower cost positive electrode material. Due to its lower electrochemical potential, LFP has less tendency to oxidize the electrolyte solvent and thus is more stable, especially at elevated temperatures. Doping is used to increase the conductivity and stability of this promising material.

It is reasonable to assume that yet other materials will prove practical and may offer specific advantages in terms of cell voltage, electrochemical reversibility, chemical stability, and/or low cost.

The electrolyte used in Li Ion battery cells is a solution of a fluorinated lithium salt (typically $LiPF_6$) in an organic solvent, enabling current transport by lithium ions. Separators are usually microporous membranes made of polyethylene or polypropylene. Because of the low conductivity of organic electrolytes, adequate cell and battery power can be realized only with electrodes and separators that are much thinner than those used in aqueous-electrolyte batteries. The need for thin electrodes has made spiral winding of positive electrode-separator-negative electrode composites the preferred method for Li Ion cell fabrication, but flat cell configurations packaged in soft plastic (often matallized) enclosures are now gaining acceptance.

b) Advantages and Challenges

A key attraction of lithium-based batteries is the high cell voltage, the direct result of the highly negative potential of lithium. With currently used mixed oxide positives, Li Ion cell operating voltage range is approximately 2.75 to 4.2 volts. The nominal (average) discharge voltage is about 3.6 volts, and most of the usable cell capacity is delivered between 4.0 and 3.5 volts. With iron phosphate positives, the nominal cell voltage is about 3.4 Volts.

The high cell voltage is the fundamental reason for the high specific energy of Li Ion cells and batteries. High cell voltage also results in a smaller number of cells for a battery of given voltage, for reduced fabrication costs and increased reliability. The second basic advantage of the Li Ion electrochemistry derives from the small size of lithium which permits reversible electrochemical intercalation of lithium atoms into carbon-based negative electrodes with little structural stress and strain. Similarly, the very small lithium ion is readily and reversibly incorporated into a variety of host oxides that form the positive electrode. These characteristics are responsible for maintaining the integrity of both electrodes during charge-discharge cycling, a key requirement for long cycle life especially in deep-discharge cycling. As discussed further below, key technology advantages of Li Ion batteries are high power density and energy efficiency due to thin-cell construction and low self-discharge rate.

The main challenges encountered in the development of Li Ion technologies for practical applications also derive from the highly negative potential of lithium. It is a powerful driving force not only for the effectiveness of lithium as a negative electrode but also for its chemical reactivity within the cell. Only the formation of an SEI prevents continued, uncontrolled reaction of lithium with the electrolyte solvent and enables the controlled discharge and recharge of Li

Ion cells and batteries. Once formed as a protective thin layer, the SEI must be stabilized chemically and kept from growing thicker because of the associated irreversible declines of cell capacity (through loss of lithium) and of peak power (through growth of cell resistance). Proper choice of electrolyte solvents and additives, and keeping cell temperatures below approximately 45-50℃, are very important for stabilization of the SEI and achievement of practical calendar and cycle life.

Another key challenge is the sensitivity of Li Ion cells to overcharge that can result in chemical decomposition of positive electrode materials and the electrolyte, and/or in the deposition of metallic lithium at the negative electrode. These processes damage the cell and can result in hazardous conditions, including gassing and release of flammable electrolyte solvent vapors if the cell safety seal is breached by excessive gas pressure. To avoid overcharge, Li Ion batteries require accurate voltage control of every cell, unlike nickel metal hydride and other aqueous electrolyte batteries that can tolerate significant amounts and rates of overcharge.

Accurate and reliable control of cell voltage and temperature thus are critical requirements for achieving long life and adequate safety of Li Ion batteries for all uses, but especially so for automotive applications with their demands for very long battery life and high levels of safety.

2. Lithium Ion Batteries: State of the Art

a) Performance and Life

For more than a decade, prospective manufacturers have been developing Li Ion batteries for electric vehicles. A number of these efforts were terminated when the initiatives to introduce electric vehicles were abandoned earlier in this decade. However, some programs continued and resulted in the development of high or medium energy/medium power Li Ion technologies. Although none of these are commercially available as yet, a few have reached low-volume production of cells and in-vehicle evaluation of prototype batteries. Key characteristics of these technologies are summarized in Table 3-6 and reviewed below. Prospective costs and availability of batteries for EV and PHEV applications are discussed in subsections 3.D and 3.E further below.

Table 3-6. Status of Li Ion High Energy/Medium Power Cell and Battery Technologies

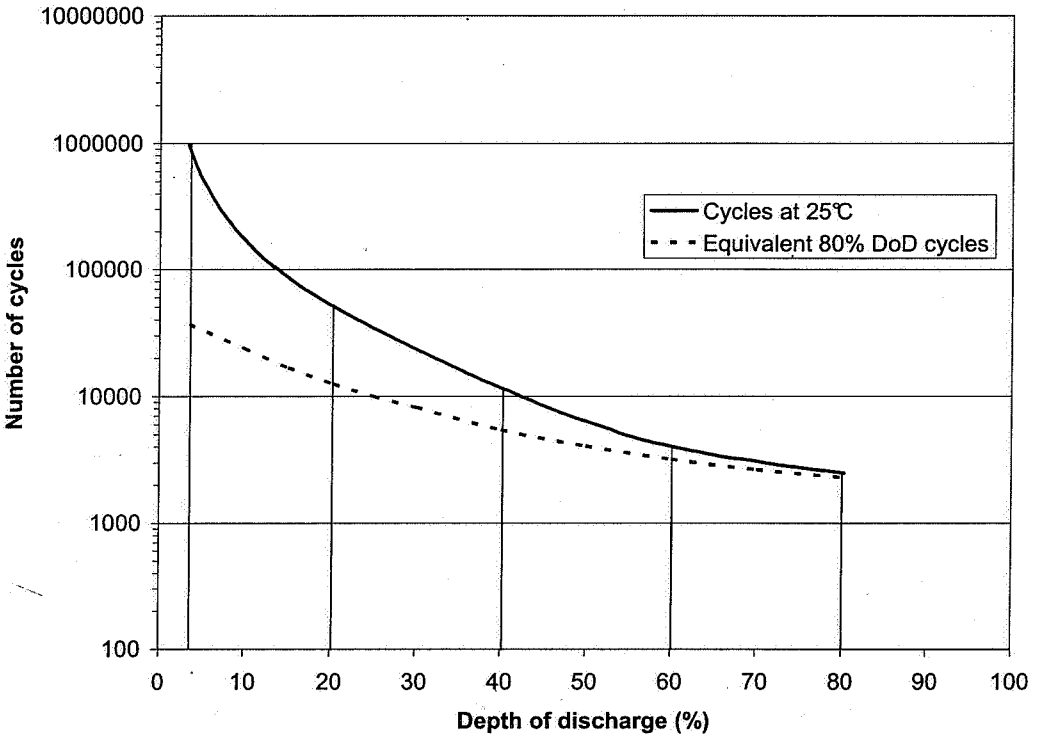
Manufacturer	JCS[1]	GAIA	LitCEL[2]	Lamilion[3]	Kokam[4]
Cell (Designation)	VL 45E/41M	HE/HP Series	EV Type	EV Type	HE/HP
Positive Electrode (Matl.)	NCA	NCA	LMS	NCM+LMS	NCM
Voltage (Volt)	3.6	3.6	3.85	3.6	3.7
Capacity (Ah)	45/41	60/45	50/33	13	100/40
Energy Density (Wh/kg)	150/136	150/105	136/142	>150	163/135
Energy Density (Wh/L)	314/286	380/284	270	270	340/285
Peak Power Density[3] (W/kg)	664/794	~900/~1500	1500	1300	~700/~1250
Power/Energy Ratio (1/h)	4.4/5.8	~6/~14	7.7	8.7	~4.3/~9
Cycle Life (Cyc. @% DoD)	>3200 (80)	~1000 (70)	~1000	>1400(100)	~3000
Calendar Life (years at RT)	>12	n.d.a.	n.d.a.	~10	>10
Development Status	LVP[5]	LVP	LVP	LVP	LVP
Battery (Application)	EV/PHEV	EV/PHEV	EV/PHEV	Small EV	EV/PHEV
Storage Capacity (kWh)	~24/15	22+/8.1	20/7.6	9.2[6]	~30/~5
Energy Density (Wh/kg)	90/94	115/74	118/117	~60 (~90[7])	~110/~100
Energy Density (Wh/L)	145/80	165/130	194/n.d.a.	n.d.a.	n.d.a.
Peak Power (kW)	55/87	50+/80	155/60	62	130/47
Peak Power Density (W/kg)	210/540	~250/730	912/917	~400 (620[8])	~490/~940
Power/Energy Ratio (1/h)	2.3/4.6	~2.2/~10	7.7/7.8	6.7	~4.3/~9.4
Weight (kg)	265/160	200/110	170/65	150 (100[5])	265/~50
Development Status	LVP; IVE[6]	LVP; IVE	LVP; IVE	LVP; IVE	LVP

[1] JCS is a joint venture of Johnson Controls, Inc. and SAFT
[2] Litcel is a wholly owned subsidiary of Mitsubishi; Litcel data are for 4-cell module; cells use stacked electrode construction and liquid electrolyte
[3] Lamilion is wholly owned by NEC
[4] Kokam cells use laminate of polymer electrolyte-separator film with electrodes
[5] low volume production
[6] two parallel strings of 96 cells in series
[7] near term goal
[8] in vehicle evaluation

The table indicates that current high energy cell designs achieve energy and power density levels of at least 150Wh/kg and 650W/kg. 20-30kWh batteries using such cells can attain energy densities of around 100kWh/kg and power densities in the range of 250-350W/kg or above sufficient for small or even full performance EV applications at acceptable battery weights (see Table 3-2). Also, medium power Li Ion cells in the appropriate size range enable construction of 7.5-15kWh batteries with energy densities above 70Wh/kg and power densities in the 500-900W/kg range, readily meeting the PHEV battery performance requirements shown in Table 3-2.

Table 3-6 includes data on cycle and calendar life, two of the remaining concerns about the readiness of Li Ion batteries for vehicle applications. The more than 3000 deep cycles achieved by SAFT and claimed by Kokam indicate the potential of large Li Ion cells for very long cycle life. This potential is documented in Figure 3-2 which shows cycle life achieved by SAFT for different depths of discharge.

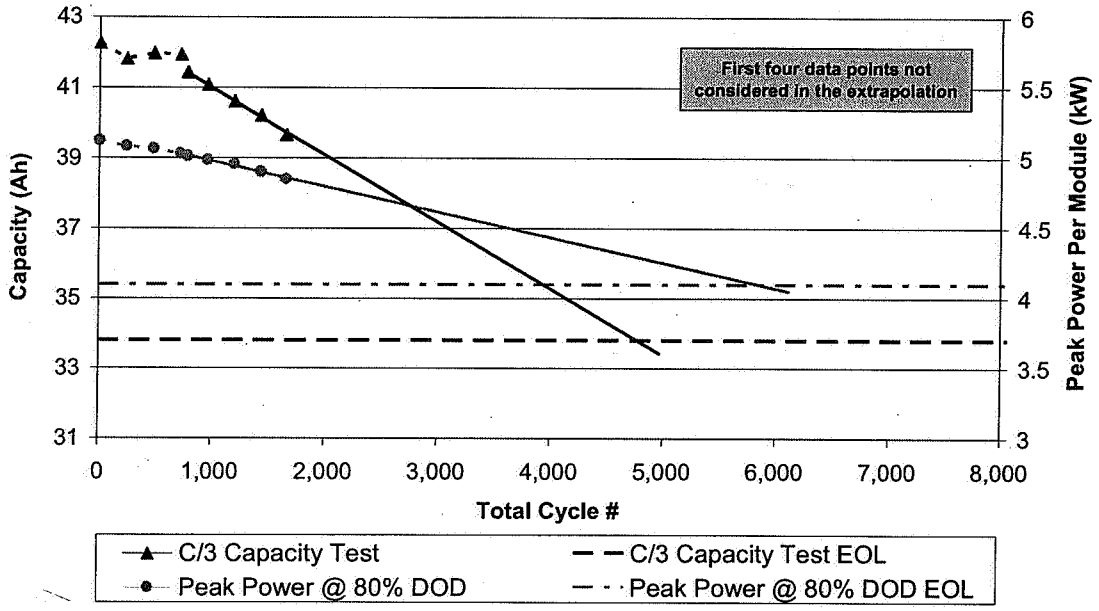
Figure 3-2: Deep Discharge Cycle Life of Li Ion High Energy Cell Technology



Included in the figure (see dotted line) is the total energy delivered by the cell over its lifetime, expressed as the equivalent of 80% DoD cycles on the same scale. Importantly, not only the actually achieved lifetime cycles but also the number of equivalent 80% DoD cycles increase progressively with decreasing depth of discharge. For example, if discharged consistently to 40% DoD (half of the maximum energy available from BEV or PHEV batteries in normal use), the battery cell under test yielded about 12,000 cycles, the energy equivalent of 6,000 cycles at 80% DoD, Thus, the lifetime energy delivered at 40% DoD is twice the energy delivered by a battery cycled at 80%DoD, and this ratio increases with decreasing DoD. This cycle life-extending effect is expected to be significant for BEV and PHEV batteries that are likely to experience a substantial number of partial discharges in practical operation.

Ongoing tests of JCS VL41M (medium energy design) multi-module assemblies at the EV and battery test facility of the Southern California Edison Co. (SCE) confirm the excellent deep cycling potential of Li Ion batteries, as illustrated in Figure 3-3 provided by SCE.

Figure 3-3. Storage Capacity and Peak Power of JCS VL41M Modules
(cycled in simulated PHEV mode)

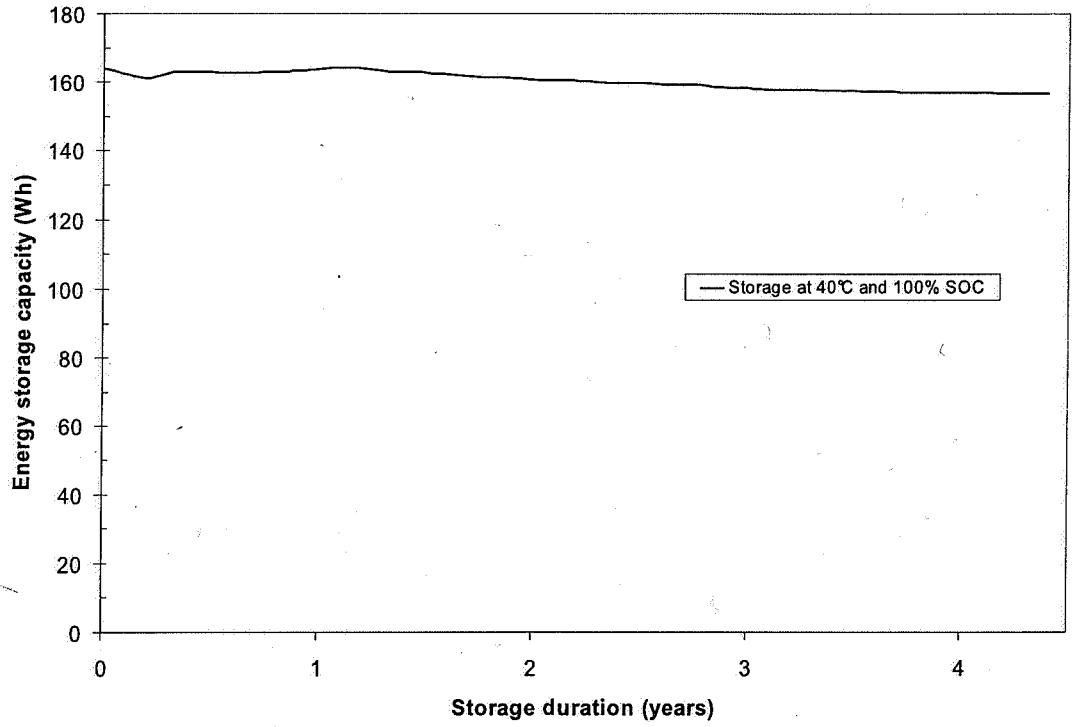


After more than 1500 cycles between 100% and 25% SoC, battery storage capacity and peak power capability each have declined by less than 6%. If the linear degradation rate of storage capacity (dark lines and left axis in Figure 3-3) continues until capacity has declined by 20%, the nominal end of life (EOL), the battery will have delivered approximately 4800 deep cycles. The extrapolation of peak power degradation (gray lines and right axis) to a 20% decline results in a projected life of 5800 deep cycles.

These test results are noteworthy not only because of the projected long cycle life but because the battery modules were cycled in a test mode that simulated one type of operation that might be experienced by the battery of a PHEV. That test cycle comprises discharging the fully charged battery to approximately 25% SoC through a series of consecutive portions of INRETS Urban I cycles in approximately 1.2 hours, followed immediately by operating the battery in the charge sustaining (HEV) mode for 1.4 hours with the same modified INRETS I cycles. This is followed by a 15 minute rest period, a full recharge in approximately 3 hours, and another rest period of 1 hour. The complete cycle most likely provides less engine assist, as well as shorter rest periods and a more rapid recharge compared with practical applications. Thus, the test cycle very likely is more stressful for the battery than its operation in a PHEV. The SCE data represent the first substantive evidence that properly designed Li Ion batteries have good prospects to meet the cycle life requirements posed by PHEV applications.

The calendar life of state-of-the-art high energy Li Ion technology also is much improved over the 2-4 years that were typical and a major concern five years ago. This progress is illustrated in Figure 3-3 obtained from JCS.

Figure 3-3: Calendar Life of Li Ion High Energy Cells at 40°C



As shown in the figure, the storage capacity of a Li Ion high energy design cell decreased less than 5% in more than four years of storage at 40°C when fully charged (100% SoC), the most demanding condition. The slope of the capacity vs. storage time relationship suggests that 20% capacity loss would not be reached for another 12 years if the capacity loss rate did not accelerate. Since that assumption cannot be made with complete confidence, battery developers test calendar life at substantially higher storage temperatures for which end-of life occurs within 2-4 years. Results from accelerated cell life testing were presented to the Panel; they indicate that calendar life of Li Ion high energy cells and batteries should attain 15 years if battery cell temperature is kept below approximately 45°C and the *average* state of charge below 50%.

Table 3-7 presents performance and life data for high power/medium energy Li Ion cell and battery technologies that are currently under test for HEV applications. Only cell technologies for which manufacturers provided the most important technical data are included in the table. Little information on complete batteries was made available to the Panel, probably because of the impending commercialization of Li Ion HEV batteries by several manufactures. Li Ion high power cell and battery developments are underway also at other manufacturers (especially in Asia), but the Panel considers the cell data in Table 3-7 sufficient to permit a technical assessment of Li Ion high power battery technologies.

Table 3-7 includes a promising Li Ion high power technology in a smaller cell size that has been commercialized by A123Systems for power tool applications. The expectation is that the basic technology can also be developed into larger cell sizes of higher power density for HEVs, an application for which it is well suited because of the safety advantages of iron phosphate-based

positives.

Table 3-7. Status of Li Ion High Power/Medium Energy Cell and Battery Technologies

Manufacturer	JCS	Matsu-shita	Hitachi VE	Kokam[1]	GAIA	A123 Systems
Cell (Designation)	VL7P		Gen 2	UHP	HP	MI 26650
Positive Electrode (Matl.)	NCA	NCA	n.d.a.	NCM	NCA	LFP[2]
Voltage (Volt)	3.6	3.6	3.4	3.7	3.6	3.3
Capacity (Ah)	7	7	5.5	7.2	7.5	2.3
Energy density (Wh/kg)	67	92	n.d.a.	114	84	110
Power Density (W/kg)	1800	3400	n.d.a.	2600	1500	~2000
Power/Energy ratio (1/h)	27	37	n.d.a.	23	18	~20
Power Density (W/L)	3525	n.d.a.	n.d.a.	4900	3750	~4000
Cycle Life (shallow cycles)	>400k	n.d.a.	>750k	n.d.a.	n.d.a.	>240k
Cycle Life (cycles/DoD)	n.t.[3]	(>1000)	n.t.	~3000/80	1000/60	7000/100
Calendar Life(years@RT)	>20	n.d.a.[4]	n.d.a.	>10	n.d.a.	>15
Development Status	LVP[5]	n.d.a.	n.d.a.	LVP	LVP	CP[6]
Battery (Application)	HEV	HEV	HEV	HEV	HEV	Power Tool
Storage Capacity (kWh)	2	3	~1	2.6	2	n.d.a.
Peak Power (kW)	50	90	47	52	25	2.1
Peak Power Dens. (W/kg)	1110	2100	1900	1850	n.d.a.	n.d.a.
Power Density (W/L)	1110	n.d.a.	2100	n.d.a.	n.d.a.	2200
Energy Density (Wh/kg)	44	70	42	93	n.d.a.	n.d.a.
Power/Energy Ratio (1/h)	25	30	45	20	12.5	n.d.a.
Weight (kg)	45	43	22.5	~28	n.d.a.	n.d.a.
Development Status	PP[7]	D[8]	PP	LVP	n.d.a.	n.d.a.

[1] cells use folded and stacked laminate of polymer electrolyte-separator film with electrodes
[2] lithium iron phosphate (modified)
[3] not tested; [4] no data available
[5] low volume production; [6] commercial production; [7] pilot production; [8] development

Even smaller Li Ion cells of the type used in consumer electronic products are being used for developmental PHEVs and FPBEVs in the form of batteries that consist of several thousand cells connected in parallel and in series. This approach takes advantage of Li Ion cells that are available now since they are being produced in very large numbers and sold at competitive prices for laptop computers. However, it raises questions regarding the reliability, safety and ultimately achievable cost of "small-cell" batteries. Several such batteries and some of the questions surrounding their use in FPBEVs and PHEVs are discussed in Appendix H.

The comparison with Table 3-2 shows that all of the Li Ion high power cell technologies included in Table 3-7 – and no doubt others not shown for lack of detailed data – meet the battery performance requirements of full HEVs. Also, available shallow cycling test data indicate (Table 3-7) that high power Li Ion cell designs can be expected to meet HEV battery shallow cycle life requirements (see Table 3-2). This is consistent with the capability of *high energy* Li Ion cells to achieve very large numbers of shallow cycles (for example, 500k at 5% DoD, see Figure 3-2). The achievement of 7000 complete discharge (100% DoD) cycles claimed by A123Systems for its technology is yet another indication of the deep cycling capability of Li Ion chemistries and technologies.

The calendar life of high power Li Ion battery cells is expected to have the same basic dependence on temperature as high energy cell designs since several of the high power cell technologies use the same basic chemistry as larger cells and thus are subject to the same kind of degradation processes. The Panel was shown experimental data that confirm this expectation. Because high power cells for HEV applications are operated around 50% SoC most of the time,

a 15 year calendar life should eventually be attainable if thermal management can keep battery operating temperatures below approximately 45℃.

As with high energy Li Ion technologies for BEV and PHEV applications, a key technical question that continues to confront high power HEV-design Li Ion batteries is whether they can meet the very high levels of safety required for vehicles operated on public roads. Information bearing on this question is discussed below.

b) Safety

Assurance of battery safety is critical for the prospects of Li Ion batteries for HEV, PHEV and EV applications. Li Ion battery safety is tied directly to the avoidance or strict control of those processes in Li Ion battery cells that, if uncontrolled, can release dangerous amounts of energy, flammable gases and/or toxic chemicals into the battery environment. These processes include electrochemical overcharging of battery cells and the ensuing reactions of the chemical species formed during overcharge, and chemical reactions of the organic electrolyte/solvent with one or both electrodes. Under normal operating conditions of cell voltage and temperature, these processes are either precluded through cell-level voltage control (overcharge) or occur at very low rates that do not constitute safety risks.

Concerns about Li Ion battery safety thus can be limited to the response of cells and batteries to "abuse", either electrical/electrochemical (shorting, high rate and extensive overcharging), thermal (heating to temperatures above the cell tolerance limit) and/or mechanical (destruction of physical integrity). Abuse tolerance testing has become part of cell development as well as battery design and engineering efforts. The degree of tolerance to various abuses is serving as a relative measure of safety as well as a guide to the development of adequately safe Li Ion cells and batteries. The procedures most commonly used in Li Ion abuse testing were developed with U.S. DOE funding under the USABC and FreedomCar programs (Unkelhaeuser, 1999) and are now widely accepted.

Results of systematic abuse testing of small commercial Li Ion cells following these procedures show that sustained high rate/high voltage overcharge and massive shorting of some Li Ion cell types can cause thermal runaway that is accompanied by cell-internal gas evolution, cell venting, and (if triggered by sparks) burning of vented electrolyte solvent. However, these conditions can be created only if the standard, multiple levels of protection devices (voltage-sensitive and pressure-driven switches to interrupt current, current-sensitive and temperature-activated fuses, cell balancing electronics) are removed. Continued external heating above 150°C (approximately 300°F) also resulted in thermal runaway for the particular Li Ion technologies tested.

Table 3-8 summarizes the abuse behavior of a high power Li Ion cell designed for HEV applications and of a prototype battery designed for small electric vehicles.

Table 3-8. Results of Abuse Testing of JCS Li Ion Technologies

Test	HEV Cell [1](VL7P)	EV Battery[2] (VL45E Modules)
Mechanical Crushing	No event	No event
Perforation (Nail Test)	Smoke (venting)	n.a.
External Short Circuit	No event	No event
Overcharging (High Rate)	Smoke (venting)	No event
Over discharging	No event	No event
Overheating (External Heat)	Smoke (venting)	n.d.a.[3]
Fuel Fire Immersion (890°C)	Flame	Flame (low rate combustion)
Water Immersion	No event	No event

[1] All tests started at 100% SoC and performed according to USABC Test Procedures,
With all safety devices disabled; similar cell abuse test results have been reported by other manufacturers
[2] Battery-level abuse tests followed USABC Procedure except with safety devices enabled
[3] No data available

Even these severe abuses did not result in catastrophic failures of single cells, and only the immersion in a hot fire resulted in combustion of gases vented from a cell. No releases of gases or toxic chemicals from the containment were observed under the battery test conditions in which the cell, module and battery-level protection systems were enabled.

It is important to recognize that, although the chemistries of the cells and batteries used in these experiments and other tests (including in-vehicle operations).are similar to the chemistries used in Li Ion laptop batteries, cell and battery designs are substantially different. Even more important, batteries for HEV, PHEV and BEV applications have sensors of voltage, pressure and temperature used in multiple, independent controls that prevent or terminate unsafe battery conditions of the type that resulted in a number of laptop battery fires..

The high level of safety achieved for current Li Ion technology is attested to by the experience with more than 200 electric and hybrid vehicles that were equipped with FPBEV-design or HEV-design Li Ion batteries and road tested in California, Europe and Japan over the past five years. No significant safety issues were encountered in these tests.

While Li Ion technology representing the state of the art of several years ago has proven safe in on-road vehicle testing, R&D is continuing to further enhance battery life and safety, as part of extensive worldwide efforts to advance all aspects of Li Ion cell and battery technology.

3. Li Ion Technology Advances and Prospects

A remarkable feature of the Li Ion battery concept is that a number of different materials can function as positive electrodes to "host" lithium ions. Similarly, several different materials work as negative electrode hosts for elemental lithium. Together with a choice of several salt-organic solvent electrolytes, this characteristic gives rise to a large number of possible Li Ion cell chemistries. Several of these have been developed into practical cell and battery technologies with the favorable performance, life and safety characteristics discussed above. It is likely that ongoing, extensive R&D will result in further advances of one or more of these characteristics.

Among recent chemistry advances are several that have become part of state-of-the-art technologies. These advances include:

- Modifications of manganese oxide-containing positive electrode materials such as NMC and LMS, to increase the *chemical* stability of these structurally stable and thus inherently safer materials that also are potentially less expensive than NCA;

- "nanostructured" (highly disperse) doped iron phosphate (olivine) positive electrodes that operate at lower positive potential and exhibit reduced reactivity with electrolyte solvents at elevated temperatures, to eliminate the danger of thermal runaway;
- nanonstructured graphite and other carbon-based negative electrode materials that permit high rate intercalation of lithium atoms during rapid and/or low-temperature charging, to minimize formation of highly reactive and potentially hazardous metallic lithium at the negative electrode surface;
- various additives to electrolytes and/or electrodes, to stabilize the SEI and/or electrode composition and structure, thus increasing cell life and safety;
- polymer (gelled) electrolyte-separator films that when laminated to the electrodes permit simplified, more flexible manufacturing of folded or stacked cell structures and that reduce venting of combustible solvent vapor when cell seals are breached by overpressure.

Currently making the transition to state-of-the-art technology is nanostructured lithium titanate to serve as a new negative electrode material for Li Ion batteries instead of the universally used carbon-based electrodes. This replacement results in a new, fundamentally different and safer cell chemistry in which ions are the only lithium species involved in the positive *and* negative electrode reactions. No SEI is present or needed for the functioning of the cell. In conjunction with the titanate electrode's nanostructure, these characteristics have already been shown to result in the capability for very high charge and discharge rates and tolerance of exceptionally large numbers of deep cycles.

For applications such as HEVs that require very high levels of power density, efficiency, lifetime cycles and safety in a small battery, the advantages of Li titanate-based cells might well balance the lower energy density and higher cost that must be expected for this chemistry because its cell voltage is approximately 1.3-1.5 Volts lower than that of Li Ion cells with lithium-in-carbon negatives. In practice, this reduction in energy density potential is partially offset by the fact that cells with lithium titanate negatives do not require an excess of lithium to make up for the lithium lost irreversibly in the initial formation of the SEI layer. Further, batteries with titanate-based Li Ion cells are likely to require less of the reserve capacity needed to make up for the slow loss of energy and power capacities due to the aging of the SEI layer in carbon-based cells.

Yet more advanced concepts still await full development and evaluation in Li Ion cell and battery technology for HEV, PHEV and/or BEV applications. Examples include liquid or polymeric *inorganic* electrolytes that are not flammable and thus inherently safer. Another potentially important advance is the discovery of an electrolyte salt that is oxidized reversibly at the positive electrode to form a chemical species that can be reduced at the negative electrode. If such a "redox shuttle" is reversible at a potential just above that of a fully charged positive electrode, it can prevent cell overcharging without causing significant self discharge. If successfully developed and incorporated into Li Ion technologies, any of these advances will improve the safety performance of Li Ion technologies even further.

New materials continue to be explored as negative and positive electrodes in Li Ion cells. Some of these materials -- for example, recently reported silicon oxynitride negatives that do not contain any of the relatively heavy transition metals -- exhibit not only good electrochemical performance but much higher specific capacities than established materials. If proven to work as electrodes in practical Li Ion cells, new high-capacity positive and negative materials could lead to significant increases in energy density over that of established Li Ion chemistries. While it is premature to quantify these improvement prospects, it is noted here that a just a 50%

increase of positive and negative capacities would increase the gravimetric energy density of a state-of-the-art 20-30Ah cell from around 150Wh/kg to approximately 180Wh/kg, with a similar percentage increase in volumetric energy density (Wh/L). Future battery technology based on such materials as well as on advances in cell designs and battery packaging should readily meet the performance goals for FPBEVs.

However, the R&D, engineering development and technology validation efforts required to move basic advances from the laboratory into commercial battery technology are likely to take at least five to ten years, depending on the extent of the attendant changes in Li Ion chemistry, cell design and/or battery operation.

4. Nickel Metal Hydride Batteries: Characteristics

a) Chemistry, Advantages and Limitations

The nickel metal hydride (NiMH) battery uses a hydrogen-absorbing alloy as the negative electrode, nickel oxide as the positive electrode, an alkaline electrolyte, and a separator made from porous polyolefin material. The NiMH cell voltage is a relatively low 1.2 Volt.

The key to the practicality of NiMH batteries was the discovery of nickel-based alloys that retain their structural integrity over a large number of charge-discharge cycles during which hydrogen is absorbed into, and released from, the alloy crystal lattice. Only a few alloys offer this characteristic at hydrogen pressures that can be managed in sealed battery cells, as well as sufficient resistance to corrosion by the caustic electrolyte used in NiMH cells. After many years of development, alloys of the general composition AB_5 (where A denotes an alkaline earth metal such as lanthanum and B stands for nickel) have emerged as the preferred composition of negative electrodes.

Before being used in NiMH batteries, the nickel oxide electrode demonstrated ruggedness and very long cycle as well as calendar life in nickel cadmium batteries. Its long life derives in good part from the minimal structural changes occurring during charge-discharge cycling during which nickel hydroxide is converted reversibly into nickel oxide–hydroxide and back to nickel hydroxide.

The main advantage of the NiMH battery is its basic potential for long cycle and calendar life. Another favorable feature is the high conductivity of the caustic electrolyte that permits high power densities to be achieved without going to very thin and thus more expensive cell structures. Other advantageous characteristics include overcharge tolerance of cells properly engineered to permit recombination (reduction) at the negative electrode of oxygen evolved at the overcharged positive electrode, and safety even under abuse conditions. All of these advantages derive from the use of an aqueous electrolyte and the relatively low cell voltage.

The main technical limitation of NiMH batteries – modest specific energy – also derives from the low cell voltage. Another disadvantage is that oxygen evolution at the positive electrode is thermodynamically favored over charging. Positive electrodes thus must not contain any of the many substances such as iron that can catalyze oxygen evolution. Even so, oxygen evolution occurs near the end of charge, and this effect increases markedly with temperature. Although recombination of this oxygen at the negative electrode can keep cell gas pressure within acceptable limits, this process reduces charging efficiency and releases appreciable heat. Higher temperature also increases corrosion of the negative alloy by the electrolyte. The associated loss of electrolyte and loss of hydrogen through the cell enclosure limit the ultimately

achievable NiMH cell and battery calendar life.

Maintaining cell temperature below approximately 45-50℃ through effective thermal management (especially during charging), keeping charging rates (especially at high states of charge) as low as practical, and limiting the extent and frequency of overcharging are the chief challenges for automotive applications of NiMH batteries.

5. Nickel Metal Hydride Batteries: State of the Art

a) Performance and Life

NiMH batteries have demonstrated high reliability and long life in automotive applications, beginning with their use as EV batteries in several thousand vehicles built and leased or sold by major automobile manufacturers under the provisions of the California Air Resources Board ZEV regulation. However, to enable driving ranges of just 75-100 miles for typical compact and midsize cars, batteries were shown to need capacities of around 30kWh and more. With a representative gravimetric energy density of 50-55Wh/kg, a complete NiMH battery of 30kWh weighs between 540 and 600kg, adding almost 40% to the weight of a conventional vehicle. This weight greatly exceeds the goals set for FPBEV batteries (see Table 3-2) and tends to disqualify NiMH batteries for application in full-performance BEVs.

The technical status of high energy NiMH batteries, with one example of the few available technologies shown in Table 3-9 (left column), has changed relatively little over the past five years. The Panel believes that this reflects lack of automobile and battery manufacturer interest in FPBEVs and in NiMH batteries for this application. The modest energy density of NiMH batteries is an inherent limitation unlikely to yield much improvement even if development efforts were continued.

Table 3-9. Characteristics of Nickel Metal Hydride Battery Technologies

Manufacturer	JCS	Varta[1]	Electro Energy	PEVE	Sanyo	Cobasys[2]
Cell Type	High Energy	Medium Energy	Medium Energy	High Power	High Power	High Power
Configuration	Prismatic	Prismatic	Bipolar	Prismatic	Cylindrical	Prismatic
Capacity (Ah)	100	40	30	6.5	6	8.8
Module (Application)	FPBEV	PHEV[3]	PHEV[4]	HEV	HEV	HEV
Weight (kg)	18.6	~35	130	1.2	1.14	2.4
Voltage (Volt)	12	48	220	7.2	7.2	12
Peak Power (kW)	3.6	8.75	~50	1.35	1.31	2.64
Power Density (W/kg)	195	250	~400	1130	1150	1100
Power Density (W/L)	405	n.d.a.[5]	~1000	2750	n.d.a.	2200
Storage Capacity (Wh)	~1200	1920	6500	47	43	106
Energy Density (Wh/kg)	65	57	~50	39	37	43
Power/Energy Ratio (1/h)	3.0	4.5	~8	29	31	26
Cycle Life (50Wh DoD)	n.t.[6]	n.t.	n.t.	>150k	~300k	.140k
Cycle Life (80% DoD)	>2000	(>3000)	>1000	n.t.	n.t.	n.t.
Calendar Life (years)	>8	n.d.a.	>10	>8[7]	>8	n.d.a.
Development Status	LP[8]	LP	P[9]	CP[10]	CP	LP

[1] Varta is owned by Johnson Controls and part of JCS
[2] website data (not updated)

[3] block of ten 4-cell modules; [4] bipolar stack of ~180 cells
[5] no data available; [6] not tested; [7] inferred from warranty period
[8] limited production; [9] prototype; [10] commercial production;

A positive observation about the capabilities of high energy NiMH battery technology can be derived from experience with the aging fleets of NiMH-powered BEVs remaining from the ZEV initiative. It is showing that even the NiMH technology of more than five years ago is capable of very good cycle and calendar life, often exceeding the cycle life goals set by USABC.

Varta's technology is a more recent design that is being used successfully in prototype hybrid buses and a prototype PHEV version of the DaimlerChrysler "Sprinter" van. Module packs of approximately 2kWh capacity are showing 100% capacity retention after nearly 2000 deep cycles in testing at the electric vehicle and battery test facility of the Southern California Edison Co. Although power capability has declined somewhat, extrapolation of the rate of decline to 20% capacity loss indicates a capability for more than 3000 lifetime cycles of 80% DoD under simulated PHEV operation.

The development of bipolar (stacked-electrode) high energy NiMH battery technology by Electro Energy is an interesting advance in NiMH technology. The technology's high gravimetric and volumetric power density (Table 3-9) is characteristic of bipolar designs and meets not only FPBEV but also PHEV battery power density requirements (see Table 3-2). Its energy density, although still falling short of the performance requirement for FPBEV applications, promises to meet the less stringent PHEV requirements. The Electro Energy battery technology still needs to demonstrate consistent long term reliability of the critical peripheral cell seals, the key issue with bipolar battery designs in the past.

NiMH high power batteries have enabled the introduction of the Toyota Prius and Honda Insight as the first practical and affordable hybrid electric vehicles, as well as the successful extension of the HEV concept to a growing number and diversity of models. Key to this success was the development of NiMH cell and battery designs with the characteristics summarized in right half of Table 3-9 above. The comparison with Table 3-2 shows that NiMH high power technologies meet the performance required for application in full HEVs, even if the module-level power and energy density data in Table 3-9 are reduced by 30% (typical for HEV-size batteries) to arrive at battery-level performance data. The technologies also promise to meet the cycling and calendar life requirements for HEV applications, as attested to by the 8-10 year warranties provided to HEV owners.

b) Safety

Nickel metal hydride batteries present no significant safety issues under normal operating conditions. Occasional brief cell venting can occur as a result of uncontrolled overcharging or charging at excessive rates and/or temperatures, but this has little safety impact. Even events caused by abnormal conditions are relatively mild although they can lead to damage or failure of NiMH batteries. Continued uncontrolled overcharging of NiMH cells will eventually lead to opening of the pressure relief valves that are standard features of NiMH battery cells. The evolving gases (primarily oxygen; on prolonged overcharge also some hydrogen) can carry some of the alkaline battery electrolyte mist with them, but the amount will be limited because cells will shut down after sufficient loss of electrolyte.

Mechanical destruction of the battery, should it occur in a severe accident, could cause leaks of the non-flammable caustic electrolyte. Such leaks will be modest and slow because the amount

of electrolyte is quite limited, and much of it will remain in the pores of separators and electrodes.

6. NiMH Technology: Advances and Prospects

Through the developments of the past decade, high power NiMH cell and battery technologies meeting the performance requirements for application in full (and other) HEVs have reached technical as well as manufacturing maturity. They are now mass-produced by two Japanese battery manufacturers, as discussed further below. Continued efforts to improve high power NiMH technology, driven by the desire to further increase specific power and enable reductions of battery capacity, volume and costs, are underway. Further improvements will continue to have commercial importance but are likely to be incremental only.

Transfer of high power NiMH technology advances to the development of medium power, medium energy NiMH technology could lead to batteries that meet performance requirements for PHEVs with nominal electric ranges of 20 miles or less. However, this type of transfer does not appear to have been attempted, probably because of the relatively recent emergence of interest in PHEVs. In view of the poor prospects of NiMH for substantial increases in energy density and cost reduction (see below), there is little incentive for seeking technology improvement and application in small or larger full performance BEVs.

7. Other Candidate Batteries: ZEBRA

Although the ZEBRA (sodium-nickel chloride) battery strictly speaking does not meet the peak power requirements for application in full performance BEVs, PHEVs and HEVs (see Table 3-2), the battery has demonstrated its usefulness in several hundred small BEVs as well as in a number of buses and other heavy vehicles. The technology, its prospective cost and its manufacturing status have, therefore, been reviewed by the Panel and are discussed below as well as in subsections 3.E and 3.F.

a) Chemistry, Advantages and Limitations

The ZEBRA battery is based on the discharge reaction $2Na + NiCl_2 \rightarrow Ni + 2\ NaCl$; in the charging reaction, this reaction is reversed. In the practical realization of the ZEBRA battery cell discharge process, liquid sodium (Na) is electrochemically oxidized to sodium ions. These migrate through the wall of a ceramic tube (surrounded by the liquid sodium) that contains nickel chloride and liquid sodium-aluminum chloride with a conducting carbon wick. At the positive electrode, nickel chloride is reduced to form nickel metal (as powder) and chloride ions. Chloride ions combine with sodium ions to form sodium chloride that is precipitated in the aluminum chloride. Cell operating temperatures in the range of 270-350℃ (520-660℉) are required to keep the sodium as well as the sodium-aluminum chloride electrolyte liquid, and to enable sufficient sodium ion conductivity of the beta-alumina ceramic tubes.

ZEBRA batteries present difficult challenges but also have unique advantages; both derive directly from the battery's cell chemistry and construction. A key characteristic is high temperature battery operation that requires start-up heating and effective thermal insulation to prevent significant thermal energy loss. It also requires tolerance of the ceramic tubes and their seals to occasional freeze-thaw cycles of the cells. On the other hand, high temperature operation facilitates battery cooling (a critical requirement and challenge for both Li Ion and NiMH batteries), and it makes operation of the insulated ZEBRA battery independent of either high or low environmental temperatures.

The development of ceramic tubes capable of conducting sodium ions and unaffected by the corrosive sodium-aluminum chloride electrolyte was the breakthrough that enabled use of liquid sodium in a battery. Because no corrosion or other side reactions occur within a ZEBRA battery cell, it has potential for excellent calendar as well as cycle life. In combination with the modest total weight of the battery active materials, the relatively high cell voltage of 2.58 Volts gives the ZEBRA battery high energy density, comparable to that of complete Li Ion batteries.

Unlike Li Ion batteries, ZEBRA batteries tolerate substantial amounts of overcharge and of cell reversal. ZEBRA batteries also tolerate a significant number of individual cell failures because they normally result in shorted cells and continued operability of the battery albeit at a slightly lower capacity. A major advantage compared to other advanced battery types is low materials cost. Finally, ZEBRA batteries can be recycled simply and completely by immersion in electric furnaces for stainless steel production, with credits for the nickel content covering all recycling costs including transportation.

The most serious drawback of the ZEBRA technology is its rather modest peak power density of approximately 180W/kg (battery level). This characteristic limits the power even of BEV-design ZEBRA batteries, and it tends to disqualify the technology for HEV and PHEV applications. Together with questions about the practicality of high temperature battery operation, this limitation has kept the technology from being accepted as a serious candidate for EV applications, especially by U.S automobile manufacturers.

b) State of the Art

Table 3-10 summarizes the current state of development of the ZEBRA battery technology. All data are for complete batteries including thermal insulation, the battery box, and the battery management system. The comparison with Table 3-2 shows that ZEBRA batteries are well matched to the energy storage requirements and battery weight constraints posed by smaller electric vehicles although peak power must be considered marginal. Nevertheless, a small but growing number of small BEVs are being equipped with ZEBRA batteries and used successfully in regular European traffic situations, typically delivering 75-100 miles on a single battery charge.

Table 3-10. Characteristics of MES-DEA ZEBRA Batteries

Cell (Type)	ML8P	ML3P	ML3C
Configuration (shape)	cruciform	cruciform	cruciform
Capacity (Ah)	25	38	32
Battery (Application)	Small EV	EV	Hybrid Bus
Battery Type	Z21-310-ML8P-50	Z5-278-ML3P-78	Z37-620-ML3C-32
Weight (kg)	137	184	203
Voltage (Volt)	310	278	619
Storage Capacity (kWh)	15,5	21.2	19.8
Energy Density (Wh/kg)	113	115	100
Energy Density (Wh/L)	173	181	154
Peak Power (kW)	23,7	32	36
Power Density (W/kg)	179	179	179
Power Density (W/L)	264	273	276
Power/Energy Ratio (1/h)	1,5	1.5	1.8
Cycle.Life (80% DoD)	1000	1000	1000
Calendar Life (years)	15	15	15
Development Status	CP	CP	CP

ZEBRA batteries meet the energy density requirements for smaller full performance battery electric vehicles and PHEVs. However, battery peak power falls short of PHEV requirements and would have to be assisted by a high power device (ultracapacitor, or small very high power battery) in meeting vehicle power requirements. The type of system performance and cost analysis required to judge the prospects of ZEBRA battery-battery hybrid energy storage systems was beyond the scope of this report.

ZEBRA batteries have already demonstrated attractive deep cycle and calendar life. In laboratory tests of battery modules, 3500 80% DoD cycles were achieved, and long term testing of complete ZEBRA batteries in vehicles show retention of full (100%) of battery capacity after delivery of 1350 deep cycles over five years, with only modest degradation of peak power over the same number of cycles.

c) Commercial Status and Prospects

ZEBRA batteries are produced commercially by the Alternative Energy Division of MES-DEA in Stabio, Switzerland, a manufacturer of electric vehicle components. MES-DEA acquired the ZEBRA technology and pilot plant facilities for its production from AABG, a joint venture of Daimler Benz (Germany) and the Anglo American Corp. (South Africa) in 1999. In 2001 MES-DEA built a new plant that combines all ZEBRA battery production operations, from processing of raw materials to the manufacture of the battery hermetic enclosure and the integration of the required thermal and electric management systems.

The plant's current production rate is around 1000 batteries per year of approximately 20kWh capacity. Production capacity will increase to 1500 batteries (approximately 30 MWh) per year in 2007, and equipment is currently being installed for 4000 units per year. On-site expansion of plant capacity to about 30,000 batteries (600 MWh) per year is a possibility given development of sufficient demand. A new "green field" ZEBRA battery plant could be built and put in operation in about three years. The market strategy of MES-DEA is to manage risk by developing and commercializing ZEBRA batteries for several independent applications in the transportation and stationary power sectors.

At present, ZEBRA batteries are used in limited numbers of electric and hybrid-electric buses, vans and light duty vehicles worldwide. In practical demonstrations, ZEBRA battery-equipped small BEVs had similar or lower AC electric energy consumption compared to BEVs equipped with NiCd batteries, attesting to the low thermal losses of the ZEBRA battery. Current initiatives include fabrication and sale by MES-DEA of 100 BEVs based on the Renault Twingo small car, provision of batteries for approximately 100 Smart city car conversions to be produced, sold and serviced by DaimlerChrysler, and supply of batteries for commercial milk delivery vans purpose-built as BEVs for use in the inner City of London.

Currently, ZEBRA batteries cost approximately $600/kWh if purchased in quantities of about 250 batteries per year. Based on detailed cost analyses of all battery materials and manufacturing operations, MES-DEA projects a selling price of around $150-200/kWh for batteries produced at an annual rate of 100,000 complete systems. (See also section 3.D below.)

8. Longer-Term Possibilities: The Lithium-Sulfur (Li-S) Battery

The lithium-sulfur electrochemical couple has the highest theoretical energy density among known battery systems. In principle, therefore, the Li-S battery is a candidate for a high-capacity

energy storage system that might give electric vehicles the ranges needed for universal acceptance. Despite sustained albeit limited R&D efforts over the past 10-15 years to exploit this potential, no viable Li-S technology has emerged. However, claims are now being made that the very difficult problems surrounding the development of practical Li-S batteries are being solved. The Panel therefore decided to include Li-S batteries in the scope of its inquiry, as a possible longer term candidate for ZEV applications.

a) Chemistry, Advantages and Limitations

The Li-S battery is based on the discharge reaction $2Li + S \rightarrow Li_2S$; in the charging process, this reaction is reversed. The theoretical energy density of the Li-S battery active materials is nearly 3000Wh/kg, far higher than that of all other candidate batteries for ZEV applications. Although only a fraction of the theoretical energy density can be realized in practical batteries (for Li Ion cells about 25-30% of a theoretical 640Wh/kg) because of the weight of the other materials needed in a battery, a reasonable goal for the Li-S battery appears to be 350-400Wh/kg. At this energy density, a 60kWh battery would weigh less than the 250kg battery weight constraint for full performance electric vehicles (Table 3-2) and would give an FPBEV a range of 200 miles or more.

However, the use of metallic lithium and elemental sulfur in a battery presents a number of difficulties. Compared to other battery negative electrodes, metallic lithium is more expensive to process because of its reactivity with moisture and air, and it is more difficult to recharge from organic electrolytes. Also, the presence of substantial amounts of metallic lithium makes it considerably more difficult to assure battery safety, especially under abuse conditions. In addition, elemental sulfur is an insulator that can be made to work as a battery electrode only by mixing it intimately with substantial amounts of an inert conductor such as carbon. Finally, the Li-S cell discharge reaction proceeds through a series of lithium polysulfide intermediates with decreasing sulfur content. Polysulfides are partially soluble in organic electrolytes, with two undesirable consequences: increase of the cell resistance due to increased electrolyte viscosity, and self discharge of cells through polysulfide-based species acting as redox shuttles that constitute a cell-internal electrochemical short.

b) Status and Prospects

Sion Power appears to be the only organization currently engaged in Li-S development. According to information provided to the Panel by Sion, major progress has been achieved over the past five years in resolving the issues with the Li-S electrochemical system. Most important, a stable SEI layer can now be formed at the metallic lithium-electrolyte interface that largely suppresses reaction of lithium with the electrolyte and prevents polysulfide shuttle species from reaching the lithium negative while at the same time passing Li ions. Also, the negative electrode is produced by vapor deposition of Li into a structure that helps retain the original electrode shape and functionality despite the well known tendency of lithium to deposit in the form of dendrites during charging. Dendrite growth and cell shorting also is suppressed by chemical reaction of dendrites with the polysulfide species.

Based on these advances, Sion Power has been able to develop small, rechargeable cells in plastic enclosure with the following specifications:

Voltage Range	Cell Size (Configuration)	Energy Density	Energy Density	Max. Rate Discharge	Power Density
2.5 → 1.7 Volt	2.2(Ah) (prismatic)	>350(Wh/kg)	>350(WH/L)	~4(A)	~600 (W/kg)

Achieving a practically usable gravimetric energy density of more than 350Wh/kg, a value that greatly exceeds the energy densities of every other practical battery type, is an important achievement. Volumetric energy density and (gravimetric) power density, on the other hand, are comparable to the corresponding values for high energy Li Ion cells (Table 3-6). The currently achieved cell life of around 100 deep cycles is expected to increase to about 300 cycles which might be sufficient for the applications currently being targeted (military and space small power; consumer electronics). Sion Power is projecting further significant increases in energy and power density, but extracting more of a Li-S cell's energy tends to shorten cycle life.

To date, Sion Power has built a number of battery systems consisting of up to 500 small cells, for evaluation by the military. The investor-owned company is now in the process of raising funds to build its first commercial battery facility in the U.S., with the goal to have a plant producing small cells operating in the first quarter of 2008. Sion's product roadmap also includes development of cells and batteries in capacities suitable for BEV and PHEV applications. Prototype 25Ah cells are scheduled to be available in early 2007 and prototypes of complete battery systems a year later.

For electric vehicle applications, envisioned by Sion Power for Li-S batteries in the longer term, 1000-1500 deep cycles would be needed, and with a required 2500-3500 deep cycles PHEVs are even more demanding. It remains to be seen whether such long cycle life is possible with Li-S batteries that do not have the fundamental potential for long life offered by "host"-type electrodes with their minimal structural changes during charge-discharge cycling. At the current stage of development, it must be considered highly uncertain whether fully developed Li-S batteries would be able to meet the cycle life requirement for FPBEV (much less PHEV) applications.

Sion has provided preliminary cost estimates for BEV-design Li-S battery modules produced at early and full commercial production rates. These estimates are about 1/3 higher than the projections for high energy Li Ion battery modules and would make Li-S batteries too expensive for FPBEV applications except in instances where users would be prepared to pay a substantial price premium for the extended range capability that might be provided by such batteries..

D. Battery Costs

The prospects of battery electric and plug-in hybrid electric vehicles for capturing significant markets will depend in large measure on the costs of their batteries. While the cost of the smaller batteries used in fuel cell hybrid electric vehicles will be a less critical factor, the prospective high overall cost of FCHEVs provides a strong motive to minimize the cost of these batteries as well.

FPBEV battery costs were assessed in the BTAP 2000 Panel report and found to substantially exceed the goals for commercialization. The technology advancements and fuel price increases over the past five years now call for updates not only of battery costs but also of the overall economics – and, thus, cost constraints – for FPBEVs and their batteries. For HEV batteries,

cost information is generally not available because of the emerging market competition. PHEV batteries are only now moving into development and pilot-level fabrication. As a consequence, their prospective costs in volume production, although most likely falling between those of FPBEV and HEV batteries, are not well understood.

In the following, the year 2000 battery cost background is updated and expanded with cost information obtained by the Panel from battery developers and prospective manufacturers, with emphasis on the cost of batteries suitable for FPBEV and PHEV applications. Because this information was made available on a confidential basis, the report does not identify the battery manufacturers that provided cost data. Also, since this data was neither complete nor consistently framed, the Panel supplemented the manufacturers' data with cost information from other sources and used its own judgment in combining and extrapolating cost information. The battery cost information so developed is compared further below with battery cost goals and with the value of the fuel cost savings achieved by HEVs, PHEVs and FPBEVs compared to conventional ICE vehicles.

1. Lithium Ion Battery Costs

The Panel collected Li Ion battery cost information from a number of manufacturers. This information came in several different formats, ranging from specific costs for cells to the costs of multi-cell modules (usually with module-level electric/electronic controls) and of complete batteries, and it covered several different cell chemistries as well as a range of cell and battery capacities all of which can be expected to affect costs.

To enable comparisons of manufacturers' data and to develop its own Li Ion battery projections, the Panel first converted the manufacturers' data to module-level specific costs using the scaling factors in Table 3-11. These factors are averages of the corresponding factors directly provided by some manufacturers, or derived from cell-, module- and/or battery-level specific costs made available for the same technology.

Table 3-11. Scaling Factors for Li Ion Technology Specific Costs:
From cells to modules and batteries

Battery Size (kWh)	Cell → Module	Module → Battery	Cell → Battery
40-45	1.03	1.2	1.24
20-25	1.04	1.25	1.3
12-15	1.05	1.33	1.4
7	1.07[1]	1.42[1]	1.52[1]
2	1.1	1.5	1.65

[1] Interpolated

The module specific costs thus derived were then normalized to the same approximate cell size (40-45Ah) and battery capacity (20-25kWh), the capacities for which a majority of the cost data were made available to the Panel. The factors used for this normalization are shown in Table 3-12 below; they were derived empirically from the cell-, module- or battery-level specific costs provided by the same manufacturer for different cell and/or battery capacities and averaged over the few manufacturers from which this information was available. (For a given cell size, these scaling factors turned out to the closely the same, whether derived from cell-, module- or battery-level specific costs.) The increase of specific costs with decreasing cell size (for a given chemistry) expressed by the factors in Table 3-12 is due to a combination of factors, primarily the increasing contributions of inactive cell materials and manufacturing to total cell costs. Because cells for vehicle applications are designed for increasing specific power levels as the

application changes from FPBEVs to PHEVs and HEVs, the scaling factors also reflect the fact that cell and battery specific costs increase substantially with increasing power-to-energy ratios.

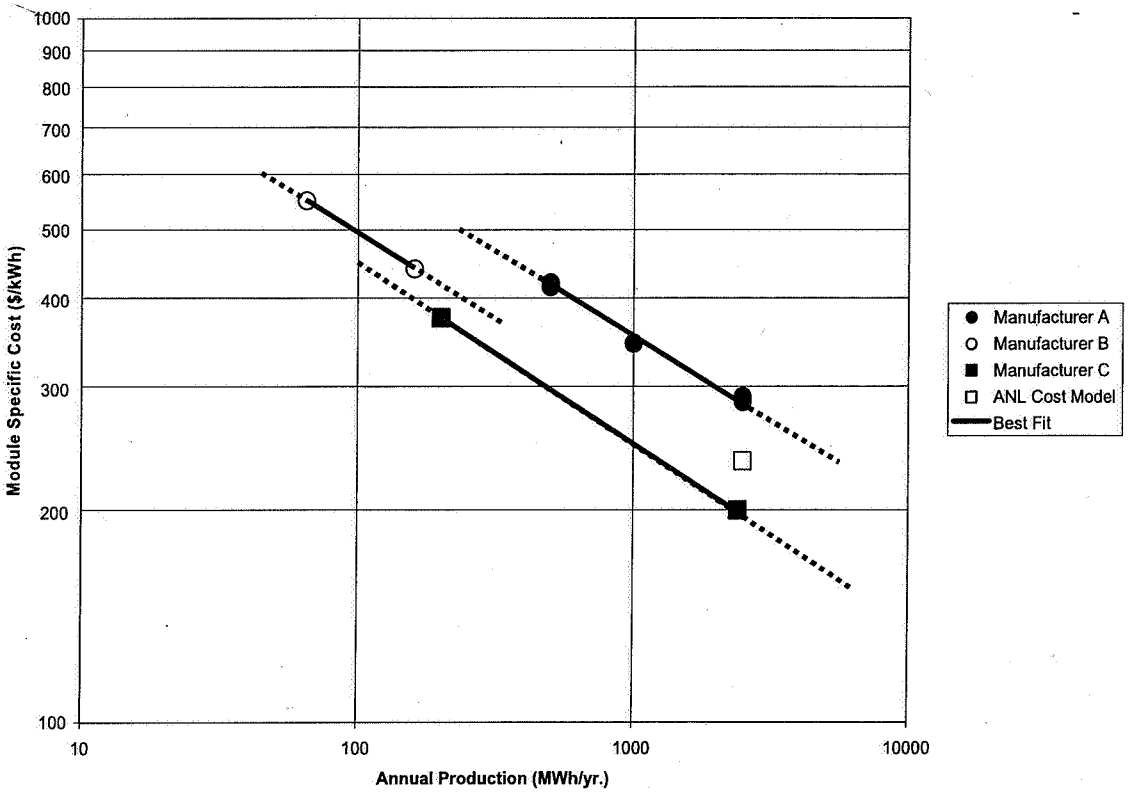
Table 3-12. Scaling Factors for Li Ion Technology Specific Costs: From larger to smaller cell sizes

From Cell Size (Ah)	To Cell Size (Ah)	Factor	From Cell Size (Ah) to 45 Ah	Factor
120	60	1.20	120	1.35
60	30	1.27	60	1.12
60	45	1.12[1]	**45**	**1.00**
45	30	1.14[1]	30	0.88
30	15	1.33	15	0.66
15	7	1.40[2]	7	0.47

[1] interpolated; [2] extrapolated

The cost projections provided by manufacturers, normalized to the specific costs for modules of approximately 45 AH cells by application of the factors in Tables 3-11 and 3-12, are plotted in Figure 3-4. The figure uses total annual battery capacity (in MWh per year) as the measure of annual battery production considered the most appropriate by battery manufacturers.

Figure 3-4. Li Ion Module Specific Cost Projections



The Panel also developed an independent check of its module specific cost methodology and projections using the results of a series of cost calculations made available by Dr. Paul Nelson with support of ANL. These detailed calculations started with complete bills of materials for several chemistries, cell sizes and power density requirements, and they built up costs to the

cell, module and battery levels through addition of the appropriate costs for materials, labor and overhead. The normalized module specific cost derived from Dr. Nelson's ANL cost model is included in Figure 3-4.

Figure 3-4 indicates a substantial spread in module specific costs even after applying the Panel's cost normalizing approach to manufacturers' cost data. These differences are due to differences in presently used materials and manufacturing methods as well as to different assumptions made when material and manufacturing costs are projected to production levels well beyond those currently practiced. For example, the manufacturer identified as "C" in Figure 3-4 used generally (but not systematically) lower materials costs that, if adjusted, would remove more than half of the difference to the module specific cost projections provided by manufacturer "A".

Taking these differences into account, the Panel considers ranges of $340-420/kWh (500MWh/year production rate) and $240-280/kWh (2500MWh/year) representative of manufacturers' specific cost projections for Li Ion modules using 45Ah high energy-design cells. These production rates correspond to annual production of 20,000 and 100,000 batteries of 25kWh capacity for small FPBEVs, or approximately 80,000 to 400,000 batteries of about 7kWh for a midsize PHEV-20.

Using the midpoint of the Li Ion module specific cost ranges above, and applying the cost scaling factors from Tables 3-11 and 3-12, the module specific and battery total costs for HEVs, PHEVs and FPBEVs summarized in Table 3-13 were calculated. The Panel recognizes that its approach – to estimate module and system costs for a range of cell and battery sizes from the specific cost of a single module type using a series of scaling factors – represents a simplification that cannot fully account for specific differences in cell, module and battery design and manufacturing features and costs. Clearly, a more sophisticated cost model, verified by comparisons with detailed materials, engineering and manufacturing cost studies, would be desirable for more confident projections of battery costs. However, in absence of such a model, and given the importance of cost projections to its assessment of advanced technology vehicles, the Panel proceeded with this approach. Confidence in its general validity comes from the fact that the projections given in Table 3-13 are generally consistent with the limited directly comparable data provided by manufacturers. The few projections the Panel received from automobile manufacturers also are broadly consistent with the costs in the table.

Table 3-13. Projected Costs of Li Ion Batteries

Vehicle Type	Battery Capac. (kWh)	Cell Capac. (Ah)	500MWh/year 20k Batteries/year			2500 MWh/year 100k Batteries/Year		
			Product. Rate (MWh/y)	Module Cost ($/kWh)	Battery Cost ($)	Product. Rate (MWh/y)	Module Cost ($/kWh)	Battery Cost ($)
FPBEV	40	120	500 800	285 255	13,680 12,240	2500 4000	195 175	9,285 8,395
Small EV	**25**	**45**	**500 20**	**380**	**11,875**	**2500 100**	**260**	**8,150**
PHEV-40	14	45	500 280	380 435	7,075 8,350	2500 1400	260 300	4,850 5,585
PHEV-20	7	30	500 140	435 595	4,305 5,190	2500 700	295 405	2,750 4,025
PHEV-10	4	15	500 80	575 880	3,265 4,990	2500 400	395 605	2,240 3,445
Full HEV	2	7	500 40	805 1,465	2,420 4,395	2500 200	550 1,010	1,650 3,025

For each application, the table lists module specific and battery total cost projections for limited production rates (left half of table) and in mass production (right half). For each of these two levels of commercialization, cost projections are given for *capacity* production rates (MWh/year, upper numbers) and for *battery* production rates (batteries/year, lower numbers).

A key point to take from the cost projections in Table 3-13 is the substantial increase of module specific costs with decreasing cell size. For example, at the same MWh production rate, module specific cost increases around 50% when going from a cell size appropriate for a FPBEV to one suitable for a PHEV-20, and it nearly doubles when going from PHEV-20 to full HEV modules. The corresponding percentage increases are even higher for *battery* specific costs (not shown in Table 3-13) because the factor for scaling module to battery specific costs increases significantly with decreasing battery size, see Table 3-11. This is explained by the fact that balance-of-plant cost factors such as the battery management systems, hardware and enclosure contribute an increasing percentage of cost as battery size decreases.

One important consequence is that the differences in the costs of batteries for the different vehicle types are substantially less than the differences one would calculate from a strict proportionality of battery cost with capacity. For example, at the same *battery capacity* production rate (in MWh/year), the cost of a complete 40kWh FPBEV battery is estimated to be less than six times the cost of a 2kWh battery for a full HEV while the capacity ratio is 20. The effect is even more dramatic when comparing battery costs for the same *number of vehicles and battery systems* because of the much larger MWh capacity production rates (scale benefits) for FPBEV batteries: in that case, the cost of a FPBEV battery is projected to be only about three times HEV battery cost.

As another example, at the same mass production rate (100,000 systems per year), a PHEV-20 battery is projected to cost only around $1000 more than a full HEV battery, despite its 3.5-fold larger storage capacity. For a PHEV-10 battery, the difference of its cost to that for a full HEV battery is projected to be less than $500. This has direct implications for the life cycle cost competitiveness of PHEVs compared to HEVs, as is discussed in section 4 below.

Several other observations on the prospective costs of Li Ion batteries for ZEV and near-ZEV applications are pertinent. In the nearer term, the costs projected for the large batteries needed for full performance BEVs are likely to remain high, with little change from those projected by the BTAP 2000 Panel six years ago. The analysis also projects rather high costs for high power Li Ion batteries, for example approximately $3000 for a 2kWh HEV battery produced at an annual rate of 100,000 systems. This represents an important motivation for battery developers/manufacturers to obtain the highest possible power densities from HEV-design Li Ion batteries and thus reduce capacities as close as possible to the minimum energy (approximately 0.7kWh, see Table 3-2) required for full HEV applications. Caveats for this approach are that the cost reductions will be less than proportional to capacity reductions for the reasons discussed above. Also, capacity reductions will increase the average depth of discharge and the power densities experienced by batteries in HEV operation both of which tend to shorten life.

In the longer term, there appear to be good prospects for reduction of Li Ion battery costs for all applications through a combination of approaches that are likely to include development of new electrode materials with lower costs and/or higher capacities, cost reductions of inactive cell materials (especially separators and electrolyte salts) through improved and larger-scale production processes, lower costs of balance-of-system components, and advanced large-scale

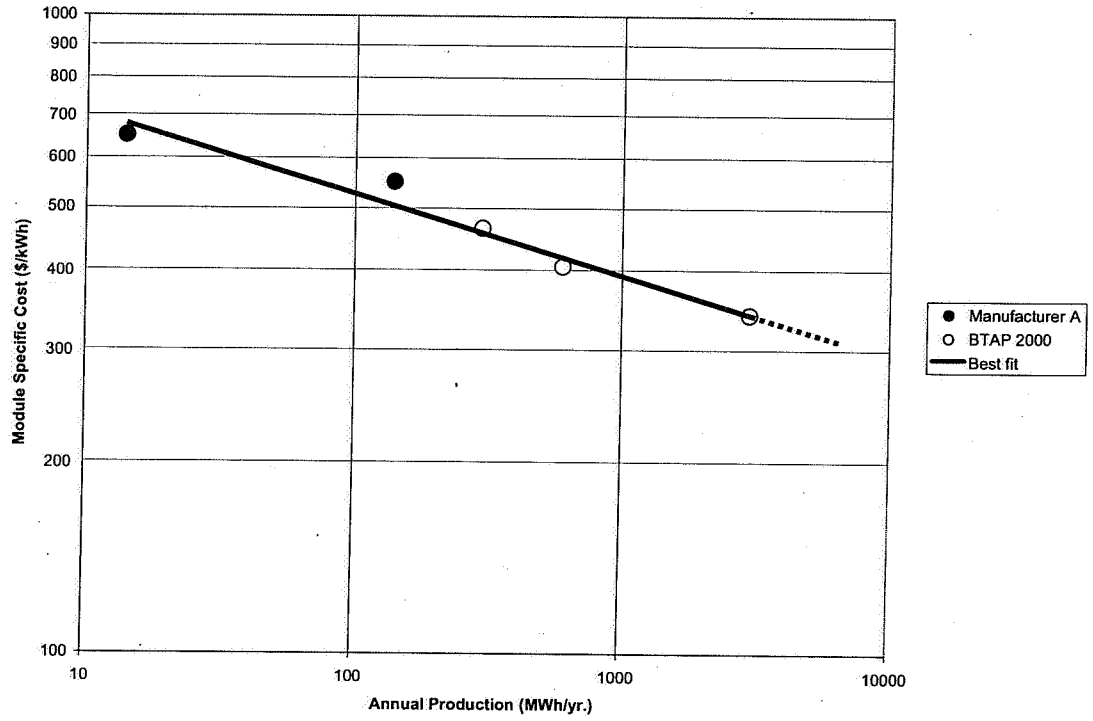
manufacturing processes, The magnitude of this cost reduction potential cannot be assessed at this time. As an example, however, just the combination of a 50% increase in specific capacity (mAh/g) and 50% reduction in cost ($/kg) of the active materials from those underlying the nearer term projections would reduce Li Ion module specific costs by about 20%.

2. Nickel Metal Hydride Battery Costs

Figure 3-5 shows the few indicators of NiMH module specific costs available to the Panel. They include projections obtained by one of the Panel members in 2003 (corrected for the higher nickel price and lower value of the US dollar in 2006) from a low-volume manufacturer of medium energy/medium power NiMH batteries. For comparison purposes, Figure 3-5 also includes projections of module-level specific costs for NiMH FPBEV batteries obtained by the BTAP 2000 Panel. (The original BTAP 2000 cost projections were increased by 10% to allow for inflation since the year 2000, and by the addition of $40/kWh to account for an approximate doubling of the nickel price since then.)

Fitting a straight line to the data in Figure 3-5 supports the projection of $430/kWh and $350/kWh as the specific costs of 40Ah high energy design NiMH modules produced at rates of 500MWH/year and 2500MWh/year, respectively. Using these costs, and assuming that the scaling factors for Li Ion technologies (Tables 3-11 and 3-12) are applicable, the projected costs summarized in Table 3-14 were estimated. This assumption is considered reasonable because material costs, cell designs and manufacturing methods for Li Ion and NiMH batteries with spiral-wound cells are quite similar.

Figure 3-5. NMH Module Specific Cost Projections



As expected from the consistency of the few newer NiMH cost data available to the Panel with

the BTAP 2000 cost projections (see Figure 3-4), NiMH battery cost projections show little change from 2000 and thus remain high. The cost factor method employed by the Panel to estimate the specific costs of smaller NiMH cell sizes results in rather high costs of NiMH batteries for full HEV applications, even in mass production (e.g., 100,000 systems per year, see Table 3-14). The projected cost of approximately $1500/kWh (nearly $2,000 for 1.3kWh) for a mass-produced NiMH HEV battery explains the extensive efforts of established manufacturers to further increase power density and thus reduce the minimum battery storage capacity needed to provide the required power and energy. Significant for the life cycle economics of PHEVs is that the incremental cost of a NiMH PHEV-10 battery over a full HEV battery is less than $800; for a PHEV-20 battery, the difference is about $1,200.

Table 3-14. Projected Costs of NiMH Batteries

Vehicle Type	Battery Capac. (kWh)	Cell Capac. (Ah)	500MWh/year 20k Batteries/year			2500 MWh/year 100k Batteries/Year		
			Product. Rate (MWh/y)	Module Cost ($/kWh)	Battery Cost ($)	Product. Rate (MWh/y)	Module Cost ($/kWh)	Battery Cost ($)
FPBEV	40	120	500 800	320 300	15,360 14,285	2500 4000	260 240	12,500 11,430
Small EV	**25**	**45**	**500 20**	**430**	**13,440**	**2500 100**	**350**	**10,500**
PHEV-40	14	45	500 280	430 520	8,005 9,680	2500 1400	350 375	6,520 6,980
PHEV-20	7	25	500 140	490 595	4,305 5,200	2500 700	400 460	3,720 4,275
PHEV-10	4	12	500 80	650 820	3,700 4,990	2500 400	530 675	3,015 3,830
Full HEV	2	6	500 40	805 1,320	2,420 4,395	2500 200	740 1,030	2,110 3,090

The comparison of Figures 3-4 and 3-5 and of the tables derived from them indicates that, for the same application and production rate, NiMH batteries are likely to cost more than Li Ion batteries. Further, the cost advantage of Li Ion is projected to grow with increasing production volume (steeper "cost learning" curve), primarily because most manufacturers' projections assume significant future cost reductions for the key materials used in Li Ion batteries. On the other hand, the prospects for cost reductions of NiMH batteries below the numbers in the Table 3-14 do not seem promising since nickel costs (the major materials and battery cost factor) may well continue to rise.

3. Zebra Battery Costs

MES-DEA, the manufacturer of ZEBRA batteries, has published its projection of ZEBRA battery costs for different annual production volumes. This information, discussed and basically confirmed with the Panel, indicates that ZEBRA batteries of approximately 21kWh can be ordered now in quantities of 250 complete systems at a cost (price to OEM) of $12,'750 per battery, corresponding to approximately $600/kWh. For production in quantities of 10,000, 20,000 and 100,000 batteries per year, battery specific costs are projected by MES-DEA to be $335/kWh, $275/kWh and $200/kWh, respectively. These costs fully account for all cost factors, including amortization of plant investment, warranties and profit. They are judged by the Panel to have good credibility because not only the basic battery technology but the complete manufacturing technology and the manufacturer's plans for expansion of capacity appear well established.

The current and projected ZEBRA battery costs are substantially lower than the costs of all other advanced battery technologies, including Li Ion and NiMH batteries of similar capacities produced in comparable quantities. The main reason appears to be the lower cost of the materials from which the ZEBRA battery is manufactured: ordinary salt, nickel (in quantities well below those needed per kWh of NiMH battery), aluminum chloride, and aluminum oxide. MES-DEA estimates the specific cost of these materials as $60/kWh of ZEBRA battery capacity. The materials specific cost for NiMH and Li Ion batteries, on the other hand, are unlikely to decline below $100/kWh.

4. Battery Costs and Propulsion Energy Cost Savings

Comparisons of the projections in Tables 3-13 and 3-14 with the cost goals in Table 3-4 above suggest that, even in mass production, the costs of Li Ion and NIMH batteries exceed the goals for FPBEVs and HEVs substantially. On the other hand, Li Ion and NiMH batteries designed for PHEV applications -- especially for PHEVs with shorter electric ranges -- appear able to meet or approach the preliminary cost goals, probably because these new goals already reflect the recent escalation of motor fuel prices that have increased the economic value of higher fuel efficiencies and of the cost savings from displacement of petroleum-based fuels with electricity.

Under these circumstances, higher first costs of advanced-technology vehicles are likely to become more acceptable to vehicle owners, and some or all of the acceptable cost difference can be allocated to the battery. It is appropriate, therefore, to compare battery cost projections not only with historic cost goals but with the value of the fuel cost savings enabled by the batteries of ZEVs and near (including partial) ZEVs. Underlying this direct comparison is the key assumption (frequently made, also in Section 6 of this Report) that the costs of mass-produced ZEVs and advanced-technology vehicles *minus* battery will be approximately the same as the cost of a complete ICE vehicle of comparable performance and accommodations.

Table I-1 in Appendix I lists the net present values (NPVs) of the fuel cost savings realized by HEVs, PHEVs and BEVs relative to conventional ICE vehicles, calculated with the assumptions noted in the appendix. A number of observations can be derived from comparisons of the cost projections in tables 3-13 and 3-14 with the fuel cost savings NPVs:

- Net present values of fuel cost savings generally exceed currently accepted battery cost goals. Specifically, for HEVs, the NPV substantially exceeds cost goals in every scenario used to calculate these NPVs. For PHEVs and FPBEVs, NPVs exceed battery cost goals in all but the conservative near term scenario.

- For full hybrid electric vehicles (HEVs), the fuel cost savings NPV approximately matches the projected cost of a mass-produced Li Ion battery and approaches the cost of a mass-produced NiMH battery in the least favorable (the conservative near term) scenario. In all other scenarios, the costs of mass-produced Li Ion and NiMH battery costs are significantly less than fuel cost savings NPVs.

- For a PHEV-20, the costs of mass-produced NiMH batteries are almost 50% higher than the NPV in the least favorable scenario, but Li Ion battery costs exceed NPV by only 15%. In all other scenarios, the cost of mass-produced batteries are below NPVs, substantially so in the favorable long term scenario. In the favorable near term and unfavorable longer term ("middle") scenarios, NPVs approach the cost of Li Ion and NiMH batteries produced even in pre-commercial quantities.

- For all but the conservative near term scenarios, fuel cost savings NPVs exceed battery costs by larger amounts for the PHEV-20 than for the full HEV. That is, a PHEV-20 has lower life cycle costs than a HEV because the substantially lower per-mile cost of electricity more than compensates for the higher cost of the PHEV battery.

- For a PHEV-40 vehicle, NiMH and even Li Ion battery costs exceed the fuel cost savings NPV significantly in the least favorable scenario. Li Ion costs are near or below NPVs in all other scenarios, NiMH costs only in the favorable long term scenario. For batteries produced in early commercialization quantities (20,000 systems per year), costs are in the range of NPVs only in the most favorable scenario. The fuel cost savings NPV approximately matches the projected cost of a mass-produced Li Ion battery and approaches the cost of a mass-produced NiMH battery

- Finally, for small and midsize full performance electric vehicles (FPBEVs), the costs of mass-produced Li Ion (25kWh and 40kWh) batteries exceed the NPVs of fuel cost savings in all but the favorable longer term scenario. In the middle scenarios, battery costs are about 15% above NPVs. On the other hand, mass-produced ZEBRA batteries for small BEVs cost less than fuel cost savings NPVs in all except the least favorable scenario.

E. Battery Manufacturers: Technology and Availability

This section summarizes information collected by the Panel on the development and commercialization status and plans of prospective manufacturers of the battery technologies reviewed in Sections 3.C and 3.D. The focus is on companies that were visited by Panel members or that provided key staff for off-site meetings with the Panel. The section also summarizes information received in response to the Panel's battery questionnaires (see Appendices A and B) and through follow-up contacts with organizations not visited by the Panel. Companies are listed in alphabetical order.

A123Systems (A123) is an investor-owned U.S. company formed in 2001 and located in Watertown, MA. The company develops and manufactures Li Ion batteries that use proprietary iron phosphate (LFP) positive electrode technology based on initial developments of MIT. Structurally and chemically stable LFP positives provide excellent safety and long life, even at elevated temperature, and the nanostructured (highly disperse) electrodes enable high charge and discharge rates, a prerequisite for high power applications. Technical details confirming these capabilities were presented by A123 staff at recent conferences, including EVS-22 and the September 2006 ZEV Symposium of the California Air Resources Board.

A123Systems owns and operates several Li Ion cell manufacturing plants in Asia and the U.S. that according to A123 meet stringent manufacturing quality standards. The company successfully developed and commercialized 2.2Ah type 26650 Li Ion cells and modules for power tools, a new and very promising application for Li Ion technology. A123 is now engaged in the development of higher-power cells for application in HEVs. In pursuit of this goal, the company received $30 million in investments in early 2006 and a $15 million contract from USABC for development of advanced HEV batteries in December 2006.

Altair Nanotechnologies (Altairnano) is an investor-owned, NASDAQ-listed U.S. materials company headquartered in Reno, NV. Altairnano is specializing in development and commercialization of pigments based on titanium oxide (TiO_2). In 2000, the company initiated development of lithiated TiO_2 into a new negative electrode material for Li Ion batteries, to

replace the universally used graphitic and/or amorphous carbon electrodes. The advantages of eliminating elemental lithium from Li Ion battery -- inherently higher safety, lower resistance and better reversibility of this new Li Ion chemistry -- were discussed in section 3.3, above. For applications such as HEVs that require very high levels of power density, efficiency, lifetime cycles and safety in a small battery, these advantages might well balance the lower energy density and higher cost that must be expected for this chemistry because of its lower cell voltage of approximately 2.5 V

Altairnano occupies a 100,000 square foot facility of offices, laboratories and manufacturing areas in Reno, NV, that includes a pilot plant for titanium dioxide nanoparticle production. An experienced battery technology team acquired by Altairnano developed a 2.5V Li Ion cell technology with the company's nano-titanate negatives and using a soft cell packaging technique. Prototypical battery modules with such cells were first fabricated in September 2006 and demonstrated in a complete 35kWh battery pack powering a Korean-manufacture SUV converted to electric drive by Phoenix Motorcars. Altairnano has developed an 11Ah cell for a 35kWh battery to be fabricated in 2007 and evaluated in BEV conversions fabricated by Phoenix Motorcar. DOE awarded Altair Nano a $2.5 million contract for continued technology improvement through materials optimization and extension of battery cell operability to a wider range of temperatures. An initiative to evaluate the Altairnano technology in PHEV conversions is in negotiation.

Electrovaya is a small investor-owned technology development company with headquarters in Toronto, Canada, and manufacturing facilities in Toronto and in Saratoga Springs, NY. The company's four groups focus on development, engineering, manufacturing and applications of Li Ion battery technology. Electrovaya's 156,000 sq.ft. manufacturing facilities have a current Li Ion cell production capacity of 5 MWh/month that is being expanded to 10 MWh/month (120 MWh/year) which will be among the largest Li Ion production capacities in North America. The company's Li Ion technology products include flat, large area batteries that provide laptop computers with extended running times, and portable power systems for astronauts. In these developments, Electrovaya has demonstrated the design flexibility of its technology and the company's capability to develop, engineer and fabricate complete power system based on that technology.

Key elements of Electrovaya's proprietary technology include use of nanostructured active materials, a highly conducting "SuperPolymer" electrolyte and Z-folding cell construction, to achieve high conductivity and charge/discharge rate capabilities. The technology can utilize all positive and negative electrode materials commonly used in Li Ion cells. In addition, Electrovaya has developed its own proprietary positive electrode material and manufacturing process to the pilot plant level. This material is claimed to exceed the specific capacity of established positive materials by 40-70% and to enable cell energy densities exceeding 200Wh/kg. Based on this cell technology, Electrovaya's 750Wh, 15V module achieves energy densities of 150Wh/kg (gravimetric) and 260Wh/L (volumetric). The company claims calendar life exceeding seven years as well as a high level of safety due to use of very stable electrode materials. UL approval for the technology has been obtained on the cell, module and battery level.

Electrovaya is now positioning itself for the anticipated expansion of Li Ion battery markets in the transportation sector. For ZEV applications, it has 750Wh/50Ah and 1.4kWh/90Ah modules that are used in complete BEV batteries. These include an 80kWh system for delivery vans being evaluated in a fleet demonstration program. The company has established the capability for development and engineering of complete, Li Ion battery-based electric drive systems including integrated battery management, high-efficiency motor and motor control technology, and the

software needed to control the system.

Electro Energy, Inc. (EEI) is a battery technology, engineering and manufacturing organization headquartered in Danbury, CT. Founded in 1992. EEI invested more than a decade and $30 million in the development of a bipolar nickel metal hydride battery technology while meeting its customers' needs with EEI's proprietary battery technologies and systems. The patented NiMH bipolar technology is claimed by EEI to be lighter, more efficient, longer lasting and less expensive, and have a greater range of applications, than other NiMH technologies. One basis of this claim is the fundamental fact that bipolar batteries of "stacked" cells have simpler design, fewer parts, lower resistance and more uniform current distribution than the generally employed monopolar cell designs. The second basis is EEI's claim to have solved the known difficulty of integrating many individual cells into a stack with seals that endure conditions in the cell over the life of the battery.

EEI has developed the technology to the laboratory prototype stack and battery level and is accumulating experience with experimental batteries, including a 6kWh, 220V battery (see Table 3-6) used to convert a Prius HEV to operation as a PHEV. Over the next two years, EEI expects to advance this technology to commercial readiness for conversion of HEVs to PHEV operation.

GAIA Accumulatorenwerke (GAIA) is a subsidiary of Lithium Technology Corp. (LTC), a publicly traded US company largely owned by a Dutch venture capital firm. GAIA's business is Li Ion technology development and production, currently on a limited-scale for military and developing commercial applications including transportation and stationary power, in a 170,000 sq.ft. facility in Nordhausen, Germany. LTC's business includes assembly of complete batteries from GAIA cells, R&D support for GAIA, and limited production of prismatic cells.

GAIA's Li Ion technology uses well established cell materials and designs: NCA positive and graphite negative electrodes, conventional electrolyte compositions and standard separators. Cell construction is by spiral winding of electrodes made by a proprietary extrusion process. This process has potential to reduce production cost, simplify scale-up, and reduce environmental impact. A variety of cell types are manufactured, ranging from high power 7.5Ah cells to high energy cell designs with 120Ah and more capacity. GAIA also has developed a battery management system based on master control and "slave" modules for electric and thermal management of individual Li Ion modules. This system is produced in limited numbers and used in complete batteries supplied by GAIA/LTC. In volume production, the cost of such a system is expected to be around $2 per cell in the battery.

Cell production capacity currently is approximately 4000Ah/day, or about 4 MWh/year, corresponding for example to 200 batteries of 20kWh for a small FPBEV. Based on the expected demand of niche markets, a 10-fold scale-up will be implemented at the Nordhausen facility within a year. A production plant representing another 10-fold scale-up could be built on site within less than 2 years if justified by demand.

Experimental transportation applications of GAIA Li Ion cell technology include a 2kWh/25kW battery for a Smart-based HEV, a 8kWh (45Ah cells) battery for a small series PHEV with 50 miles electric range, a similar battery for an experimental PHEV of an automobile manufacturer, and a 25kWh/200kg battery for a BEV converted from a Daihatsu small car by Innosys, a small Dutch company. All of these batteries use air cooling, considered adequate because of the very low impedance, low heat generation and good heat dissipation of GAIA cells. The Innosys BEV has a nominal range of 250km (about155 miles), with actual ranges falling between 150-300 km

(about 95-190 miles), depending on conditions and drivers. GAIA executive management foresee lifecycle cost competitiveness of volume-manufactured, Li Ion battery-powered small BEVs with conventional ICE cars in Europe.

GS Yuasa (GSY) was formed in 2004 by merging GS (formerly Japan Storage Battery Co.) and Yuasa, battery companies with similar history, size and battery products. A joint venture company with Sanyo produces small (type 18650) Li Ion cells for consumer electronic products but price competition is severe in that market. Li Ion technology in larger cell sizes has been developed, and 40 and 80 Ah cells are now in limited-scale production (roughly 1 MWh/year) for special applications, including leveling of electric train peak loads, automated guided vehicles (more than 1000 systems on order), stand-by power and other industrial applications. These cells use lithium manganese spinel-based positives and other established cell materials. Cells are assembled into multi-cell modules that include their own battery management units, with cells making up 90% of module weight. Air cooling is considered adequate for discharge rates up to 5C.

For the emerging power tool application of Li Ion batteries, GSY has developed technology based on lithium manganese spinel positives, polymer (gelled) electrolyte and laminated cell construction; cell life is limited to around 3 years because of slow electrolyte solvent loss through the plastic cell enclosures.

Under the Japanese NEDO (Government-funded) battery R&D program, GSY developed 10Ah Li Ion cells and a 0.3kWh prototype module for HEV applications. A battery using these modules would meet the program's power and energy density targets of 1800W/kg and 70Wh/kg, respectively; these targets are somewhat more demanding than the USABC targets, see Table 3-2. GSY also is participating in the new NEDO program to develop Li Ion technology suitable for PHEV applications.

Hitachi Vehicle Energy (HVE) was established in 2004 as a joint venture of Shin Kobe Electric Machinery, Hitachi and Hitachi Maxell, to develop, manufacture and market Li Ion batteries for HEV and other applications. The venture's Li Ion battery capability is based on the competency and technology established by Shin Kobe during the preceding decade which included development of Li Ion modules and batteries for BEV and HEV applications. One of the developments, the Li Ion battery used in BEVs based on the Nissan Tino compact van, has demonstrated more than 6 years of service life.

Efforts are ongoing at HVE to improve the power density and energy density of modules and batteries for light vehicle (electric bike and scooter) and HEV applications. HVE 1.8kWh Li Ion high power batteries currently are under test in 20 FedEx vehicles that use a HEV drive train developed by Eaton.

HVE's high power Li Ion technology is considered ready for industrialization. The key for commercial success will be the development of manufacturing processes capable of large scale production of high quality cells, modules and battery systems at competitive costs. HVE expects to see Li Ion batteries introduced in HEVs in 2008, with mass production (e.g., 100,000 system per year) to begin in 2010. In the meantime, battery cell materials, designs and manufacturing are being advanced.

Hitachi Vehicle Energy is a participant in the NEDO-sponsored program to develop a 3kWh Li Ion battery that meets the targets for the energy storage system of fuel cell vehicles. HVE also may participate in the new NEDO program to develop a PHEV battery, but the targets for that

program have not yet been set.

JCI-SAFT Power Solutions (JCS) is a joint venture of Johnson Controls, Inc., the world's largest manufacturer of lead acid automotive batteries, and SAFT, a French company with established leadership in nickel cadmium and nickel metal hydride industrial batteries, primary lithium batteries, and Li Ion batteries for defense and space applications. The mission of the joint venture is to develop and commercialize Li Ion batteries for a range of passenger car and heavy duty HEVs, BEVs and PHEVs.

The Li Ion technology base of the joint venture centers on established (NCA) positive and graphite negative electrode materials, electrolytes, separators, and the spiral winding manufacturing technique developed by SAFT over the last 15 years. Supported by world-class R&D, this development has yielded high-quality, mature cell and module technology in a range of cell sizes of both, high energy and high power designs that have been manufactured and tested in vehicles for 6-7 years by now. Many of the data in this report (see section 3.C) attesting to performance, long cycle and calendar life, and high safety levels of Li Ion technology were obtained by SAFT and provided to the Panel by JCS.

JCS is currently operating a pilot plant in Bordeaux (France) capable of producing 6 MWh/year of Li Ion cells in various capacities and power densities. Batteries made with cells and modules produced in this plant have been used in more than 60 experimental and demonstration BEVs that have accumulated an excellent safety record. Current applications include 23kWh batteries for 30 Renault Kangoo subcompact delivery vehicles converted to FPBEVs and PHEVs by Dassault, with a potential market of 60,000 such vehicles for the French Postal Service, and several prototype DaimlerChrysler vans converted to PHEVs with about 20 mile electric range. DaimlerChrysler just announced plans to fabricate about 20 Sprinter Li Ion battery powered PHEVs in the next phase of this program. Earlier in 2006, the joint venture was awarded a contract by USABC for improvement of high power Li Ion technology for HEV application.

JCS is in the process of negotiating a contract for production of high power Li Ion batteries for a major automobile manufacturer. This will require establishment of an automated battery manufacturing plant with a lead time of 1½ to 2 years from the go-ahead decision to validation of the process and product, indicating a possible 2008 start of volume production. Because of the high degree of automation of such a plant, it does not have to be sited in a low-wage country.

Through its affiliation with Varta, JCS also has NiMH technologies for application in ZEVs and near-ZEVs. Varta's 7Ah high power NiMH cell and module technology meets the performance and cycle life requirements for HEV applications, and its 25Ah and 45Ah technology has been used successfully in hybrid buses and, more recently, in prototypes of the DaimlerChrysler "Sprinter" PHEV-20 van. Both of theses technologies are in low volume production.

Kokam Co., Ltd. (Kokam) is a Korean company established in 1989 to develop and manufacture polyester film processing machinery. Drawing on its technology leadership and experience in film processing, Kokam developed a novel continuous process for production of Li Ion cells. This proprietary process involves lamination of positive and negative electrodes to a continuous polymer electrolyte-separator film, followed by a precision folding process and sealing of the resulting laminated cell stack into a metallized plastic enclosure. Due to this electrolyte and the very low resistance of the stacked-design cells, Kokam considers its technology to be safer than liquid-electrolyte cells. Performance of Kokam's cell technology equals or exceeds that of conventional spiral-wound cells; deep cycle life also is excellent, with more than 3000 cycles achieved at 80%DoD.

Kokam's cell production process is simpler and more flexible than conventional spiral winding of cell structures followed by electrolyte filling, and Kokam claims it can produce a new cell size in less than two months. With this flexibility, Kokam is able to rapidly utilize the excess capacity of existing Li Ion cell manufacturing plants for the production of a large variety of cells, from fractional Ah sizes to 240Ah, and in high energy as well as in high power designs. Kokam claims that its process is readily adaptable to different Li Ion chemistries, and a that new Li Ion chemistry promising exceptional levels of power, safety and cycle life is currently being adapted.

A wide range of consumer products applications is presently served by Kokam, and plans include establishment of technology and manufacturing capability for light vehicle, HEV and small BEV batteries. Prototype 30kWh FPBEV batteries comprising 100Ah cells and 5kWh PHEV batteries with 40Ah cells have been built as have 2.6kWh batteries for HEV applications. Because of the low resistance of Kokam's cells, even the high energy (FPBEV) design cell and battery has high power density.

Current cell production capacity is about 50 MWH per year, approximately the capacity of an economically viable, stand-alone cell manufacturing plant. A new plant of that size can be established in less than one year because of Kokam's vertical integration that includes fabrication of battery manufacturing equipment. Kokam America, a wholly owned subsidiary of Kokam, has taken steps to establish a cell manufacturing plant in the U.S., with the goal to have the plant on line in 2008 if justified by demand for the product.

Matsushita Battery Industrial Co. (Matsushita) headquartered in Osaka, Japan, is a major manufacturer of nickel cadmium, nickel metal hydride and lithium ion batteries marketed under the "Panasonic" name. Matsushita's strong corporate R&D was responsible for the development of the first generation of the NIMH battery technology for the Prius and Insight HEVs. Together with Toyota, the company owns Panasonic Electric Vehicle Energy (PEVE), the battery company manufacturing the very high power NiMH batteries for Toyota's HEVs.

Matsushita is a major manufacturer of type 18650 Li Ion cells for consumer products (400 million cells, or approximately 2000 MWh per year), and the company is now also manufacturing Li Ion cells for power tools. As part of NEDO's Japanese national program for development of Li Ion batteries for HEV applications, Matsushita met the program technical targets with cell technology based on NCA positives and an improved, partially graphitized negative electrode material. Matsushita's cells combine very high power density and good energy density. With some changes (including the positive material), this technology could become the basis for commercially produced Li Ion HEV batteries. These would be manufactured by an established HEV battery production company, presumably PEVE.

Litcel Co. (Litcel) is a small Japanese company, founded in 2000 and located in Fukuda-cho. Litcel is owned by Mitsubishi Motors Corporation (majority owner) and TDK Corporation. The mission of Litcel is to develop and manufacture Li Ion batteries for mobile and stationary applications. The Litcel technology uses a recently developed positive electrode composition (50% NCM/50% LMS) in combination with standard cell materials and spiral (oval) winding construction. Over the past five years, the technical team of Litcel has advanced this technology to the point (see Table 3-6) where it is believed to meet the performance, durability and safety requirements for BEV applications. Development work is continuing with the goal to increase cell and module energy densities (currently 115 Wh/kg) by 20% in the near term.

Construction of modules and batteries for BEV applications has been initiated, with focus on a

20kWh battery system for the recently announced "MIEV" minicar of Mitsubishi Motors. Litcel's current production capacity is about 60 batteries (~ I MWh) per year, planned to increase to 1200 batteries (~20 MWh) per year within two years.

NEC Lamilion Energy (Lamilion) is a small Japanese company established in 2002 and located in Kanagawa near Tokyo. Lamilion, now owned entirely by NEC, has as its mission the development and manufacture of Li Ion batteries based on the laminated-electrode/polymer electrolyte Li Ion cell technology originally developed at NEC. Among the advantages of Litcel's technology is simplified manufacturing and ease of thermal management of the flat cells. The technology uses lithium-manganese spinel (LMS) positive electrodes because of the high structural stability and potentially lower cost of LMS. The chemical stability against manganese dissolution has been improved through use of proprietary additives to the electrode and/or electrolyte.

The current focus of Litcel is the limited-scale manufacture of a Li Ion battery for evaluation and possible commercialization in the small R1e battery electric vehicle developed jointly by Fuji Heavy Industries (owners of Subaru) and Tokyo Electric Power Company (TEPCO). The R1e battery delivers about 9kWh, has a peak power of more than 60kW (90kW when fully developed), can be recharged to 80% in 15 minutes, and is expected to last 10 years or 200,000 km in deep cycling. Together with the projected battery costs and fuel cost savings, this is expected to make the battery and vehicle economically competitive in providing transportation services for TEPCO staff in the Tokyo metropolitan area.

Panasonic EV Energy (PEVE), jointly owned by Toyota (majority share holder) and Matsushita Electric Industrial Co., is the world leader in the manufacture of NiMH batteries for transportation applications. PEVE was formed in 1996 to manufacture and market NiMH batteries, originally for BEVs. The 95Ah NiMH cell technology, an early product of PEVE, established the technology's excellent reliability and durability in nearly 3000 FPBEVs produced by several major automobile manufacturers, largely in response to the California ZEV regulations (see also Section 6 of this report). PEVE also produced 28Ah NiMH cells and modules for Toyota's now abandoned eCom city electric vehicle. Production of the 95Ah and 28Ah NiMH technologies was discontinued by PEVE in 2003/04.

The PEVE plant in Kosai City, Japan, is the world's largest, fully automated manufacturing facility for NiMH HEV batteries. The plant's capacity has been increased several times and now enables module production for approximately 500,000 batteries per year, used in Toyota's HEVs and most of Honda's HEV products. In 2007, PEVE will add a new plant with an annual module capacity for 500,000 HEV batteries (approximately 750 MWh). According to PEVE, the costs of batteries produced in smaller volumes (e.g., 15-30k systems per year) are broadly consistent with the projections of the Panel's cost model, but mass production costs were not disclosed.

In parallel with NiMH battery production, PEVE and its owners are carrying forward development and engineering activities to further improve the technology, with emphasis on achieving higher power densities to reduce the minimum capacities -- and thus the costs -- of batteries capable of meeting the performance requirements posed by established and emerging HEV types and models. PEVE is collaborating with Toyota and Matsushita in Li Ion high power battery development and expects to become involved in Li Ion battery manufacturing once the technology is considered ready for commercial application in HEVs.

Sanyo Electric Co. (Sanyo) is the world leader in the production of NiMH cells for consumer

products, holding a 50% market share. On the basis of its commercial D-size NiMH cell technology, Sanyo developed several generations of spiral-wound cells for HEV applications. First generation batteries met peak power requirement for HEV applications but only at a 100% weight penalty over the generally accepted 50kg target for an HEV battery. Sanyo's 3rd generation NiMH technology has much higher power density that will enable a substantial cell and battery capacity reduction to meet the weight target. Further increases in cell and battery energy and power density, as well as improved life, are expected from introduction of Sanyo's "superlattice" nickel-based alloys as negative electrode materials.

Sanyo's HEV-type cell production capacity will soon reach 2 million cells per month, corresponding to an annual production rate of approximately 100,000 HEV batteries per year. Even at this rate, HEV cell production will make up not much more than 1% of Sanyo's total production of NiMH cells. Sanyo does not produce NiMH technology in the larger cell sizes that would be appropriate for PHEV or (FP) BEV batteries.

Sanyo also is the world leader in the production of small Li Ion cells for consumer products. From this technical basis, Sanyo has been developing Li Ion technology for HEV applications. The gravimetric power and energy densities of developmental high power Li Ion cells double NiMH cell performance while volumetric densities and shallow cycle life are comparable. Further gains are expected from continued development. Sanyo is prepared to make the large investments in mass production facilities once the technical and market prospects of Li Ion technology in the automotive market are sufficiently favorable.

F. Summary and Conclusions

The Panel's investigation of vehicle energy storage systems focused on batteries as the only viable energy storage option for zero and near-zero emission vehicles, at present and in the foreseeable future. The emphasis was on Li Ion technologies because of their rapid technical progress and excellent potential to meet the energy storage requirements for full (including fuel cell) hybrid, plug-in hybrid, and full performance battery electric vehicles. However, the Panel study also covered nickel metal hydride batteries because of their near term importance for HEVs (including fuel cell HEVs) and their potential for PHEV applications. Finally, it examined the status of ZEBRA (sodium-nickel chloride) and lithium-sulfur batteries because of their near and, respectively, longer term potential for FPBEV applications.

The investigations of the Panel established that battery technologies have advanced remarkably since the 1999-2000 review commissioned by the California Air Resources Board. These advances were, and still are, driven by several diverse but interrelated factors: the emergence of a substantial and growing market for hybrid electric vehicles, especially in the U.S.; the blossoming of lithium ion battery technology through discovery and exploitation of the extensive technical opportunities surrounding this "family" of batteries; and the resurgence of interest in battery electric vehicles under the double impact of escalating fuel prices and advancing battery technologies. The rapidly growing interest in plug-in HEVs is adding another incentive and challenge for the development of more capable batteries.

The main findings and conclusions of the Panel from assessing the technical and cost status and prospects of these battery types are summarized below, followed by some observations on the strategies and positions of battery and automobile manufacturers that bear on development and availability of batteries for ZEVs and near (including partial) ZEVs.

1. Panel Assessment

a) Nickel Metal Hydride Batteries

High power NiMH batteries designed for HEV applications are now mass-produced in Japan for a growing number and variety of HEVs. The performance (especially the gravimetric and volumetric power density) of the technology has been increased through several generations of cell and module design improvements, and batteries in the range of 1-3kWh now meet all performance requirements for full HEVs. The technology also appears to have sufficient shallow cycling capability and calendar life to last through manufacturers' warranty periods and for a nominal 10-year vehicle life. It is not yet clear whether the endurance of NiMH batteries can be extended to 15 years. To meet growing demand, the manufacturers' production capacities are being expanded by adding new plants with module capacities sufficient for up to 500,000 battery packs (complete systems) per year. These nearly fully automated plants reflect extensive manufacturing technology learning and represent large investments, likely to make it difficult for competitors to enter the market.

The biggest issue for the manufacturers and automobile industry users of high power NiMH batteries for full (including fuel cell) HEVs is their relatively high cost. While cost data were not made available by the manufacturers, we estimate on the basis of a simplified cost model developed by the Panel that such batteries cost approximately $1500/kWh to $1,000/kWh (100,000 to 1 million systems per year). This translates into a cost of about $2,000 to $1,300 for a compact HEV (1.3kWh) battery and $4000 to $2,500 for a midsize full HEV (e.g. 2.5kWh) battery. These costs make up much of the cost difference between presently marketed HEVs and their counterpart ICE vehicles, and they represent a strong motivation for manufacturers to seek battery cost reductions.

Higher battery power density permits the power and energy required by a full HEV to be delivered by a smaller and thus less expensive battery. However, because high power NiMH technology is getting close to the limits of power density, and since the costs of mass-produced NiMH batteries per kWh of capacity are unlikely to decline, the Panel concludes that reductions of HEV-design NiMH battery costs beyond incremental savings through the economies of mass production are unlikely. This is an important reason for the large current efforts to develop and introduce HEV-design Li Ion batteries that offer higher power densities and potentially lower costs (see below).

Medium energy/medium power NiMH battery technology is of possible interest for application in PHEVs with shorter (e.g., 10-20 mile) nominal electric range for which the technology can meet power and energy density requirements. PHEVs pose very demanding deep cycle life requirements that would have been considered beyond the capabilities of NiMH batteries five years ago. However, at least one manufacturer is claiming capability for 3000 deep cycles for his technology, and the results of ongoing PHEV-type battery cycling tests are confirming this claim. For all types of NiMH batteries, achieving the goal of a "vehicle lifetime" (10-15 year) battery is contingent on careful management of battery temperature (level and uniformity) and of battery charging. To reach a 15 year life may require materials advances to further reduce the already very low rates of negative electrode corrosion and hydrogen loss through cell walls.

The costs projected by the Panel's model for mass-produced medium energy NiMH batteries for PHEVs with 10 and 20 miles of nominal electric range are not much higher than the preliminary cost goals currently being considered for PHEV batteries. More importantly, for most of the foreseeable fuel and electricity price scenarios and vehicle efficiencies, the estimated fuel cost

savings realized by shorter-range PHEVs in comparison with their counterpart ICE vehicle exceed projected battery costs. The Panel's battery cost model also projects lower life cycle costs for shorter-range PHEVs than full HEVs. This finding appears to mitigate the concerns about unacceptably high costs of PHEV batteries mentioned by automobile manufacturers.

The Panel concludes that medium energy/medium power NiMH batteries appear to have reasonable prospects for meeting the technical requirements and cost constraints for PHEVs with relatively short nominal electric range. However, only a few small manufacturers of NiMH batteries have built PHEV-design NiMH batteries and demonstrated them in experimental PHEVs and the major battery and automobile manufacturers do not seem interested in this NiMH application. One reason may be that medium energy Li Ion batteries appear to offer better technical and cost potential for PHEV applications (see below).

High energy NiMH battery technology is no longer a target of development and possible cost reduction efforts because of the realization that such batteries are unlikely to meet the performance and cost targets for full performance battery electric vehicles. The Panel's review did not identify significant advancements in FPBEV-design high energy NiMH battery technology. The costs of such batteries in mass production would likely be even higher than those projected in 1999/2000, primarily because of the nickel price escalation in recent years. These costs exceed not only FPBEV battery cost goals but the value of the fuel cost savings achieved by BEVs in all currently envisioned scenarios. The Panel concludes that large weight and high costs are likely to limit the technical and market prospects of the large-cell, high energy NiMH batteries that would be appropriate for FPBEV applications.

b) Lithium Ion Batteries

High power Li Ion battery technologies have been developed by a number of prospective manufacturers in Asia, Europe and the U.S., among them major producers of small Li Ion cells for consumer applications who are aiming to enter the expanding markets for power tool and HEV batteries. The high power Li Ion technologies and production techniques of these manufacturers appear to be close to commercialization. It seems likely that one or more of these manufacturers will be the first to commercialize Li Ion batteries for HEV applications, in close collaboration with automobile manufacturers, probably in Japan. The Panel was led to believe that commercial introduction of Li Ion batteries in HEVs will occur in 2008. In view of the number and capabilities of the companies engaged, it seems likely that substantial competition will develop over time to drive Li Ion technology forward and costs down.

Several entrepreneurial organizations, some associated with larger companies, are targeting the same markets for their Li Ion technologies, and a number of smaller organizations are concentrating on development and limited production of high power cells for premium applications in the space, military and industrial fields. These developments have resulted in a variety of advanced Li Ion cell materials including nanostructured (highly disperse), doped lithiated iron phosphate positives and titanium oxide negatives, and new manufacturing techniques such as lamination of cells using polymeric electrolyte-separator films. Most of these technologies have reached the limited cell production and prototype battery levels, and several U.S. companies in this group have, or are closely associated with, Asian Li Ion cell manufacturing facilities. Whether any of these developers has the focus and resources to enter the market for HEV high power batteries is not clear at this time. As little as one year, but typically 2-3 years, were mentioned as the time required from a go-forward decision to establishment of a first production plant, assuming availability of the required technical and financial resources.

The Panel's model projects that in mass production the costs of HEV-design, high power Li Ion technologies could be lower than those of high power NiMH batteries for the same storage capacity, substantially lower on the more important basis of equal power capability. The introduction of Li Ion batteries for HEV applications thus could reduce the cost difference between HEVs and conventional vehicles. It also can be expected to assist and accelerate the development and introduction of Li Ion batteries for PHEVs and for FPBEVs.

Medium energy/medium power Li Ion battery technologies meeting the performance and life requirements for application in small FPBEVs and in PHEVs have been developed to the prototype and low volume production level in Asia and Europe but apparently not in the U.S. The developing companies include several that are also active in high power Li Ion battery development and that use the same, well established Li Ion cell chemistries and manufacturing methods. A somewhat special role is played by JCI-SAFT Power Solutions, the joint venture between SAFT, a world leader in larger Li Ion cell and battery technology, and JCI, the world's largest battery company. The joint venture appears committed to the commercialization of Li Ion batteries not only for HEV but also for PHEV and small FPBEV applications, and its technology has established very long calendar life and the capability for more than 3000 deep-discharge cycles.

A few Li Ion battery developers are engaged exclusively with medium power/medium energy technologies. Driven by the need for the lowest possible costs per kWh of storage capacity to meet the cost constraints for PHEV and FPBEV batteries, these companies typically use lower cost positives such as NCM or LMS modified to increase stability, cell fabrication methods based on lamination and z-folding of electrodes, and lower-cost soft cell enclosures. While there are still questions whether the cycle and calendar life of these technologies can meet requirements for BEV and PHEV applications, at least one of the manufacturers (Kokam) claims a life of more than 3000 deep cycles and ten years, characteristics that would meet the requirements for BEV and even PHEV applications. Achievement of very long cycle and calendar life for all types of Li Ion batteries requires appropriate controls that keep average temperatures below approximately 45℃ and limit the time that batteries spend at high states of charge.

The costs projected by the Panel's model for PHEV-10 and PHEV-20 batteries are below the preliminary goal and below the NPV of fuel cost savings in all but the least favorable scenario. Further, the incremental cost of these batteries over HEV batteries is projected to be $1000 or less in mass production. Because of their projected propulsion energy cost savings, PHEVs using such batteries would have lower life cycle battery plus energy costs than HEVs. Even for the PHEV-40, projected Li Ion battery cost is comparable to, or less than, fuel cost savings except in the least favorable scenario.

The Panel concludes that medium energy/medium power Li Ion battery technologies have good prospects to meet the technical requirements and cost constraints for applications in PHEVs and small FPBEVs. Several fleet demonstrations of such vehicles, initiated or planned in Europe and Japan (see Section 6 A below), are expected to yield important information not only on performance, reliability and life expectancy of medium energy/medium power Li Ion batteries but also on life cycle ownership costs of PHEVs and small FPBEVs powered by such batteries. If these demonstrations establish technical and economic viability of Li Ion batteries for these applications, early commercial production of batteries could be established by several manufacturers beginning around 2009-2010.

The nature and variety of the candidate Li Ion technologies now being developed hold out considerable promise for availability of increasingly capable and lower cost batteries for future ZEV and near-ZEV applications.

High energy Li Ion battery technologies in cell sizes suitable for powering of medium- and larger size, full performance BEVs experienced a period of active development in the 1990s but have not received much attention since then, and their costs remain high. However, should a broad interest in FPBEVs arise again because of changing economic, energy-strategic and/or environmental conditions and concerns, the Panel concludes that many of the advances being achieved in medium energy and high power Li Ion technologies should be transferable to result in better-performing and lower-cost high energy Li Ion technologies.

Li Ion battery safety is an important concern of automobile manufacturers for all automotive applications of Li Ion batteries, and a key objective of battery developers. Under simulated abuse test conditions (excessive overcharge and/or heating; massive shorting), Li Ion cells can rupture due to evolution of internal gas pressure and vent flammable gases that can be ignited by sparks. However, cell and complete battery abuse tests by SAFT and other prospective manufacturers have demonstrated safe behavior, and some of the newer Li Ion chemistries are even more tolerant of overcharging and/or excessive heating.

The Panel observes that safety systems are part of candidate Li Ion battery technologies for ZEV and near-ZEV applications. These systems utilize several independent control variables and strategies on the cell, module and battery levels to prevent unsafe conditions such as those that caused overheating and fires of a number of laptop batteries. Li Ion batteries have proven safe under the operating conditions maintained in U.S. and worldwide field tests and demonstrations of several hundred BEVs and HEVs during the past ten years. The Panel concludes that recent and emerging advances in battery chemistry and control strategies can be expected to further reduce the already small safety risks with Li Ion batteries for HEV, PHEV and BEV applications.

Longer Term Outlook. Beyond the recent and prospective nearer-term advances discussed in subsection 3.C, it seems very likely that full exploitation of presently known and yet to be discovered advances in materials, chemistry and manufacturing techniques will result in Li Ion battery technologies that combine substantially higher performance with longer life and yet more robust safety at lower costs. In mass production, these costs should permit payback through fuel cost savings for PHEVs and HEVs but also for FPBEVs, especially if fuel costs continue at high levels and vehicle technologies keep advancing. However, realization of the ultimate performance and cost potential of the Li Ion "family" of battery chemistries for ZEV and near (including partial) ZEV applications is likely to take another decade

c) Other Candidate Batteries

The ZEBRA high temperature (~300°C) battery offers a number of attractive characteristics for vehicle applications but, compared to Li Ion and NiMH technologies, is handicapped by relatively low power density. This limitation appears to exclude the battery from HEV and PHEV applications. Automobile manufacturers are concerned also about the need to operate ZEBRA batteries at high temperature. However, ZEBRA batteries meet the performance requirements of smaller BEVs, and effective thermal insulation has permitted ZEBRA batteries to sustain operating temperature for periods up to 2 weeks without connection to a source of power. A number of successful applications are demonstrating the practicality and durability of ZEBRA batteries in small BEVs and heavy duty vehicles (including hybrid buses) driven regularly on

public roads.

ZEBRA batteries are now produced in a fully integrated manufacturing plant at costs well below those of other candidate BEV batteries manufactured in similar limited volumes. Its material cost advantage will make ZEBRA batteries the lowest-cost high energy battery for FPBEVs also in early commercial and mass production. MES-DEA, the Swiss exclusive manufacturer of ZEBRA batteries, is currently taking steps toward these production capacities. The Panel believes, however, that large-scale introduction of the ZEBRA battery in ZEVs will be contingent not only on the battery's technical characteristics and cost but on acceptance of the technology by automobile manufacturers.

2. Industry Strategies and Perspectives

The Panel's interactions with battery and automobile manufacturers identified strategies, concerns and recommendations that, in the Panel's view, deserve consideration when contemplating measures to foster the development and availability of batteries for ZEV and near ZEV applications.

a) Battery Manufacturers

As expected, the strategies and positions of the manufacturers and/or developers of candidate ZEV/near-ZEV batteries depend on their current technology thrusts, capabilities and market positions. Mass-manufacturers of NiMH high power cells and modules for HEV batteries are focused on technology cost reduction and involved in capital-intensive production capacity expansions that assume increasingly competitive HEV mass-markets exceeding 1 million vehicles by 2010. FPBEVs are not a target of their NiMH battery technology development efforts and they consider PHEV battery requirements insufficiently defined to permit an assessment of NiMH technology and market prospects for this new application. Few development activities appear underway to explore whether NiMH has technical potential for PHEVs.

The mass-manufacturers of Li Ion cells for consumer products are now engaged in the development of established Li Ion chemistries for HEV applications, with commercialization possible as early as 2008 if Li Ion technology is perceived to meet all requirements including safety. Given the number of competent manufacturers (largely in Asia), a vigorous market competition of technologies and manufacturers can be expected to emerge. The same manufacturers do not appear to be pursuing development of Li Ion batteries for FPBEVs or PHEVs. Most of them stated that currently projected Li Ion battery costs would make FPBEVs too expensive, and government financial incentives are considered unlikely to induce a large number of customers to buy vehicles of limited range. There is also concern about high costs of Li Ion batteries for PHEV applications. However, the major impediment to engagement of these companies in developing Li Ion batteries for PHEVs appears to be that the battery requirements for this new application are insufficiently defined by automobile manufacturers, thus making it difficult for battery manufacturers to establish development targets and programs. Battery manufacturers are looking for a clear interest and active involvement of automobile manufacturers in PHEVs before becoming engaged in PHEV battery development.

Several smaller organizations in Europe and Japan have been developing medium and high energy Li Ion technologies for possible ZEV and near-ZEV applications. Their strategy appears to be the pursuit of limited-volume applications and markets that may be emerging, especially in small BEVs (including FPBEVs) and more recently also in PHEVs. The perception is that inner city operation of these vehicles as ZEVs could well become a market, and European automobile

manufacturers are thought to favor PHEVs over HEVs for that reason. These organizations hold the view that Li Ion-powered PHEVs and small (FP) BEVs will be able to attain life cycle cost competitiveness with conventional vehicles in urban fleet applications, but it was left unclear which production volumes will be needed to achieve competitiveness. A few of them have established prototypical cell and module technologies as well as sufficient cell production capacities for hundreds to a few thousands of 10-25kWh batteries per year, sufficient for demonstration fleets. Although most of these organizations are owned by large companies, the resources being invested in development and demonstration of batteries for PHEVs and small (FP) BEVs are still very modest.

Investments by all types of Li Ion battery manufacturers in PHEV and small BEV batteries are likely to increase, possibly substantially, once automobile manufacturers commit resources and plans to the development and introduction of such vehicles. While the commercial prospects of (FP) BEV- and PHEV-design Li Ion technologies still seem unclear, several manufacturers noted that development of such technologies was likely to benefit from supported demonstration programs and/or financial incentives.

b) Automobile Manufacturers

Most major global automobile manufacturers have in-depth battery expertise and extensive capabilities in the evaluation, integration and testing of batteries in BEVs and HEVs. These capabilities are now engaged in the extensive efforts of automobile manufacturers to evaluate and advance the HEV design Li Ion battery system technologies that are likely to be commercialized within the next few years. Confidence in the readiness of Li Ion batteries for deployment in mass-produced vehicles is likely to grow with the experience from Toyota's "Vitz" minicar that uses a small Li Ion battery to perform the automatic start function of that ICE vehicle.

Based on their experience with the FPBEVs developed, constructed and sold or leased under the California ZEV initiative, most automobile manufacturers continue to hold the view that FPBEVs will remain niche vehicles, in large measure because of the current and foreseeable large weight and high costs of the required batteries. No efforts to advance battery technologies for FPBEV applications are being supported by them at present. It remains to be seen whether recent announcements by Mitsubishi and Nissan of plans for introduction of BEVs are going to stimulate efforts to develop Li Ion batteries that meet the requirements of these vehicles.

The prospects of PHEVs also were judged negatively by most major automobile manufactures until recently, largely because of concerns about battery costs and cycle life. However, several manufacturers are now active in modeling, designing and evaluating various PHEV architectures and technologies, with consequent attention to candidate battery technologies and their prospects. In the U.S., an effort sponsored by DOE and supported by USABC is now underway with automobile industry expert participation to establish PHEV battery performance, life and cost targets for a planned R&D program, and in Japan NEDO is launching an initiative to develop PHEV batteries with involvement of leading Li Ion battery developers. These initiatives and automobile manufacturers' initiatives such as GM's recently announced plans to offer a PHEV version of the Saturn VUE HEV and to launch the "Volt" PHEV if suitable Li Ion batteries become available are the signals needed by the major battery manufacturers to become engaged with their own resources in the development and manufacture of batteries for PHEVs.

4. Hydrogen Storage

A. Background and Introduction

Storing sufficient hydrogen on a vehicle to power it for adequate distance, safely, and at reasonable cost, without an excessive weight penalty has been and remains a serious challenge for the vehicle industry and its suppliers. All of the major potential manufacturers of fuel cell vehicles interviewed by the Panel highlighted hydrogen storage to be among the two or three areas of greatest concern, including all of the other cost and technology challenges associated with developing fuel cell systems for consumer vehicles; one major manufacturer identified it as the single greatest challenge.

Unlike other technologies being pursued in support of ZEVs, hydrogen storage technologies have advanced relatively little in recent years. The primary system advancements have been in the area of improving compressed gaseous hydrogen storage and, to some extent, improving liquid hydrogen storage. There are, in addition, many alternative storage concepts being pursued very recently (the last 3 or 4 years) at the research level, and a couple of concepts (e.g., metal hydrides and carbon nanotubes) which have been investigated at relatively low levels of effort for many years. However, as far as could be determined, none of the recent or earlier concepts has reached the point of representing realistic complete system alternatives.

It is also known that several major automobile manufacturers are researching alternative hydrogen storage technologies, although none seem to have progressed to the point of suggesting that they have developed viable complete systems. Further, as far as the Panel could determine, none of the manufacturers have plans for other than liquid or compressed gaseous storage for their hydrogen-fueled vehicles for the foreseeable future.

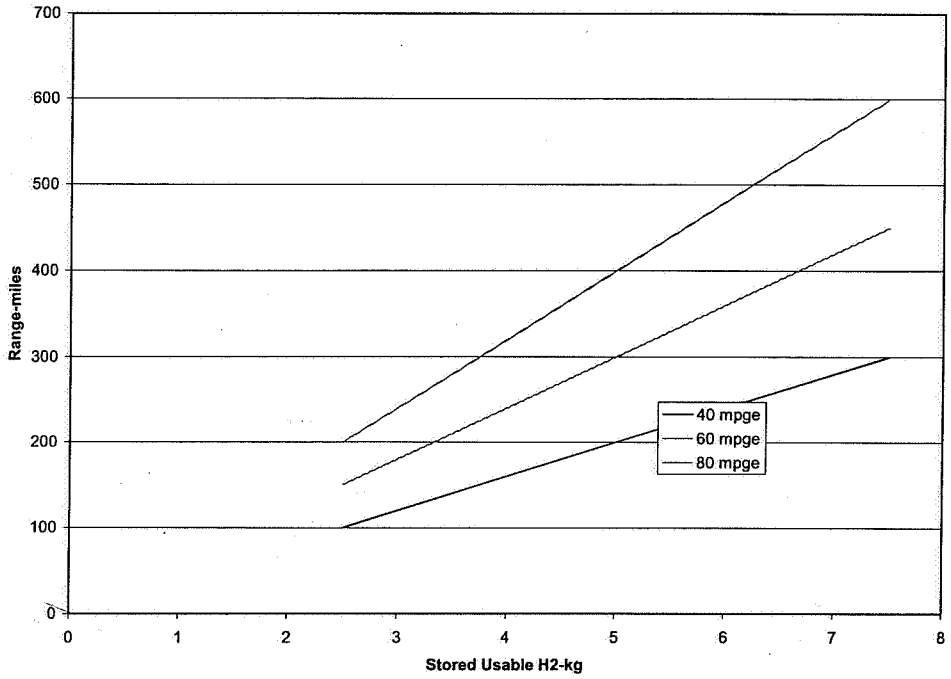
This apparent lack of major accomplishments and industry involvement is not too surprising since it has been only in the last 4 or 5 years that onboard hydrogen has begun moving towards industry acceptance as a workable transportation fuel. As a result, almost all visible work in progress for hydrogen storage concepts, other than liquid and compressed gas, is the result of efforts sponsored by the Department of Energy.

Range is a key vehicle performance attribute and virtually all vehicles sold in the United States for many years have had a normal operating range between fuel refills of 300 miles or more. Working closely with industry, the Department of Energy (DOE) has selected hydrogen storage parameters corresponding to a 300 mile range for its 2015 targets. Designing for any range significantly less than 300 miles, except for some niche applications, is not likely to result in a successful consumer vehicle.[1] Presumably, since the automobile industry was very much involved in setting all of the hydrogen storage targets for 2010 and 2015, none of the manufacturers seem to be pursuing significantly different targets.

The mass of hydrogen to be stored to meet any design range depends on the fuel efficiency of the vehicle in question as the range of a vehicle is equal to the vehicle efficiency in miles per kilogram multiplied by the usable kilograms on board the vehicle. This is illustrated in Figure 4-1.

[1] Since the first generation of fuel cell vehicles is likely destined for controlled fleets and other niche applications, a range as low as 200 miles might be acceptable for an interim period but a range of 300 miles or more is necessary if fuel cell vehicles are to be competitive with conventional ICE vehicles.

Figure 4-1 Vehicle Range



mpge – fuel mileage converted to equivalent miles per gallon of gasoline

The National Renewable Energy Laboratory (NREL) has finished the first year of a five year DOE demonstration program currently involving over 60 hydrogen-fueled fuel cell vehicles. Most of these vehicles use 350 bar compressed hydrogen storage with only 4 using 700 bar and only 4 using liquid hydrogen storage. From this and other limited test results from existing experimental fuel cell vehicles currently being demonstrated, a reasonable efficiency estimate is about 40 to 60 miles per kg of hydrogen[2].] Thus, for a 300-mile range, fuel cell vehicles will probably need about 5 to 7.5 kg of onboard usable hydrogen. The focus of hydrogen storage efforts over the past several years has been finding sufficient space to carry a minimum of 5 kg of hydrogen onboard a vehicle while minimizing the weight increase and doing so at reasonable cost.

B. Physical Characteristics of Hydrogen and Resulting Storage Considerations

Table 4-1 shows a comparison of some selected properties of hydrogen as compared to other fuels.

[2] Note: one kg of hydrogen has approximately the same fuel energy as one gallon of gasoline.

Table 4-1: A Comparison Of Selected Fuel Properties

Fuel		Hydrogen	Natural Gas	Ethanol	Gasoline*	Diesel*
Formula		H_2	CH_4	C_2H_5OH	C_4 to C_{12}	C_6 to C_{25}
For Liquid @ I Atm.						
• **Density**	Kg/L	0.071	0.72	0.79	0.74	0.85
• **Boiling Temp.**	℃	-253	-162	78	27-225	188-343
• **Heat of Vap.**	Kcal/kg	110	122	210	83	56
For Comp. Gas - 25℃						
• **Density**	Kg/L					
o **350 Bar**		0.023	0.23			
o **700 Bar**		0.04				
• **Energy Density**	Kcal/L					
o **350 Bar**		650	2700			
o **700 Bar**		1125				
Mass LHV	Kcal/kg	28,600	11,900	6,400	10,300	10,100
Vol LHV	Kcal/L	2,000	8,500	5,050	7,500	8,500
Autoign. Temp.	℃	~550	~540	~423	~257	~316
Stoich. A/F	By weight	34.3	17.2	9	14.7	14.7
Flam. Limits	% By Vol.					
• **Lower**		4	5	4.3	1.4	1
• **Upper**		75	15	19	7.6	6

* Gasoline and Diesel are both blends with properties depending on the blends and additives. Approximate average properties are given.

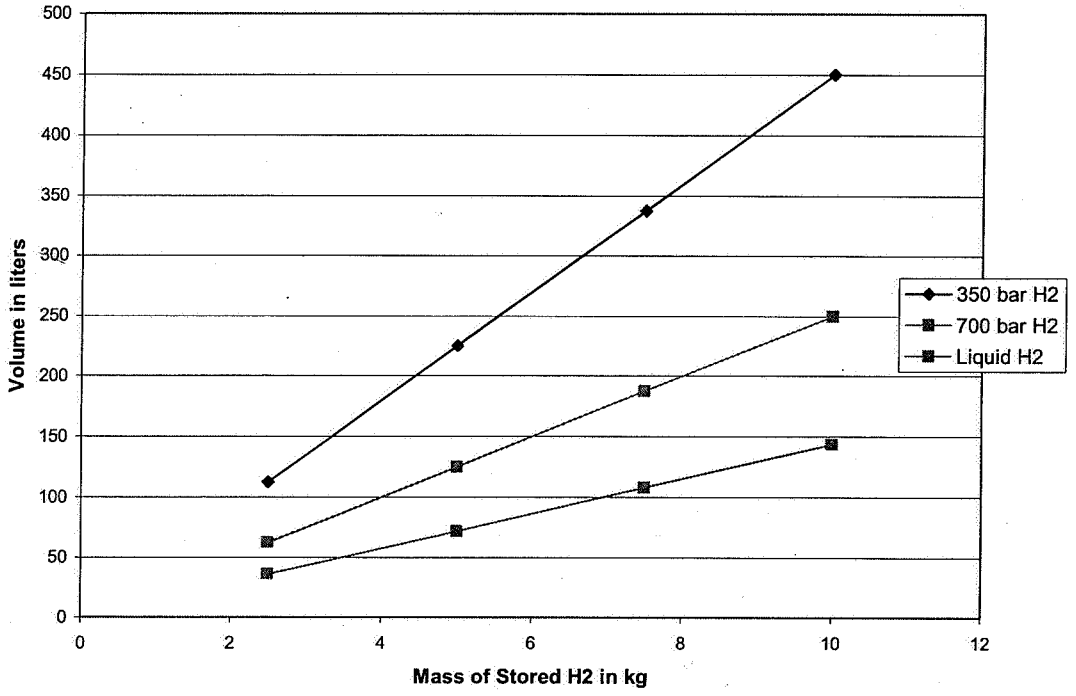
Hydrogen has higher energy per unit of mass than any alternative fuel being considered for automobiles. In fact, it has approximately three times the specific energy (energy per unit of mass) of gasoline and five times that of ethanol. Unfortunately, it also has the lowest energy density (energy per unit volume) of any of the fuels considered. For example, in liquid form, it has less than one-third of the energy per gallon compared to gasoline. In other words, for equal fuel energy, the internal volume of a liquid hydrogen tank would have to be about three times the volume of the gasoline tank but the hydrogen contained in the tank would weigh only about one-third as much as the gasoline. Note that the actual hydrogen tank volume would be even greater relative to the gasoline tank since a very sophisticated method of insulation around the contained hydrogen would be necessary to prevent excessive boil-off from the hydrogen at -253℃ (-423℉).

The volume situation is even worse when the hydrogen is in compressed gas form instead of liquid form. At 350 bar (about 5000 psi), for example, the required volume for a given hydrogen storage mass increases by a factor of about 2.5 compared to liquid hydrogen. That means that, compared to gasoline, for the same fuel energy the required internal volume would be about seven times greater. Further, to contain the high pressure, the tank will have a required wall thickness which will add significant volume and weight to the tank system. Increasing the storage pressure to 700 bar increases the energy density (although not quite double due to non-ideal behavior of hydrogen gas at this pressure) compared to 350 bar. However, the additional

tank wall thickness to contain the higher pressure results in a reduced internal volume for a given system (outside) volume, or an increased system volume for a given internal volume. Even at this pressure, the required internal volume would still be about 40% greater than liquid hydrogen and about 5 times that of gasoline for the same fuel energy. Figure 4-2 shows the internal volume required for these storage options.

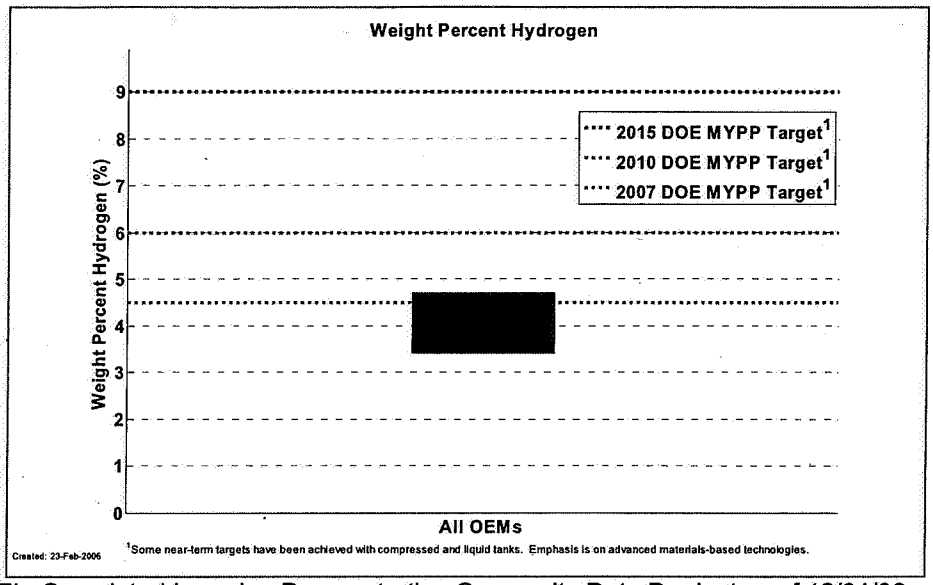
Corresponding to the increased volume required for either liquid or highly compressed hydrogen is increased weight. The weight penalty due to the larger size is further increased due to the need to highly insulate the cryogenic liquid hydrogen or safely contain the high pressure gas.

Figure 4-2 Required Internal Volume for Stored Hydrogen



Hydrogen storage systems employed on the current fleet of NREL/DOE fuel cell vehicles involved in the demonstration/infrastructure program have a hydrogen weight percentage (weight of hydrogen divided by weight of the storage system) of about 3.5% to 4.6%. Figure 4-3 shows the composite weight fraction of hydrogen data compared to DOE targets.

Figure 4-3 WEIGHT PERCENTAGE HYDROGEN



Source: NREL, Completed Learning Demonstration Composite Data Product as of 12/01/06

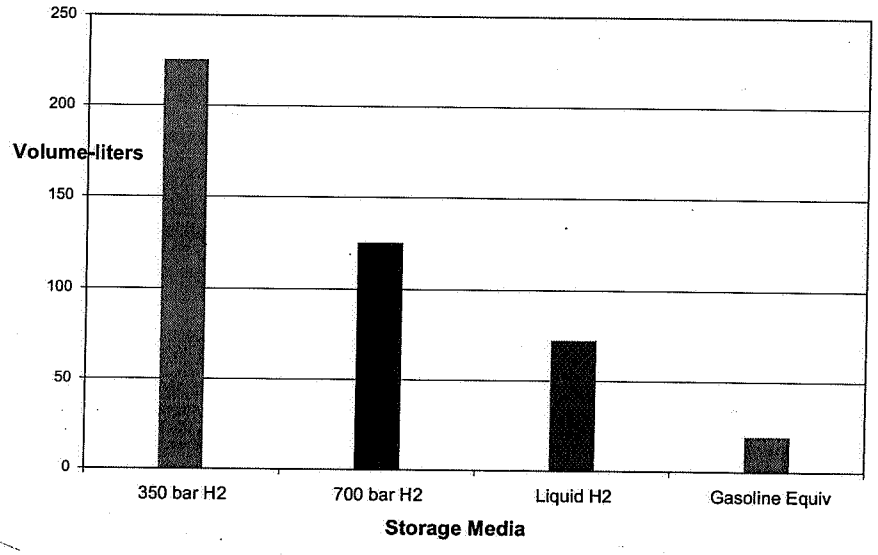
The systems included in the composite data actually store from somewhat less to somewhat more than 5 kg of hydrogen. If normalized to contain 5 kg of hydrogen, these systems would weigh between 110 and 140 kg.

C. Characteristics and Issues of Various Candidate Technologies

At present, only compressed gas and liquid storage are being used by the OEMs in their hydrogen-fueled vehicles. In fact, as far as is known, only BMW is using liquid hydrogen and that is for ICE vehicles. All of the other OEMs visited by the Panel use compressed gas storage, at either 350 bar or 700 bar storage pressure, for all of their fuel cell vehicles including buses and personal vehicles.

Volume requirements are clearly important issues for any type of hydrogen storage as compared to liquid fuels. For example, vehicle fuel efficiency and design range will determine the necessary amount of hydrogen to be stored onboard the vehicle. However, most OEMs seem to be targeting about 5 kg. This amount of onboard storage would require internal volumes of about 225 liters for 350 bar compressed hydrogen, about 125 liters for 700 bar compressed hydrogen, and about 72 liters for liquid hydrogen. These volumes are in sharp contrast to about 19 liters, for the same total fuel energy, for gasoline storage. This is illustrated on Figure 4-4. It should also be noted that for both liquid and compressed gas hydrogen, the external volume of the storage tank is considerably greater than the internal volume, especially for 700 bar.

Figure 4-4 Minimum Internal Volume for 5 kg of H2 Using Various Storage Media



Considerable research, funded both privately and by governmental agencies (mostly DOE) is continuing for alternative means of storing on-board hydrogen. These alternatives include novel concepts such as chemical storage, carbon-based materials, high surface-area sorbents, and metal hydrides as well as cryo-compressed gas. Some of the specific technologies being funded by DOE are listed below:

1. Reversible complex metal hydrides
2. Ionic liquid media
3. Binary clathrate hydrates
4. Metal-assisted nanostructured carbon
5. LiNH2 and related compounds
6. Boron nanoclusters

Many of these various hydrogen storage media being studied have the potential for absorbing and releasing relatively high weight fractions of hydrogen. However, essentially all are in research phase activities, too early for system projections. A few alternatives are briefly described below.

Metal hydrides.—The DOE hydrogen/system mass storage fraction targets of 6% (2010) and 9% (2015) are very ambitious. To reach these targets with metal hydrides, the bonding between hydrogen and the storage chemical specie must be stronger than between two hydrogen atoms. On the other hand, to achieve a rapid release of the hydrogen from the chemical specie suggests weak bonding. Using innovative approaches involving nanostructure to increase sorption rate while simultaneously decreasing desorption temperatures, researchers are achieving promising results.

Ionic liquid media.—Materials such as ammonia Borane, NH_3BH_3, contain relatively high weight fractions of hydrogen; in this case, 16.9%. Partial dehydrogenation can be thermally induced in

solid state but more useful and controllable reactions can be obtained in a solution. The volatile organic solvents traditionally used are not suitable for storage. Research is being conducted to use ionic liquids to induce dehydrogenations at lower temperatures with better controllability.

Binary clathrate hydrides.—Clathrate hydrides are inclusion compounds where cages formed by a hydrogen-bonded water network accommodate "guest" molecules. It was demonstrated that hydrogen molecules can be stored in binary H_2/THF clathrate hydrides at much lower pressures than in pure hydrogen hydrates. Hydrogen storage is completely reversible in these materials, thus potentially offering advantages not found in other classes of materials.

Boron nanoclusters.—Boron is lighter than carbon and forms many compounds with high hydrogen weight fraction. A hypothesis being pursued is that at certain length scales, the structural units in certain boron-rich solids can be reversibly hydrogenated in the presence of appropriate catalysts to form boranes and/or carboranes.

There are also many funded studies focused, not on specific materials, but on better fundamental understanding of hydrogen absorption and release by various classes of materials. Based on these studies, several of the materials appear to have the potential for increasing hydrogen weight fraction capabilities well above those for compressed hydrogen. However, it is not clear that a complete storage system would offer a cost or weight advantage. It will require much additional work before potential system advantages can be ascertained.

Little was learned about any success that OEMs might be having with alternative means of hydrogen storage such as metal hydrides, carbon nanotubes, or liquid form hydrogen carriers. Most, if not all, of the OEMs are known to be looking at these alternative storage technologies but since all (except BMW) are currently using compressed gas storage, it is obvious that as yet there is no better alternative.

DOE prepared a table showing, mostly qualitatively, the expected pros and cons of some of those alternatives. Comments from that DOE table are reproduced in Table 4-2.

Table 4-2: Alternative Hydrogen On-Board Storage Systems

Storage Technology	System Status	Advantages/Disadvantages
Chemical hydride	1.6 kWh/kg, 1.4 kWh/L, $8/kWh	√ Low pressure x Low cost, energy-efficient regeneration processes have not been developed x By-product removal
Complex metal hydride	0.8 kWh/kg, 0.6 kWh/l, $16/kWh	√ Low pressure √ Reversible H_2 uptake and release x Insufficient storage capacity at practical temperature and pressure
Liquid hydrogen	2.0 kWh/kg, 1.6 kWh/L, $6/kWh	√ Lowest capital cost √ Highest gravimetric & volumetric capacities x Most energy intensive Boil-off requires venting, and presents an energy penalty and potential safety hazard
10,000 psi compressed Hydrogen tanks	1.9 kWh/kg, 1.3 kWh/L, $16/kWh	√ Near-term solution to hydrogen storage √ Most energy efficient method to densify H_2 x High pressure
5,000 psi compressed Hydrogen tanks	2.1 kWh/kg, $12/kWh	x Cost is high due to high pressure containment materials

Department of Energy 2010 and 2015 System Goals	
Year 2010	Year 2015
• 2.0 KwH/kg (6 wt %)	• 3.0 kWh/kg (9 wt %)
• 1.5 kWh/L	• 2.7 kWh/L
• $4/kWh	• $2/kWh

Source: U.S. Department of energy, Hydrogen, Fuel cells and Infrastructure Technologies Program, 2003

It should be noted that "system status" does not refer to the actual commercial status of these technologies but refers to projections based on many assumptions.

D. Areas of Concern For On Vehicle Storage of Hydrogen

1. Volume

As noted earlier, compressed or liquid hydrogen will require substantially greater volumes than gasoline or diesel fuel to provide sufficient range between refills. Indeed, this will be true even if DOE targets for 2015 are achieved. Finding available space for the larger volumes will be less of an issue when new platforms are designed for fuel cell vehicles. However, for the first few generations of fuel cell vehicles, it is unlikely that most manufacturers will make the huge investment required to produce new platforms for relatively small numbers of vehicles. The high mass energy content of hydrogen and the expected high fuel efficiency of fuel cell vehicles somewhat alleviate the hydrogen storage problem, but it is still likely that a minimum of 5 kg will be required for a 300-mile design range. Even stored as 700 bar compressed hydrogen, about 33 gallons of internal storage volume would be needed with current technologies as compared to less than 10 gallons for a gasoline-fueled vehicle achieving around 30 miles per gallon or only about 5 gallons for a gasoline-fueled HEV achieving around 60 miles per gallon.

2. Weight

Current technology for compressed hydrogen yields a weight fraction (hydrogen/storage system) of around 4% as compared to DOE targets of 6% by 2010 and 9% by 2015. At 4%, the storage system to contain 5 kg of compressed hydrogen would weigh about 125 kg. This represents a very large weight penalty compared to the few kilograms required for a sheet metal or plastic gasoline tank. This problem is compounded by the lack of a universal and accepted procedure for certifying compressed hydrogen tanks for personal vehicle applications. The present procedures for certifying non-vehicle storage tanks to ASME standards apparently require testing to burst pressures of 4.5 times the maximum design operating pressures. By comparison, most hydrogen pressure tanks currently being used on fuel cell vehicles are burst tested to less than 2.5X. If higher burst pressures are ultimately required, tank weights will increase even more making it even more difficult for vehicles to accommodate.

3. Cost

At this time, both the materials and procedures for producing the high-pressure tanks are very expensive. For example, tens of kilograms of carbon fibers, at current costs of $25 to $30 per kilogram, are used in 5 kg capacity pressure tanks. Further, the procedures for winding the fibers, applying the epoxy bonding materials, and curing are slow and essentially one-of-a-kind procedures. Of course, this is to be expected at this point in time since they are indeed almost one-of-a-kind production runs. The point is that current costs for tanks, which is in the range of $50 to $100 per kWh, while certainly not representative of mass production costs, are thousands of dollars per tank. Even with mass production, to reach DOE cost targets of $4 per kWh of stored hydrogen by 2010 and $2 by 2015 will require significant "breakthroughs" if the technology of choice is compressed gas storage.

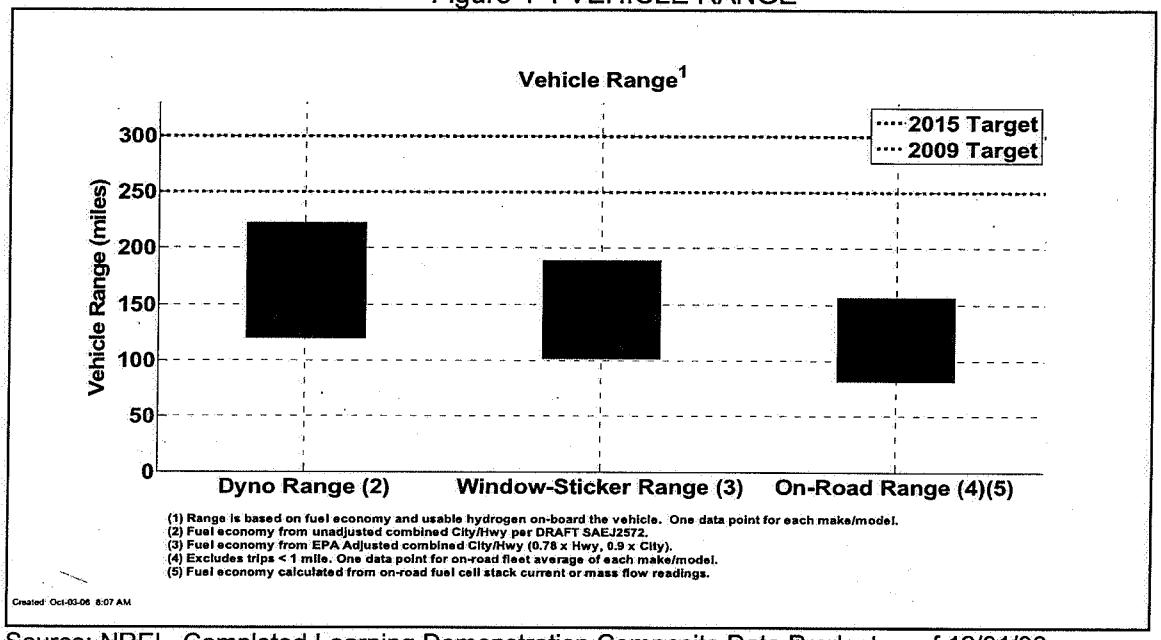
Even if the DOE targets are met, the storage system costs for 5 kg of hydrogen would be over $650 in 2010 and over $325 in 2015. These costs while far less than current hydrogen storage costs would still represent an incremental cost increase compared to most current gasoline or diesel storage systems. Clearly, if DOE targets are not met, onboard hydrogen storage could be a significant factor in the consumer price of hydrogen-fueled vehicles.

Since the boiling temperature of liquid hydrogen at atmospheric pressure is about –253℃ (–423℉), extensive insulation is required. The insul ation not only adds significantly to costs, it also increases the volume required for a given mass of hydrogen storage. In addition, at such deep cryogenic temperatures, there are many materials limitations essentially excluding most materials currently used in automobile manufacturing. As a consequence, current liquid hydrogen storage technology is very expensive.

4. Vehicle Range

A range limitation of hydrogen-fueled vehicles is a major concern of essentially all of the major vehicle manufacturers. Consumers have become accustomed to vehicles which can be driven 300 miles, or more, between fueling stops. Vehicles which cannot at least approach the 300 miles are likely to be considered less desirable compared to conventional-fueled (gasoline or diesel) vehicles. Since the hydrogen-fueled vehicles are also likely to be more expensive, the reduced range would clearly add to the difficulty of getting beyond government and fleet sales. Figure 4-4 shows the composite range data for the DOE/NREL program previously discussed and illustrates that none of the 60+ vehicles being monitored has an actual on-road range approaching 200 miles.

Figure 4-4 VEHICLE RANGE



Source: NREL, Completed Learning Demonstration Composite Data Product as of 12/01/06

5. Safety

The ability of the storage system to safely contain the hydrogen is a major concern. In the case of high pressure gaseous storage systems, this means primarily insuring that the tank will not fail under normal operating conditions for the life of the vehicle. However, it also means that only negligible amounts of hydrogen will diffuse through the walls of the tank or leak from the valves and fittings bonded to the tank. It also means that the tank must not fail catastrophically in the event of severe collisions, fires, and even bullets from firearms penetrating the tanks. In addition, it must be possible to refuel the tanks with no danger to the person performing the refueling and no significant leakage of hydrogen. At present, some procedures for testing the tanks have been established through cooperative efforts of DOE, vehicle manufacturers, tank developers, and various other groups and agencies. In addition, apparently safe interfaces between refueling stations and vehicles have been developed along with protocols for conducting refueling operations. However, there are as yet no international or even national codes and standards for these devices and procedures.

Safety issues are different with other means of onboard hydrogen storage such as liquid storage or storage in solid or liquid materials that can absorb and release hydrogen. Of these, only liquid hydrogen storage is developed to the point where its use in early generation vehicle applications seems likely.

Safety issues with liquid storage are generally different, but just as challenging, when compared to compressed gas storage. Liquid hydrogen in the tank is stored at near-atmospheric pressure so, if the supporting system is operating properly, containing high pressures is not a factor. However, the liquid at –253℃ can be extremely haza rdous. Even air will liquefy if it comes into contact with surfaces at this temperature. Further, the liquid stored in the tanks is at, or very close to, saturation. This means that any heat absorbed by the liquid by transfer through the

container walls or connecting wires and tubing, will cause evaporation of the liquid. Some of the evaporation can be reduced by temporarily "sealing" the tank and initially allowing the tank pressure to increase slightly. While this procedure can delay the need for venting the tank, it cannot eliminate it. Depending on the quality and quantity of the insulation, this process can delay venting for hours or possibly even days. Ultimately, though, venting must occur. When it does, it is obviously not desirable to simply vent hydrogen gas into the surrounding atmosphere which could be inside an enclosed space. Neither is it desirable to have an open flame where the escaping hydrogen is burned in air. An alternative, favored by BMW, is to pass the hydrogen through a catalytic burner such that no open flames or high temperatures are created.

There are many hydrogen absorbing (not referring to any specific process) materials which have promise and could become of wide interest, but they have not reached the maturity of compressed gas or liquid storage. Some of the resulting systems could offer potential safety advantages over cryogenic liquid or highly compressed gas storage. Only additional years of research and development can provide definitive answers.

There are some physical characteristics of hydrogen, and the burning of hydrogen, which are cause for concern for storing onboard a vehicle. For example, hydrogen has a far greater flammability (fuel/air ratio) range than any other known vehicle fuel. This range is from about 4% to 75% (fuel volume/air volume) where stoichiometric is about 40%. This means that the fuel/air mixture will burn from extremely lean (about 10% of stoichiometric fuel) to extremely rich (nearly double the stoichiometric fuel). By comparison, the range for gasoline is about 1.4% to 7.6% where stoichiometric is around 1.6%. Hydrogen gas also diffuses very quickly into the air, thus quickly making a near-homogenous mixture. This means that it would be much easier for a persistent fuel leak of gaseous hydrogen to produce a large volume of combustible mixture, in a confined space such as a garage, than it would for gasoline.

On the other hand, the density of gasoline vapor is much greater than air since the average molecular weight of gasoline is about 4X that of air. Thus, a small leak of liquid gasoline would produce a fuel-rich and highly combustible layer, just above and surrounding the "puddle", which would persist for a long period of time. In this regard, a small gasoline leak might be a greater fire hazard where a hydrogen leak might present a greater potential for an explosion.

The likelihood of a hydrogen-air explosion is increased, relative to gasoline, not only by the very wide (especially lean) flammability range but also by the extremely fast flame propagation speed and low ignition energy. A hydrogen-air flame front moves at roughly an order of magnitude faster than a gasoline-air flame front. This greatly increases the possibility of a detonation wave explosion. The low ignition energy means that very weak sparks could initiate ignition.

Hydrogen has other properties which could pose additional risks associated with a storage tank leak, or leaks, during refueling processes. Namely, it is colorless and odorless. Those properties make it very difficult to detect a leak unless appropriate instruments are used. On the positive side, it is also non-toxic. This means that people or animals would not be harmed by breathing hydrogen vapor in air unless the concentration was sufficient to displace a significant portion of the oxygen in air or it was exposed to an ignition source.

The flames from burning hydrogen are also nearly invisible, especially in daylight or a well-lighted area. Therefore, a vehicle hydrogen leak could become ignited (especially since the ignition energy for hydrogen-air is extremely low) and be unknown to an observer. Clearly this could present a hazard to not only vehicle owners but those who service vehicles and especially to first-responders of vehicle accidents.

Another consideration associated with possible leaks of onboard hydrogen storage is parking in enclosed parking garages on driving through tunnels. In reality, the hazard associated with these is not very great due to the rapid rate of diffusion of hydrogen in air. This phenomena means that the leak would have to be of sufficient rate and time duration to create a combustible mixture, essentially throughout the interior of the structure. Thus, even if 5 kg of hydrogen escaped into an enclosure (with no ventilation), the volume of air with which it mixed would have to be less than 50,000 cubic feet to form a combustible mixture. For typical parking garages and tunnels which always have some ventilation and are generally much larger than 50,000 cubic feet, this would be a near impossibility. Nonetheless, there are many codes and regulations on such structures which currently could limit access for any vehicles with stored onboard hydrogen, or any other compressed gas which is flammable. Thus, whether hydrogen-fueled vehicles present a real hazard or not due to leakage, there are perceived hazards and restrictive codes and regulations that will have to be addressed.

6. Energy Requirements for Storage

Since uncombined hydrogen does not occur naturally in significant quantities on Earth, energy to produce it is clearly an issue. However, additional energy is required in conditioning the hydrogen (or hydrogen carrier) for storage or for removing it from storage. For example, depending on the initial pressure and temperature (as well as the extent of the compression system thermal integration), it could take from about 5% to over 20% of the hydrogen LHV to compress it to 700 bar. Liquefaction of hydrogen requires even more energy, up to 30% of the LHV. Further, all of the novel hydrogen storage concepts being considered require to either store the hydrogen or to liberate it after it has been stored. Some of the chemical hydrides require from 25% to over 50% of LHV to store the hydrogen and some of the metal hydride alanates require over 25% of LHV to liberate it. The key to a minimum efficiency effect due to storage requirements are the required temperatures. If the waste heat from the stack (~85C) can be utilized, then the efficiency effect will be minimal. On the other hand, if significantly higher temperatures are required (which is the case for most of the potential carriers) then additional fuel will have to be consumed. For compressed gas or liquid hydrogen, the additional energy will be reflected in the cost of the hydrogen. However, for storage systems which utilize fixed onboard storage media, the additional energy will likely be reflected in a reduced fuel efficiency of the vehicle.

7. Refueling Time

A major criticism of the EV was the length of time it typically took to recharge (refuel) the vehicles. This criticism was clearly based on hours for an EV recharge versus minutes for a conventional vehicle. It remains to be determined how many minutes beyond those required for gasoline vehicles will be deemed acceptable. Most likely, the acceptable refueling time will be related to the range; the more often a refill is required, the shorter will be the acceptable time increment for refills. For the composite compressed gas and liquid hydrogen tanks, the NREL data showed refill rates typically between about 0.3 and 0.9 kg per minute, with only a few events between 1.0 and 1.7, and a few between 0.05 and 0.3 kg per minute. The greatest number of refill events occurred at about 0.85 kg per minute which would correspond to a 5 kg refill time of slightly less than 6 minutes.

8. Accessibility of Refueling Stations

The vast majority of current vehicle owners in the United States refuel at one of approximately

200,000 gasoline stations with little or no deviation from their normal driving routes. It would be a negative factor in the acceptance of hydrogen-fueled vehicles if a detour of miles was necessary to refuel the vehicle. However, as is likely the case with regard to acceptance of refueling time, vehicle range will probably be a major factor in the acceptability of limited numbers of refueling stations; the more often one has to refuel, the less acceptable it will be to make a significant deviation in route to refuel.

9. Fuel Costs

Storage technology used on the vehicle will also likely have an effect, possibly significantly, on the delivered price of hydrogen. Currently, hydrogen is typically delivered by producers either in liquid or compressed gas form. Liquid is typically delivered in tankers with highly insulated, multi-walled containers. Compressed gas is typically delivered in trailers with a series of high-pressure cylinders. Liquid is generally more expensive to produce than compressed gas (additional energy of roughly 30% of the hydrogen heating value is expended in liquification) and, in both cases, the consumer price depends to a great extent on the location of the customer. Transportation of hydrogen is currently much more expensive than gasoline or diesel due to its very low energy density (see Table 4-1).

In addition to the difference in the price of liquid versus compressed gas, price will also be affected by the cost and complexity of interface facilities as well as any type of pre-treatment or post-treatment of the fuel. For example, to rapidly refill a vehicle tank to 700 bar might require pre-cooling the hydrogen fuel. In this case, in addition to the incremental energy cost of providing the higher pressure, there would be an energy cost of pre-cooling the gas as well as the capital cost of the facility to perform the cooling. Thus, the price of 700 bar hydrogen would likely be somewhat higher than 350 bar hydrogen and the price of pre-cooled 700 bar would probably be even somewhat higher.

While it is very early in the technology developments, many of the other storage concepts involve hydrogen-bearing solids or liquids. Most of these technologies will likely have some special interface requirement (e.g., control of temperature, pressure, rate of delivery, etc.) which could affect delivered hydrogen price. At least one, a liquid-bearing hydrogen concept, involves off-board treatment of the spent fuel to recharge it with hydrogen. The cost of such off-board treatment is unknown but the unit hydrogen price could be quite different from delivery to other means of hydrogen storage.

10. Public Perception of Hydrogen

For many years, there was a perception by a large segment of the population that hydrogen is extremely dangerous; even explosive. However, it appears that the perceived hazards of hydrogen are diminishing with time. This possibly is due to the ever-increasing awareness of the potential environmental benefits of replacing petroleum fuels with hydrogen. Indeed, there are many local demonstration programs, newspaper articles, television news or talk show segments, and even advertisements by OEMs touting these potential benefits. Obviously one or two serious accidents involving hydrogen could greatly diminish its acceptance by vehicle buyers.

11. Codes and Standards Affecting Hydrogen Storage

Codes and standards are vitally important to every aspect of hydrogen storage if mass-produced, hydrogen-fueled vehicles are ever to become reality. Without widely accepted and reasonable codes governing permanent storage facilities, transportation, and on-board storage,

hydrogen might never achieve widespread distribution needed to be an acceptable vehicle fuel. In a similar light, standards are needed to insure compatibility between vehicles and various refueling stations, accurate determination of hydrogen flow rates and quantities transferred to the vehicles while avoiding many safety problems and many other issues.

One indication of the importance of hydrogen codes and standards emerged from a meeting convened on November 12 and 13, 2002, entitled, "Global Forum on Personal Transportation." Attendance at the forum was by invitation from Secretary of Energy Spencer Abraham and involved "125 Senior automotive and energy experts from government, industry, and academia representing 12 countries, the European Commission, and The World Bank." There were only four summary recommendations. The first two of these recommendations, were:

1. Commit to a global fuel cell and hydrogen infrastructure.
2. Reach agreement internationally on a common certification process, and harmonized codes and standards, for advanced technologies and move forward.

Clearly, this group of experts considered common certification processes and harmonized codes and standards to be of vital importance.

The U.S. Department of Energy has a separate budget line for safety, codes, and standards as part of the Hydrogen program. Recent funding in this category was:

2003 -- $4.53 million (including little or no earmark)
2004 -- $5.75 million (after earmarks removed)
2005 -- $5.80 million (after earmarks removed)
2006 -- $4.72 million (after earmarks removed)
2007 – Request $13.85 million

Table 4-5 (see section E-iii) shows DOE solicitations and awards for "Codes and Standards" as well as for "Storage" since 2003. The only major contract for codes and standards was for $6 M (over 5 years) and was awarded in Dec, 2006, to Regulatory Logic, LLC. This award, which included 15 sub-contracts, has only just begun and codes and standards activities are typically notoriously slow.

E. Current Research and Development Efforts

1. Introduction

Primarily because of the cost and weight problems noted above, considerable effort is being devoted to finding alternative technologies to liquid or compressed onboard hydrogen storage. Many of these efforts were initiated by, and are supported by, DOE. They are, however, generally research oriented (as opposed to development programs) and have goals of finding, and understanding, promising science which could then provide the basis for new system developments. Consequently, these various projects are typically not mature enough for reasonable predictions of cost or even, in most cases, overall storage system performance. They represent valuable efforts by researchers in industry, government, and academia and present an excellent possibility that one or more will lead to new system concepts with cost and/or performance advantages over current systems.

2. Department of Energy Hydrogen Storage Targets

As part of the PNGV program, various government/industry technical teams were formed in different areas of technology specialization. The combined efforts of these government and industry experts in the various teams provided a major input for the establishment of the DOE technology targets. Usually, the targets were based on compromises, using auto industry input for values which could result in competitive vehicles and technical specialists input for values that were based on reasonable expectations of being achievable.

At the time they were established, many of the fuel cell and hydrogen storage targets seemed, to many people familiar with the technologies, to be unachievable. Examples are some of the fuel cell performance parameters such as start time, freeze/thaw tolerance, power density, and others. Progress has been so rapid that most of these fuel cell targets have either been met or at least seem achievable. Hydrogen storage seems to be an exception in that none of the industry representatives contacted or surveyed seemed to expect either hydrogen storage weight fraction or cost targets to be met for 2010 or 2015.

Some of the hydrogen storage targets have already been shown and discussed earlier in this section. A further list of technical targets is shown below in Table 4-3.

Table 4-3: Selected DOE Hydrogen Storage Technical Targets

Storage Parameter	**Units**	**2010**	**2015**
System Gravimetric Capacity	kWh/kg	2	3
Usable, specific-energy from H_2 (net useful H_2/max system mass)[a]	Kg H_2/kg/system	(0.06)	(0.09)
System Volumetric Capacity			
Usable energy density from H_2	kWh/L	1.5	2.7
(net useful H_2/max system Volume)	(kgH_2/L system)	(0.045)	(0.081)
Storage System Cost[b]	$/kWh net	4	2
	($/kg H_2)	(133)	(67)
(Fuel cost)[c]	($/gge)	2-3	2-3
Durability/Operability			
• Operating ambient temperature[d]	℃	-30/50 (sun)	-40/60 (sun)
• Min/Max Delivery Temperature	℃	-40/85	-40/85
• Cycle Life (1/4 tank to full)[e]	Cycles	1000	1500
Charging/discharging Rates			
• System fill time (for 5 kg)	Min	3	2.5
• Minimum full flow rate	(g/s)/kW	0.02	0.02
Fuel Purity (H_2 from storage)	% H_2	99.99 (dry basis)	
Environmental Health and Safety			
• Permeation & Leakage	Scc/h	Meets or Exceeds Applicable Standards	
• Toxicity	-		
• Safety	-		
• Loss of Usable H_2	(g/h)/kg H_2 stored	0.1	0.05

Source: Dr. Sunita Satyapal, DOE Hydrogen Storage Team Leader, January 2007

Note: Above targets are based on the lower heating value of hydrogen and greater than 300-mile vehicle range; targets are for a complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and/or other balance-of-plant components. Unless otherwise indicated, all targets are for both internal combustion engine and for fuel cell use, based on the low likelihood of power-plant-specific fuel being commercially viable. Also note that while efficiency is not a

specified target, systems must be energy efficient. For reversible systems, greater than 90% energy efficiency for the energy delivered to the power plant from the on-board storage system is required. For systems generated off-board, the energy content of the hydrogen delivered to the automotive power plant should be greater than 60% of the total energy input to the process, including the input energy of hydrogen and any other fuel streams for generating process heat and electrical energy. All targets must be achieved at end of life.

[a] Generally the "full" mass (including hydrogen) is used, for systems that gain weight, the highest mass during discharge is used.
[b] 2003 US$; total cost includes any component replacement if needed over 15 years or 150,000 mile life.
[c] 2001 US$; includes off-board costs such as liquefaction, compression, regeneration, etc.; 2015 target based on H_2 production cost of $2 to $3/gasoline gallon equivalent untaxed, independent of production pathway.
[d] Stated ambient temperature plus full solar load. No allowable performance degradation from -20℃ to 40℃. Allowable degradation outside these limits is TBD.
[e] Equivalent to 200,000 and 300,000 miles respectively (current gasoline tank spec).

Meeting performance and cost targets is certainly not a guarantee of commercial success but the converse is probably true. Not meeting the targets will make commercial success very difficult. As an example, consider three important hydrogen storage targets for 2010 and 2015, volumetric energy density, gravimetric energy density, and cost for 5 kg of hydrogen storage:

3. Department of Energy Funding History for Hydrogen Storage

It should be noted that much more emphasis is put on DOE efforts regarding hydrogen storage than on other ZEV-related technologies. The reason is that, as was mentioned earlier, there is little evidence of significant industrial accomplishments for complete storage systems other than compressed gas or liquid hydrogen.

Funding for hydrogen storage was begun during the PNGV under the general heading of storage and fuel processors. After onboard fuel processors were no longer considered viable and it was decided to emphasize the FreedomCAR program, a separate budget item was created for hydrogen storage. Table 4-4 gives a summary of these funds for the last several years.

Table 4-4: Doe Hydrogen Budgets
(Thousands of Dollars)

	Fuel Processing and Storage[1]	Storage R&D[2]	Codes and Standards[2]
FY 2001	20,806		
FY 2002	21,300		
FY 2003	24,100	3,000	4,531*
FY 2004		13,628*	5,557*
FY 2005		22,418*	5,801*
FY 2006		26,600*	4,727*
FY 2007 (Req.)		34,620	13,848

- After earmarks removed

4. Major DOE Initiatives and Solicitations

For the last century, the only media used to store fuel onboard light vehicles were either liquid or compressed gas. However, since neither offer desirable characteristics for storing hydrogen, serious efforts are being made to develop other means of storage.

Many materials are known which contain larger weight fractions of hydrogen than the 6%, DOE 2010 target, or even 9% of the 2015 target. Unfortunately, there is much more to a storage system than a hydrogen-bearing material. Energy must be expended, usually by a controlled temperature, under controlled pressure, to absorb and release the hydrogen at appropriate rates. This requires a considerable amount of support equipment which adds cost, weight, and volume to the system.

Some R&D has been conducted for alternative hydrogen storage concepts for many years, but especially since early consideration of fuel cell vehicles over 20 years ago. However, major organized efforts involving government agencies, national laboratories, universities, and private industry expanded greatly as a result of the hydrogen-oriented FreedomCAR program. This led to increased budgets and efforts by DOE to resolve many hydrogen issues.

Especially significant among DOE efforts was the hydrogen storage "Grand Challenge" solicitation in July, 2005. Awards of $150 M (over 5 years) were announced in April 2004. This resulted in Centers of Excellence as well as independent projects. Table 4-5 gives a summary of DOE hydrogen storage solicitations and awards since 2003. Since these awards are multiyear and mostly involve basic research, there are generally insufficient results to date to make realistic projections for alternative storage systems.

Table 4-5 DOE Solicitations and Awards, Hydrogen Codes and Standards and Storage

TOPIC	SOLICITATION #	$ AMOUNT	SOLICITATION DATE	AWARD/Comments
Codes & Standards for the Hydrogen Economy	DE-PS36-06GO96011	$6M (over 5 yrs)	December 2005	December 2006; to Regulatory Logic, LLC (includes 15 sub-contracts)
Off-Board Hydrogen Bulk Storage	Small Business Innovation Research Phase I (hydrogen component)	up to $100,000 for Phase I grants	September 2006	NO AWARD YET - PROPOSALS UNDER EVALUATION
On-Board Vehicular Hydrogen Storage	DE-PS36-06GO96003F (Equivalent lab call: DE-PS36-06GO96012F)	$6M (over 2 - 5 yrs)	August 2006	NO AWARD YET - PROPOSALS UNDER EVALUATION
Novel Materials for Hydrogen Storage (Basic research for the Hydrogen Fuel Initiative)	DE-PS02-06ER06-17	~$12M annually (including storage, over 3 years)	April 2006	NO AWARD YET - PROPOSALS UNDER EVALUATION
Novel Materials for Hydrogen Storage (Basic research for the Hydrogen Fuel Initiative)	DE-FG01-04ER04-20	~$19.8M (over 3 years for storage out of $64M over 3 years for basic research for Hydrogen Fuel Initiative)	May 2005	Announced May 2005
The Hydrogen Storage "Grand Challenge"	DE-PS36-03GO93007	$150M (over 5 yrs)	July 2003	Announced April 2004 (includes Centers of Excellence and independent projects)

5. The Role of PNGV and FreedomCar

The Partnership for a New Generation of Vehicles (PNGV) was initiated by the Clinton administration in 1992. Among the power systems given consideration for the 80 mpg vehicle were fuel cells. Even though many individuals and organizations had previously done studies and simulations for fuel cell-powered vehicles, the PNGV was probably the first time that there were multiple groups working simultaneously on essentially common targets. In addition, the DOE was budgeting significant funds for fuel cells to help resolve some of the technical and economic barriers. Among the results were a rapidly expanding interest in fuel cells and some remarkable progress in advancing the technologies.

Initially, the PNGV fuel cell efforts focused almost entirely on liquid fuels, gasoline in particular, which would utilize onboard fuel processors. The fuel processors would produce a hydrogen-rich gas (reformate) from the liquid fuel to fuel the stack. Using gasoline it was believed would eliminate many of the problems associated with hydrogen, including lack of infrastructure, high fuel costs, and onboard hydrogen storage. Towards the end of the program it became apparent that the additional costs, efficiency losses, and resulting emissions associated with the fuel processor would negate many of the potential benefits and make meeting cost targets even more difficult. In addition, it was also obvious that operational demonstrations of fuel cell vehicles would not be feasible within the time frame set for the PNGV, the year 2000. Even so, the potential efficiency and emission benefits for fuel cells along with the impressive progress being made kept the focus on fuel cell vehicles active in the PNGV. Therefore, while the fuel cell-powered vehicle received considerable attention during the PNGV program, there was

relatively little emphasis during most of the program on hydrogen-fueled vehicles and onboard hydrogen storage.

Independently of the PNGV program, however, DOE efforts continued on onboard hydrogen storage. The storage efforts included certification of pressurized tanks/cryotanks in 2000 and 2001, continuing R&D on hydrides/Alanetes hydrogen carriers with hardware demonstrations in 2000, and carbon nanofibers hardware milestones in 2000, 2001, and 2002. DOE hydrogen-related programs began to increase after President Bush announced his Hydrogen Fuel Initiative in January 2003. His entire proposed program emphasized hydrogen and fuel cells thus prompting increased efforts by DOE.

Based on the President's Hydrogen Initiative, the FreedomCAR program was created in the fall of 2003 and by early 2004 a substantial increase in hydrogen activities was underway, including focused efforts on hydrogen storage.

In summary, the PNGV was responsible for a considerable increase in the interest in fuel cells, including hydrogen-fueled fuel cells. Many productive programs were initiated in national laboratories, universities, and private industry but the major emphasis was not on hydrogen. The FreedomCAR program, on the other hand, put a great deal of emphasis on hydrogen fuel, fuel cell vehicles and many of the hydrogen-related barriers, including hydrogen storage. Thus, both of these programs had positive effects on the pursuit of hydrogen-fueled vehicles, especially fuel cell vehicles.

6. Active Participants in DOE Hydrogen Storage Technology Programs

DOE had an annual Merit Review, May 16-19, 2006, in Arlington Virginia, involving DOE contractors working in hydrogen technologies. There were 12 oral presentations and 12 poster presentations by DOE contractors. Virtually all of the contractors participating in the hydrogen storage sessions were from national laboratories or universities. The oral presentations were all fundamental research-oriented with most involving hydrogen interactions with solid materials and a few involving interactions with condensed phase materials. A summary of the presentation titles, lead author and affiliations, and a few words from their abstracts describing the projects are shown in Appendix G. Among the participants, were:

a) Government and National Laboratories

Ames Laboratory (AMES)
Argonne National Lab (ANL)
Berkeley National Lab (BNL)
DOE
JPL (JPL)
Lawrence Berkeley Natl. Lab (LBNL)
Los Alamos National Lab (LANL)
National Renewable Energy Lab (NREL)
Natl. Inst. of Science & Tech. (NIST)
Oak Ridge National Lab (ORNL)
Pacific Northwest National Lab (PNNL)
Sandia National Lab (SNL)
Savannah River National Lab (SRNL)

b) Universities

Caltech.
Clemson
Colo. School of Mines Tulane
Columbia
Drexel
Georgia Tech
Hamilton College
Iowa State
La. Tech
LSU
MIT
N.C. State
Penn State
Rice
Rolla
Rutgers
So. Illinois
UC Berkeley
UC Santa Cruz
UCLA
Univ. of Tenn.
Univ. of Illinois
Univ. of Michigan
Univ. of Missouri
Univ. of Pennsylvania
Univ. of Washington
UNLV
Va. Commonwealth
Washington State

c) Private Industry

Air Products
GE
HRL Industries
Intematix Corp.
Phillips Research
Rutherford-Appleton Laboratory
TIAX
United Technologies Research Center
UOP LLC
WUSTL

7. Industry Activities

With the exception of BMW, all of the major automobile OEMs in the USA, Japan, and Germany are devoting time, effort, and resources to hydrogen-fueled vehicles utilizing compressed hydrogen gas, either at 350 bar or 700 bar storage pressure. Honda alone indicated that they did not intend to go to 700 bar storage and would stay with the lower 350 bar.

All of the OEMs using compressed hydrogen storage chose either type 3 or type 4 tanks as further described below. Although several of the OEMs had developed, or were in process of developing, their own tanks (or other types of storage), apparently all had used either Dynetek type 3 or Quantum type 4 tanks in fuel cell test vehicles. Toyota had, for example, already fabricated tanks of their own design but these were similar to the Quantum type 4 tanks. Both types utilize small high-strength, carbon fibers wrapped tightly around a core body (actually the inner liner of the storage volume) and bonded with an epoxy-type material. Type 3 tanks utilize a metallic liner (e.g., aluminum) where the type 4 tanks utilize a high-strength, plastic-type material (e.g., HDPE). Both types have an outer covering of HDPE-type material to provide impact and environmental protection. Both types have also been successfully built and tested for both 350 bar and 700 bar applications, and each seems to have advantages and disadvantages relative to the other.

The windings and bonding agents are nearly identical for both types of tank, thus they both have similar upper limits on the temperature of these materials - about 85℃. Above this upper limit, the bonding agent could weaken sufficiently to potentially allow the winding to shift (creep), which could compromise the integrity of the tank.

The primary concern in exceeding the upper allowable temperature of the tank is during rapid refueling. The normal refueling procedure is to transfer hydrogen from a higher pressure supply tank into the vehicle tank. During this process, hydrogen in the vehicle tank is heated by compression. This causes a temperature gradient between the tank interior and the ambient air surrounding the tank. Thus, as the gas is heated by compression during the refueling process, heat is transferred from warmer hydrogen to the surroundings (e.g., the container walls then to the atmosphere) thereby reducing the interior temperature. The upper gas temperature reached in the tank during refueling is a function of many variables including the refueling rate, the temperature of the supply hydrogen, the initial temperature of the tank and residual gas in the tank, the ambient air temperature, and the amount of residual hydrogen in the tank prior to refueling.

For a given mass of hydrogen transferred into the tank during refueling, the temperature first increases and then due to heat transfer, it begins to decrease. However, as the gas temperature drops, so will the pressure. That means to achieve a desired tank pressure after the increased gas temperature has dropped back (which it will, after a period of time) to near-ambient, the tank must be filled to a pressure above, and possibly considerably above, the design service pressure. Essentially, the faster the fill and the higher the initial temperatures of residual and supply hydrogen, the higher would be the peak internal temperature reached and thus the higher the necessary fill pressure. However, this process must be carried out without exceeding either the maximum fill pressure or allowable maximum wall temperature. Thus, there is an upper limit on the fill rate which could be determined to be either the maximum allowable pressure or the maximum allowable temperature.

The allowable fill rate could be increased due to any, or all, of these factors:

1. A higher allowable material temperature.
2. An increase in the rate of heat transfer from the tank interior to ambient air.
3. A lower temperature of the supply hydrogen.

Number 1 above requires the "invention" of new bonding materials. Number 2 is affected somewhat by having a tank liner that is more conductive. In this regard, the type 3 tank with the highly conductive aluminum liner might have an advantage over the type 4 with the poor-

conducting plastic liner. Alternative 3, a decrease in the temperature of the supply hydrogen, is achieved by "pre-cooling" the supply hydrogen prior to filling. Such pre-cooling might be optional for 350 bar tanks (to allow faster fill times) but might be necessary to achieve what might be considered minimum acceptable refill times when filling a near-empty tank to 700 bar.

In a paper entitled, "Fast Filling of Type 3 Hydrogen Storage Cylinders," by M. Duncan of Dynetek Industries Ltd. and S. Macfarlane of General Hydrogen, presented at the Hydrogen and Fuel Cell Conference in Vancouver, B.C, 2003, test results on filling 205 liter, type 3 cylinders to 350 bar were reported. This tank, a Dynetek W205H350G8N, has a capacity of close to 5 kg of hydrogen at 350 bar and 15℃ and is therefore repre sentative of single tank configuration that might be used in some early- generation, fuel cell vehicles. It should be noted, however, that some such vehicles will probably use multiple tanks and others will probably use much longer and smaller diameter tanks, which would cause refill parameters to be different.

For the referenced test tank (2110 mm long, 418 mm diameter, and 90 kg weight), tests were reported for two average fill rates. One fill rate was 10.6 g/s. In both cases, the peak nominal fill pressure was 400 bar. With the higher fill rate, the peak hydrogen temperature (measured at the non-fill end) was 94℃ and, for the lower fill rate , it was 85℃. The respective fill times were 400 and 496 seconds, respectively. In both cases, the average supply hydrogen temperature was 22℃. Of special interest is the result that the pe ak liner temperatures, measured at 63℃ and 61℃, respectively, were considerably lower than th e peak hydrogen temperatures. Since it is the tank materials, not the gas, which should be kept below 85℃, this suggests that a more rapid filling (without pre-cooling) might be possible. The test results also suggest a temperature gradient in the hydrogen gas inside the tank, with the highest temperatures at the non-fill end. This would likely be due to the fact that the cooler, entering supply hydrogen is compressing the gas already in the tank. If so, this might have implications for the allowable fill rates of long, thin tanks.

Type 3 tanks have a potential disadvantage compared to Type 4 due to the differences in thermal expansion coefficient between the aluminum liner and the carbon fiber/epoxy structure surrounding it. In type 4 tanks, the thermal expansion coefficients are much more similar. Whether the dissimilarity could be a significant issue is not really known at this point in time. On the other hand, the various connectors, valves, etc., fastened to the tank (both internally and externally) are metal, which would appear to be more compatible with the Type 3 liner. As previously stated, both types have been successfully fabricated and tested for both 350 bar and 700 bar applications.

There are three major companies in North America which are known to design and fabricate high pressure, composite gas storage tanks. They are Lincoln Industries of Lincoln, Nebraska; Quantum Fuel System Technologies Worldwide, Inc., of Irvine, California; and Dynetek Industries of Calgary, Canada. All of the tanks noted at the various OEMs using pressurized hydrogen appeared to be fabricated by either Quantum or Dynetek, and all tanks have passed vigorous performance and safety tests.

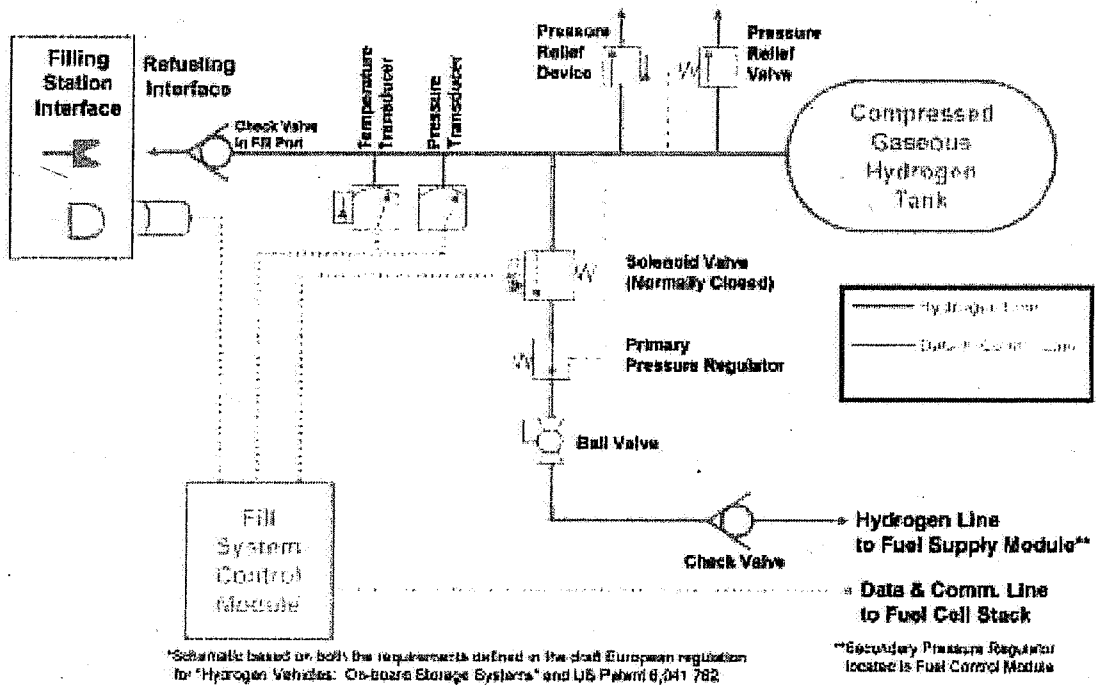
Visits were made to both Quantum and Dynetek and both demonstrated impressive capabilities to design and fabricate composite high pressure tanks. Of the two, Quantum is more R&D oriented, building relatively small numbers of special-purpose tanks. Dynetek seems to be primarily a manufacturing operation that has been producing and marketing high pressure tanks (mostly for compressed natural gas) for years. Dynetek also has a 100% owned subsidiary, Dynetek Europe Gmbh, in Europe also producing compressed gas storage tanks.

Quantum is pursuing primarily Type 4 tanks with high density polymer liners while Dynetek builds Type 3 with metallic (aluminum) liners. Each type has advantages and disadvantages with no obvious compelling reasons to choose, or not choose, either type.

F. The Status of Candidate Technologies Compared to DOE Targets

It is difficult to compare most of the alternative hydrogen storage technologies to DOE targets since all but compressed gas and liquid are still in research phases. Even comparisons of compressed gas and liquid hydrogen storage are difficult, especially from cost standpoints, since neither have benefited from mass-manufacturing cost reductions. However, a DOE-sponsored Cost Analysis Study[3] gave some projected costs. The study used a hydrogen storage system as shown in Figure 4-5 as a basis for the cost assessments. It was also based on typical Type 3 or Type 4 tanks.

Figure 4-5: Hydrogen Storage Schematic Used for Cost Studies



The TIAX cost study was based on tracking all required materials and components separately as well as costs for assembly and inspection. It was concluded that the majority of the weight (about 52% for 700 bar tanks and about 45% for 350 bar tanks) and cost (almost 60% for both 350 bar and 700 bar tanks) is due to the carbon fibers. It also concluded that "Aerospace-grade carbon fibers must be used to achieve reliability, safety, and life." Further, they concluded "Aerospace fibers are currently made in high volume and we do not anticipate much further cost reduction." Table 4-6 shows the model results from this study compared to DOE targets.

[3] "Compressed Hydrogen and PEM Fuel Cell System," prepared by TIAX and presented October 20, 2004, for discussion by the FreedomCar Fuel Cell Technical Team. TIAX is an organization that specializes in cost studies, breaking costs down into basic materials and manufacturing costs including accounting for volume of production. They have done previous studies for DOE.

DOE, as well as the industry leaders in producing compressed gas tanks, recognize the importance of the cost of carbon fibers and are pursuing potential cost reduction alternatives. However, so far no path has been found to keep the high quality/strength (which minimizes weight) while reducing costs. The fibers are already being mass-manufactured so innovative changes in materials or processes are needed to accomplish this.

Table 4-6

TIAX STUDY RESULTS FOR COMPRESSED HYDROGEN STORAGE

System Metric	DOE Targets 2010	DOE Targets 2015	Model Results 350 bar	Model Results 700 bar
Cost ($/kWh)	4	2	9-13	12-16
Specific energy (kWh/kg)	2	3	2.2	2.1
Energy density (kWh/L)	1.5	2.7	0.6	0.9
Hydrogen weight (%)	6	9	6.7	6.3

It is noteworthy that even though the study was based on a production volume of 500,000 systems per year, projections for costs were far above (2x to 6x) the targets. Further, the cost per kWh increases if more than one tank is assumed. Using two or three tanks results in projected cost increases of about 50% for three tanks at 350 bar and about 25% for two tanks at 700 bar. Projections for performance metrics are closer to targets than cost, but none are projected to meet the 2015 targets.

No such detailed studies are known to have been performed for other storage technologies, even liquid storage. However, some less detailed projections such as shown in Table 4-7 from a January 2005 DOE presentation, have been made. Interestingly, the cost projections from the DOE presentation for liquid hydrogen storage seem to be somewhat lower than the estimates provided by BMW, who are actually developing liquid hydrogen storage systems. The DOE study shows liquid hydrogen storage (mass produced) at about $6 per kWh where BMW expects "mid-term" costs to be perhaps over $100 per kWh and "long-term" to be as much as $15 to $30 per kWh. Part of the difference is probably due to the volume production assumptions. DOE projections are based on the production of hundreds of thousands of units while BMW is projecting only for a relatively small number of large luxury class vehicles.

Table 4-7: HYDROGEN STORAGE TECHNOLOGIES

Approximate Status* as Compared to DOE Targets for Energy Density And Cost Per kWh for Hydrogen Storage Systems

	Vol. Energy Density (kWh/l)	Grav. Energy Density (kWh/kg)	Cost Per kWh ($/kWh)
DOE 2015 Target	2.7	3.0	$ 2
DOE 2010 Target	1.5	2.0	$ 4
Chemical Hydride	1.4	1.6	$ 8
Complex Hydride	0.6	0.8	$16
Liquid Hydrogen	1.6	2.0	$ 6
Gaseous Hydrogen 10,000 psi	1.3	1.9	$16
Gaseous Hydrogen 5,000 psi	0.8	2.1	$12

*Taken from US DOE presentation by Mark Paster, "Hydrogen, Fuel Cells and Infrastructure Program," January 2005.

G. Future Outlook for Hydrogen Storage

1. Near Term

In the near term, there is little doubt that, with the exception of BMW, the only hydrogen storage that will be widely used onboard light vehicles is compressed hydrogen gas storage. Every other OEM contacted indicated that this was the only real short term choice available and only Honda indicated that they intend to limit the storage pressure to 350 bar. The other OEMs seemed to prefer 700 bar, which will provide storage of over 50% more fuel in the same space envelope and correspondingly up to about 50% more range. Using 700 bar storage pressure is not, however, without problems. The volumetric density (kWh/L) will be higher but unit energy cost ($/kWh) is also expected to be higher and the gravimetric energy density (kWh/kg) about the same. It may also require either reduced fill rates or pre-cooling of the hydrogen prior to transferring into the vehicle tank to avoid overheating the tank structural materials.

Liquid hydrogen storage was also demonstrated to be workable, with limitations. It provides both higher gravimetric and volumetric density advantages over compressed gas storage but has issues with boil off and dealing with cryogenic liquids. It is not likely to be widely accepted by automobile OEMs in the judgment of the Panel.

Another issue with either the 350 or 700 bar compressed gas or liquid hydrogen storage is the need for widely accepted codes and standards for permanent storage, onboard storage, and all aspects of transferring and transporting hydrogen. This could be a major problem area, but probably it will be less of an issue in the short term since relatively small numbers of vehicles will be involved and they will likely be closely monitored and maintained.

Cost is also very much of an issue, especially for the short term since none of the storage systems are produced in volumes to allow significant production economies of scale. While

none of the OEMs gave specific values for current or near-term costs for the essentially one-of-a-kind hydrogen storage systems, the Panel estimates them to have cost the industry $10,000 or more (in some cases, apparently much more) each for both liquid and compressed gas storage.

2. Longer Term

For the longer term, there is a possibility that some of the alternative storage technologies being researched can evolve into effective hydrogen storage systems. Both solid and liquid carriers are being researched with hydrogen "recharging" being carried out both onboard and off of the vehicle. There don't appear to be any clear winners at the present among these alternatives and, in fact, none of the researchers who responded to the hydrogen storage questionnaire made any projections for complete system performance or costs. It appears to be simply too soon to make reasonably accurate projections.

H. Summary and Conclusions

On-board hydrogen storage is a major problem enroute to a consumer hydrogen fuel cell vehicle. At present, the only technology being demonstrated by the OEMs, with the exception of BMW, is compressed hydrogen storage. Major issues for compressed hydrogen storage are volume, weight, and cost.

The volume issue can be partially resolved by using 700 bar storage (thus a smaller required volume) and by innovative vehicle design or modification. Such innovations might include utilization of a long, small-diameter tank running longitudinally where the center "tunnel" is located. An innovative modification could be replacing rear coil springs with leaf springs to increase space available for hydrogen tanks. Thus, depending on the type of vehicle and system efficiency, it seems likely that compressed hydrogen storage could provide a range in excess of 200 miles, perhaps reaching 300 miles or more.

Liquid hydrogen storage technology appears to have advanced sufficiently (primarily by BMW) that, within certain constraints, it could be utilized. The advantages of liquid hydrogen, higher storage density and low pressure, suggest that it also could provide an adequate range.

However, it seems unlikely that either compressed or liquid hydrogen storage systems can meet weight or cost targets, especially for 2015. Using the TIAX estimates for mass-manufactured tanks, the system cost would be about $10 to $12 per kWh for 350 bar systems and $13 to $15 per kWh for 700 bar systems. This is compared to DOE targets of $4 per kWh for 2010 and $2 per kWh for 2015. If it is assumed the compressed hydrogen storage system cost $12 per kWh, then for a 5 kg storage system (about 165 kWh), the cost would be about $2000. Similarly for liquid storage, the BMW projections would be about $2500 for the long term. There seems to be little expectation that the cost of either of these systems will go much lower even with the volumes projected for the respective vehicles.

The weight outlook is a little better than cost. The TIAX projections for weight fraction are slightly over 6% for both 350 bar and 700 bar systems, compared to the DOE targets of 6% for 2010 and 9% for 2015. The pressure tank manufacturers have also indicated that 6%, and perhaps a bit higher weight fraction is within reach. For a 6% weight fraction system to contain 5 kg of hydrogen, the system would weigh about 83 kg (about 183 lb). Neither the TIAX effort nor the tank manufacturers project that the 2015 target of 9% can be met with pressurized hydrogen tanks.

There are many alternative hydrogen storage systems under investigation. Some of the absorption materials being investigated are relatively inexpensive and have shown, at least in the research phases, the capacity to contain well over 6% hydrogen. However, the remainder of the support system could have a huge effect on both cost and weight fraction. It should be noted that most research efforts for novel hydrogen storage technologies have been underway for only a couple of years. There are many very capable researchers pursuing a number of novel approaches simultaneously, so there is reason for cautious optimism, although there are no apparent clear "winners" at present.

Therefore the main conclusion concerning onboard hydrogen storage systems is that there is currently no completely satisfactory solution and none in sight. It is fairly certain that the next generation (and possibly several generations) of fuel cell vehicles will utilize compressed hydrogen storage even though liquid hydrogen systems will apparently be used in some BMW vehicles. It appears likely that using innovative approaches, with compressed hydrogen, ranges of over 200 miles, and possibly over 300 miles, can be achieved. Such tanks, however, even if mass-manufactured, will be expensive (probably around $2000 for 5 kg storage) and heavy (probably between 75 and 100 kilograms) for 5 kg of storage). They will also require 5 or 6 times the volume (as much as 33 gallons for 5 kg of hydrogen storage) as would be necessary for equivalent gasoline energy (about 5 gallons).

As stated, it is certainly possible that some of the alternative hydrogen storage materials being studied will result in successful hydrogen storage systems. However, at this time, the technologies are simply too immature to make realistic cost and/or performance projections for complete functional systems.

5. Automotive Fuel Cell Systems

Since the review of automotive fuel cell technology by the 1998 ARB Fuel Cell Technical Advisory Panel (Kalhammer, et al, 1998), massive efforts by the major fuel cell developers and automobile manufacturers have resulted in impressive advances in every aspect of fuel cell technology. This section summarizes the most important of these advances and identifies remaining challenges in the production of technically and economically viable automotive fuel cell systems.

The 1998 Panel concluded that fuel cell technology had advanced to the point of meeting automotive requirements, that hydrogen was not a feasible fuel and, that the favored fuels were gasoline or methanol. To facilitate use in a fuel cell, the gasoline or methanol needed to be chemically processed on-board into a hydrogen rich fuel. The Panel recognized that the integration of the fuel processor, fuel cell stack and balance of plant was a significant technical challenge. However, the largest challenge was the achievement of cost goals to compete on a first cost basis with the internal combustion engine. Major resource commitments by large organizations were in place and the optimistic scenario was that the fuel processor, FCEV would be commercially available in 2004/2005.

Since the 1998 report, it is now clear that on-board hydrogen is the only fuel considered viable for FCEVs, and the change is attributed to:

- The failure to develop a cost effective fuel processor that would physically fit into and meet the operational dynamics of a FCEV,
- The fuel efficiency and emissions for the fuel processor FCEV were not clearly better than advanced diesels or hybrids that are now commercialized, and
- The FreedomCAR program with the emphasis on hydrogen was initiated. The issues of energy security, climate change and non petroleum based fuels such as hydrogen as a chemical energy carrier are now considered of national interest.

These changes lead to a major shift in focus and resources from fuel processors to hydrogen related issues and created a greater emphasis on fuel cell system efficiency to counter the limitations of hydrogen storage and related refueling infrastructure.

The following review of fuel cell systems is divided into five sub sections.

- The first, 5A, provides a general discussion of fuel cell technology,
- The second, 5B, summarizes technical requirements,
- The third, 5C, describes specific fuel cell components and development challenges,
- The fourth, 5D, presents the Panel findings including a description of the developers visited, the issues of cost and performance compared to goals, and
- The final, 5E, provides the assessment and conclusions of the Panel.

A. Fuel Cell Overview

A fuel cell is an electrochemical device that directly converts the chemical energy of fuel into electricity. The fundamental advantage of a fuel cell is the relatively high efficiency and zero

tailpipe emissions when operating on hydrogen. The fuel cell concept was first recognized in 1839 and the first successful application of the fuel cell came in the 1960s for space flight. Although fuel cells have been in continuous development in stationary and mobile terrestrial applications for almost 50 years, only now are they being developed for use as a practical automotive power source.

1. Fuel Cell Operating Principles

All energy-producing oxidation reactions are fundamentally the same and involve the release of chemical energy through the transfer of electrons. During combustion of hydrogen and oxygen, there is an immediate and chaotic transfer of electrons in which heat is released and water is formed. A fuel cell accomplishes the same oxidation reaction in a controlled manner that allows the direct utilization of the electron transfer. A fuel cell produces direct current electricity and, in the case of a Polymer Electrolyte Membrane (PEM) fuel cell, low grade heat.

As illustrated in Figure 5-1, in a fuel cell, hydrogen and oxygen are fed separately to anode and cathode electrodes which are separated by an electrolyte that is impervious to the gases.

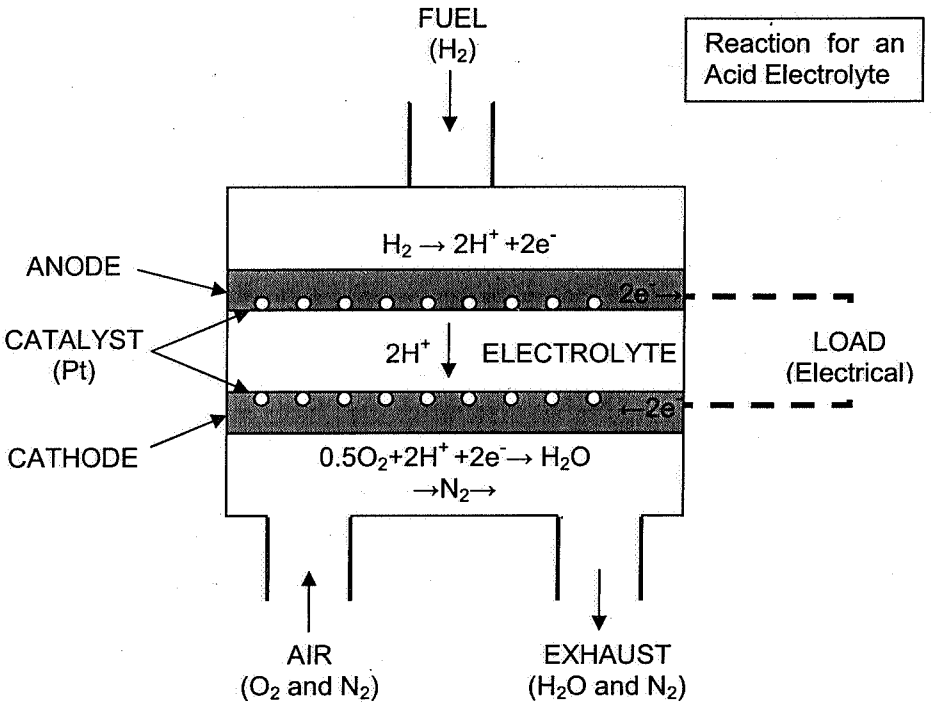


Figure 5- 1: Fuel Cell Operation Schematic

At the anode, the hydrogen molecules are split into hydrogen atoms (protons) that release electrons to the conducting anode which in turn becomes electrically negative. These processes are greatly accelerated by a catalyst, usually platinum, if the electrolyte is acidic and operates at relatively low temperatures. The electrons are separated from the hydrogen molecule by the

catalyst (oxidation) creating a hydrogen ion (no electrons). The protons thus formed leave the anode surface and pass through the electrolyte to the oxygen (cathode) side. The electrons released from the hydrogen atoms at the anode cannot enter the electrolyte and are forced to take an external electrical circuit which leads to the oxygen side. At the cathode, oxygen is electrochemically reduced to hydroxyl ions in a series of steps that require a catalyst (again, platinum or a platinum group metal or alloy), leaving the cathode positively charged. Driven by the potential difference, electrons travel from the anode to the cathode if an external circuit is provided. The protons combine with hydroxyl ions to form water, which is the only chemical reaction product of a hydrogen-oxygen fuel cell. If air is used as the oxidant, only the oxygen is involved in the fuel cell process; nitrogen passes the cathode unchanged and is exhausted, together with the product water.

Chemical Reaction of PEM Fuel Cell

Anode side: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode side: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Overall reaction: $2H_2 + O_2 \rightarrow 2H_2O$

Table 5-1 provides the hydrogen/oxygen/water reaction enthalpy (heating value) and the resultant theoretical cell voltages. The Higher Heating Value (HHV) is the value that results when the product water condenses to a liquid. The Lower Heating Value (LHV) is the value that results when the product water does not condense but remains in gaseous form.

Table 5- 1: Hydrogen Thermodynamic Properties

Heating Value	ΔH Enthalpy of Formation J/Mole	kWh/kg	Voltage Based on Enthalpy
Higher (HHV)	-285900	39.4 kWh/kg	1.48
Lower (LHV)	-241800	33.3 kWh/kg	1.25

A theoretical fuel cell voltage can be calculated based on the energy of the reaction (enthalpy of formation) and the number of electrons that are transferred. This theoretical voltage of conversion $E_{\Delta H}$ is calculated by considering Faraday's constant (approximately 26.8 Amp hours = 1 mole of electrons) and the energy value of the fuel. The reaction provides 2 electrons per H_2 molecule. The voltage of the fuel cell is independent of its physical size.

$E_{\Delta H}$ = Energy (J) / (Amp/Sec)

$E_{\Delta H}$ (LHV) = -241800 J / (-26.8 x 2 x 3600) = 1.25 Volts
$E_{\Delta H}$ (HHV) = -285900 J / (-26.8 x 2 x 3600) = 1.48 Volts

The fuel cell cannot take advantage of the difference in the HHV and LLV to produce additional electricity. As a result, the actual fuel cell voltage (E_{cell}) is compared to the $E_{\Delta H}$ (LHV). Assuming a perfect condition in which all electrons from the reaction are forced to take the external circuit and there is no loss of hydrogen fuel, the energy conversion efficiency can be calculated by dividing the fuel cell voltage by the calculated $E_{\Delta H}$ (LHV),

Efficiency (LHV) = E_{cell} / $E_{\Delta H}$ (LHV)

In a typical fuel cell, the electrical power production usually occurs between 0.6 and 0.85 Volts per cell. Ideal conversion efficiency results in calculated efficiencies of 48 to 68% of the LHV of

hydrogen. The large difference between the E_{cell} and $E_{\Delta H}$ (LHV) is the result of electrode kinetics (particularly on the air electrode). The voltage drop as a function of current is due to internal resistance (electronic and ionic) as well as reactant gas flow limitations and product water flooding of reaction sites.

Multiple cells are connected in series to ensure a practical voltage (100s of Volts) and are referred to as a fuel cell stack. To produce a large current (100s of amps), the cross-sectional area of the fuel cell must be large (100s of cm^2).

2. Fuel Cell Performance Characteristics

The performance characteristics of a fuel cell can be shown in graphical form in terms of voltage (E_{cell}), power (W) and efficiency (LHV) as a function of current. By convention, the power and current are defined in terms of W/cm^2 (specific power) and $Amps/cm^2$ (Specific Current).

The relationship between E_{cell} and specific current is typically characterized by three regions: 1) an initial region followed by 2) a linear region, and finally 3) a mass transfer limited region as illustrated in Figure 5-2.

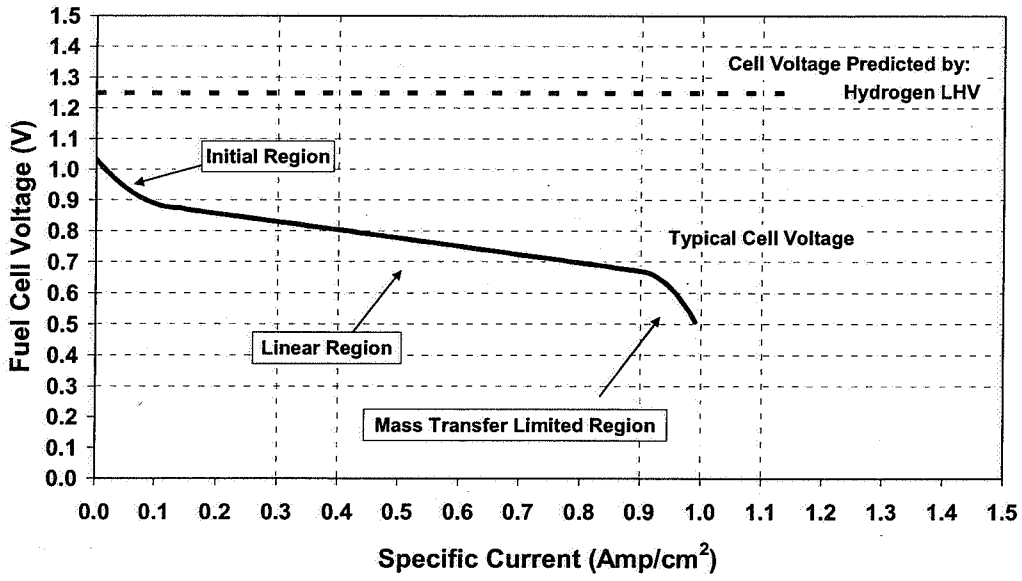


Figure 5- 2: Typical Fuel Cell Voltage, Specific Current Curve

1. The initial region shows an initial steep drop in the cell potential due to slow cathode kinetics. With sufficient voltage drop (0.1 to 0.15 volts over potential), the kinetics improves and is no longer limiting.
2. The linear region is characterized by a linear voltage drop primarily due to ionic resistance in the electrolyte.
3. As the current density further increases, the polarization curve enters the mass transfer limited region and cell potential drops off rapidly, primarily due to the inability of oxygen

to reach reaction sites fast enough. This inability may be caused by a combination of an oxygen gradient through the electrode, water blockage and/or nitrogen blanketing. Advanced engineering delays the onset of the mass transport region.

The calculated product of the cell voltage (V) and specific current (Amps/cm^2) is the specific power (W/cm^2) as shown in Figure 5-3.

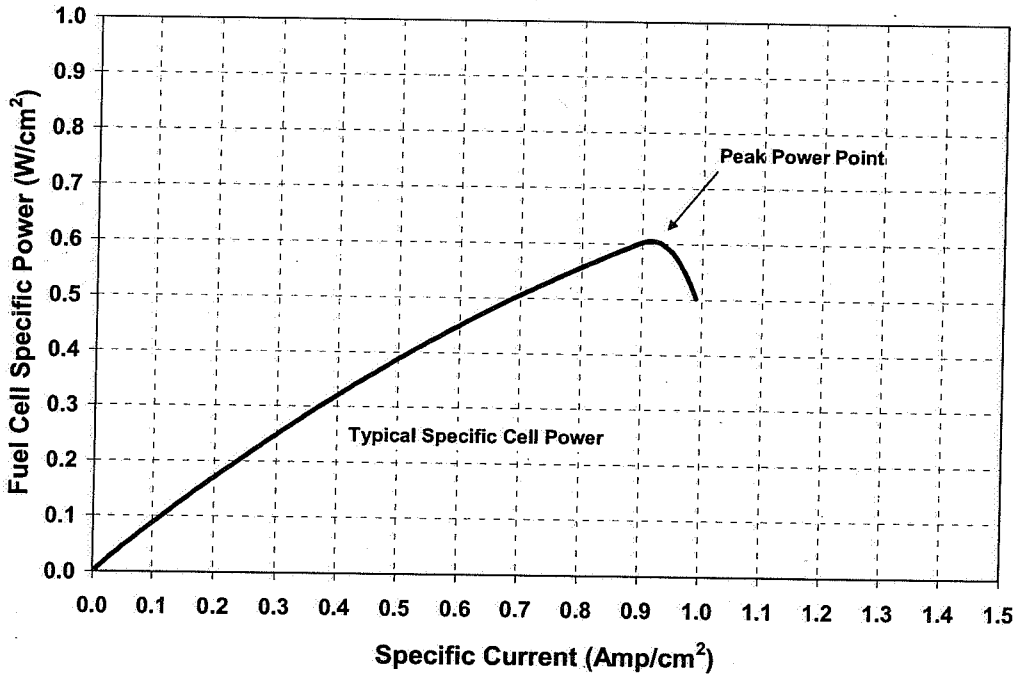


Figure 5- 3: Typical Fuel Cell Specific Power, Specific Current Curve

Up to the peak power point, the fuel cell produces more specific power as the specific current is increased. Operating the fuel cell at a higher current density than that which produces the peak specific power increases heat generation and fuel consumption and reduces specific power.

The peak specific power is a useful parameter for measuring progress in fuel cell performance. Higher specific power means that more power is available for a given size fuel cell and is likely to result in higher power per kg for the fuel cell system at a lower cost ($/kW).

The energy conversion efficiency of a fuel cell is primary related to the operating voltage as described in the previous section. Figures 5-4 and 5-5 present typical calculated and net energy conversion efficiencies as a function of specific current and as a function of specific power, respectively. The difference between calculated and net efficiency is due to the fuel cell requiring external support in its operation (i.e., a forced air supply must be provided).

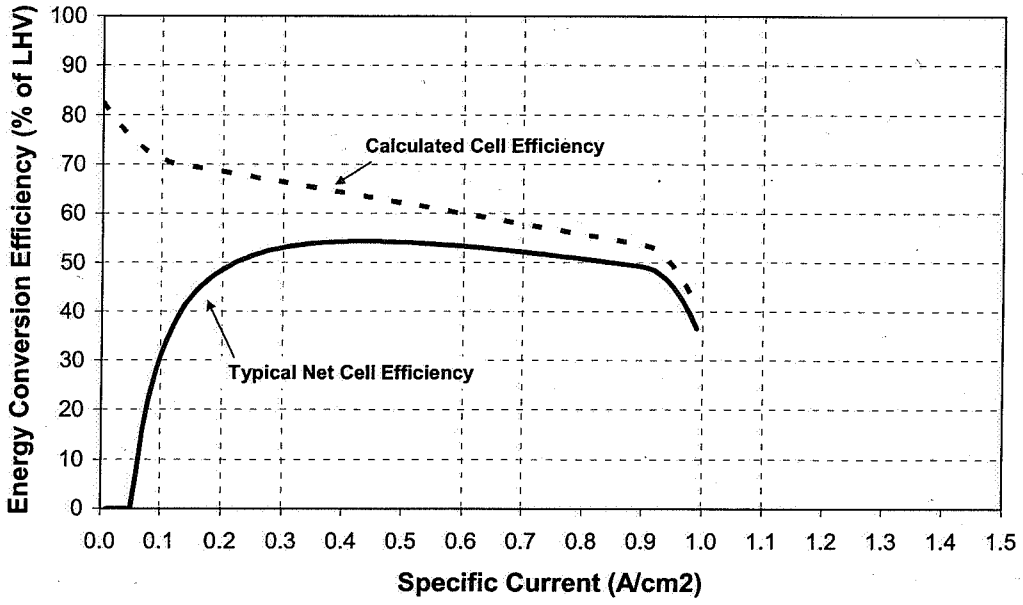


Figure 5- 4: Typical Fuel Cell Efficiency Specific Current Curve

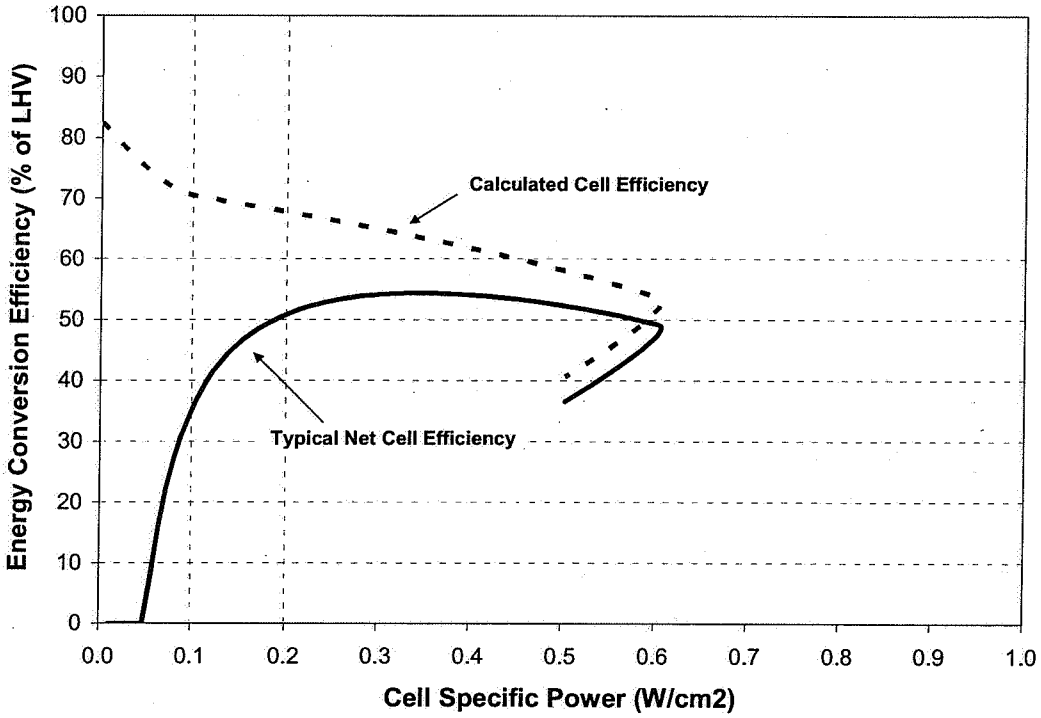


Figure 5- 5 Typical Fuel Cell Efficiency Specific Power Curve

The calculated cell efficiency curves shown in the two figures indicate that increasing current and power results in lower energy conversion efficiency. The net cell efficiency curves indicate that the cell is not energy sustaining at very low specific current conditions. As the specific current increases, the fuel cell then experiences a rapidly rising efficiency followed by decline in efficiency that approaches the calculated value. The characteristic of the net efficiency is the result of the overhead associated with support systems to operate the fuel cell (these support systems are described later). At very low current densities the idle power of the support system exceeds the cell power resulting in more energy being required than that which is being produced. In practice, the fuel cell would idle at the point where it just supports the system requirements.

3. Fuel Cell Electrolyte

Fuel cells are generally classified by the electrolyte used. The chosen electrolyte affects the specific chemical reaction, the cell operating temperature and the support system requirements. Suitable electrolytes for a fuel cell include alkaline, polymer electrolyte membrane, phosphoric acid, molten carbonic and solid oxide. Table 5-2 provides the normal operating temperature, and chemical reactions for each electrolyte. The specific application characteristics (automotive, utility power etc.) dictate which type of fuel cell is best.

Table 5- 2: Fuel Cell Types

Fuel Cell Type Operating Temperature Electrolyte State	Anode Reaction	Cathode Reaction
Alkaline (AFC) 80 to 120 °C Liquid Electrolyte	$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$ water production	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$
Phosphoric Acid (PAFC) 160 to 210 °C Liquid Electrolyte	$H_2 \rightarrow 2H^+ + 2e^-$	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ Water production
Proton Exchange Membrane (PEM) 60 to 90 °C Solid Electrolyte	$H_2 \rightarrow 2H^+ + 2e^-$	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ water production
Molten Carbonate (MCFC) ≈ 650 °C Liquid Electrolyte	$H_2 + CO_3^= \rightarrow H_2O + CO_2 + 2e^-$ water production	$O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^=$
Solid Oxide (SCOFC) ≈ 1000 °C Solid Electrolyte	$H_2 + O^= \rightarrow H_2O + 2e^-$ $CO + O^= \rightarrow CO_2 + 2e^-$ $CH_4 + 4O^= \rightarrow 2H_2O + CO_2 + 8e^-$ water production	$O_2 + 4e^- \rightarrow 2O^=$

Note: Temperature refers to nominal operating temperature, not necessarily start-up temperature.

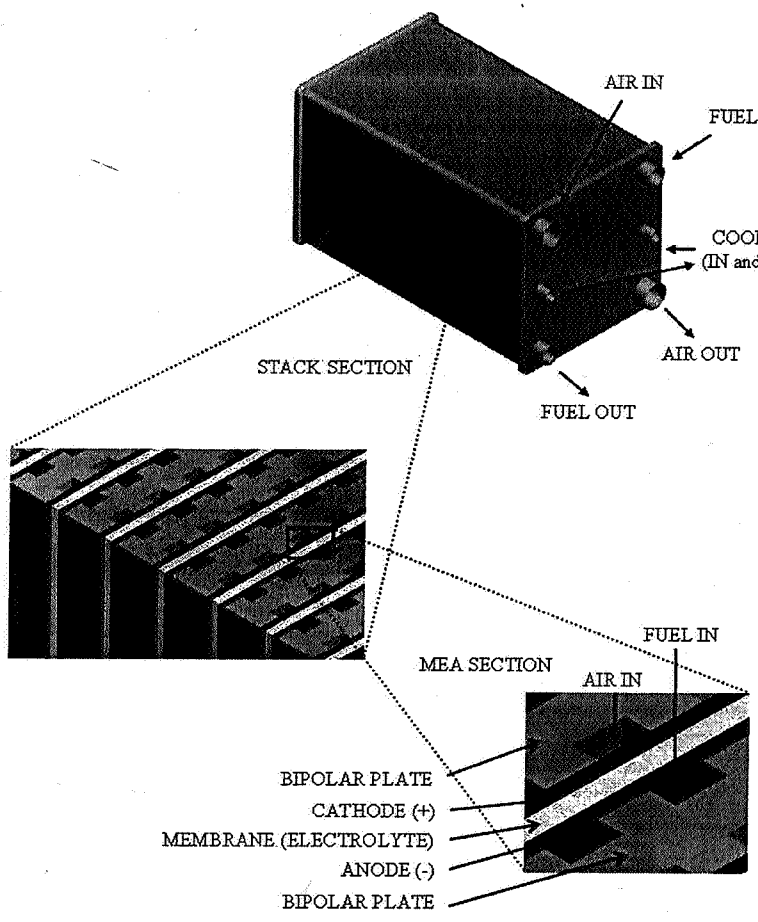
The Proton Exchange Membrane (PEM) technology has been selected by all automotive developers of fuel cells. The PEM has a relatively high specific power at an operating temperature near ambient. It can use air directly without concern for CO_2 and the solid electrolyte of the PEM can sustain a pressure differential from the fuel to air side which is important under dynamic electrical loading conditions. Recent PEM developments provide the ability for rapid startup under frozen conditions.

The solid electrolyte of the PEM is a polymer membrane. The membrane is impervious to the hydrogen and air gases and will only allow positively charged ions to pass through it. The membrane can be very thin and allows for a very compact design in comparison to a liquid electrolyte that must be physically constrained.

4. Fuel Cell Stack and Balance of Plant

To achieve a practical working voltage, individual fuel cells are arranged in a series configuration and are referred to as a fuel cell stack. Unlike typical storage batteries which will use a bus bar and strap approach, the typical fuel cell is constructed with bi-polar plates as shown in Figure 5-6. The reactants are typically introduced by a parallel manifold arrangement.

Figure 5- 6 Fuel Cell Stack Schematic



A typical cell pitch ranges from 3 to 5 cells per cm. A 100 cell stack would have a length of 20 to 33 cm. The stack voltage is the product of the individual cell voltage and the number of cells. The fuel cell stack design must allow for heat exchange and humidification of incoming reactant gases, thermal management, product water management, exhaust gases, and electrical management.

A PEM fuel cell uses a polymer electrolyte membrane. The membrane and associated electrodes are typically in a permanently laminated construction and are referred to as a Membrane Electrode Assembly (MEA). The MEA is the basic fuel cell component. The voltage of the fuel cell stack is determined by the number of laminations and the current is a function of the area of the MEA. To raise the power output, it is necessary to increase the number of laminations or enlarge the area of the MEA.

A fuel cell stack is not a naturally aspirating device like an ICE engine. When the fuel cell is in operation, the reactants, air and hydrogen must be supplied to the electrodes while heat, water and electricity must be removed. The systems that provide these functions are referred to as the

Balance of Plant (BOP). Figure 5-7 illustrates a typical automotive fuel cell power system consisting of the stack and the BOP components.

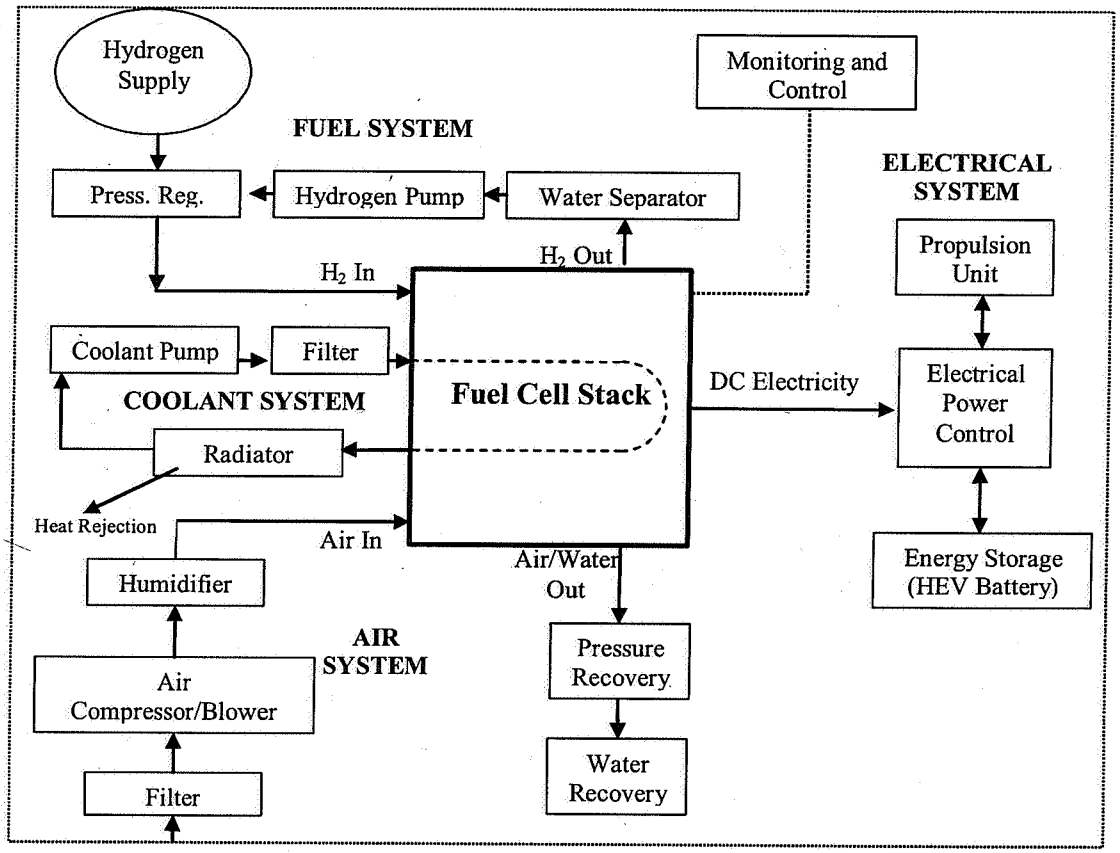


Figure 5- 7 Fuel Cell Subsystems "Balance of Plant"

To support the fuel cell operation, the balance of plant consists of the following subsystems:

- Hydrogen Supply System
- Air Supply /Water Management System
- Thermal Management
- Sensors and Control
- Energy Storage for Start-up Transient Response

The hydrogen and air supply systems provide the fuel and oxidant to the individual cells. These systems generally create a parasitic electrical load due to pumps and blowers. The water management provides gas humidification and product water removal as necessary. The thermal management system maintains the operating temperature of the fuel cell stack by removing heat as necessary. Sensors and controls monitor, manage and sequence the balance of plant to accommodate the electrical load demands on the fuel cell system. Energy storage provides the energy necessary for the fuel cell start up in order to meet automotive peak and regenerative power requirements.

B. Technical Goals and Standards

1. US DOE FreedomCAR Technical Goals

The US Department of Energy (DOE) FreedomCAR Partnership set technical goals for automotive fuel cell systems. The goals were created in cooperation with the automotive industry to identify and bench mark what was considered generally necessary for hydrogen fuel cell vehicles to be affordable and reliable.

Specifically, the FreedomCAR goals were chosen to be first cost comparable to conventional internal combustion engine/automatic transmission systems. The Partnership adopted specific cost goals for 2010 and 2015. The values are provided in the Table 5-3. For comparison, the table includes the FreedomCAR goals for internal combustion engine power trains fueled by hydrogen and clean hydrocarbons.

Table 5- 3: US DOE FreedomCAR Technical Goals

	Specific Power Power Density[1]	**Cost/Selling? Price[1,2]**	**Peak Energy Efficiency LHV**	**Life**
FC system H2 no traction electronics	325 W/kg 220 W/L Operating on Hydrogen Does not include hydrogen storage	$45/kW in 2010, $30/kW in 2015	60% fuel cell power system efficiency Including Hydrogen storage	15 Years
Hydrogen Fuel based ICE power train		$45/kW in 2010, $30/kW in 2015	45%. peak brake engine efficiency	
Clean hydrocarbon based ICE power train		$30/kW	45%. peak brake engine efficiency	

[1]Does not include Vehicle Traction electronics. [2]Cost references based on CY 2001 dollar values.

The table indicates that for a 100 kW fuel cell system to meet the technical goals it would have a mass of < 307 kg a volume < 454 liters and a cost of $3000 in 2015 based on 2001 dollar value. Assuming an inflationary rate of 2.5% this would mean that a 100 kW fuel cell system would cost approximately $4200 in 2015 ($42/kW).

The peak energy efficiency goal based on LHV means that every kg of hydrogen consumed at peak energy efficiency will provide at least 20 kWh of DC electricity. Based on the peak value, it is anticipated that a mid sized FCEV with a DC electrical consumption of 200 Wh/km would have a 100 km range per kg of hydrogen.

Implicit to the fuel cell system life goal of 15 calendar years, 5000+ hours of operation and 5000 to 10,000+ start/stop cycles are to be expected.

2. Automotive Fuel Cell System Standards

Standards benefit the commercialization of a new technology by helping to create an orderly market evolution and associated re-fueling infrastructure. Standards define the basic guidelines for design, manufacturing, safety and ease of use.

Standards in a new technology such as automotive fuel cells require industry cooperation to assure that the advantages are realized while not reducing the flexibility necessary to ensure technological developments. Typically, standards deal with general product safety, performance, compatibility and interchangeability. Standards may be necessary to facilitate the import and export of FCEVs and associated parts.

Automotive Standards for fuel cell systems in place or pending include:

- SAE 2572 (Draft) Recommended Practice for Measuring the Fuel Consumption and Range of FCEVs and HEVs Using Compressed Hydrogen. (Publication is anticipated in 2007) This draft standard is being used by NREL for FCEV dynamometer testing of efficiency values.
- SAE J2574 Fuel Cell Terminology
- SAE J2578 Recommended Practice for General Fuel Cell Vehicle Safety
- SAE J2616 Recommended Practice for Testing Performance of the Fuel Processor Subsystem of an Automotive Fuel Cell System
- SAE J2615 Testing Performance of Fuel Cell Systems for Automotive Applications
- SAE J2617 Recommended Practice for Testing Performance of PEM Fuel Cell Sub-System for Automotive Applications
- SAE 2722 Durability
- SAE TIR J2719 Hydrogen Quality

Non-Automotive Standards for fuel cell systems include:

- IEC, Standards for Fuel Cell Modules, Stationary Power
- NFPA Standards for Fuel Cell Installations

Regulations are necessary to establish the legal requirements for certification and approval of a product and must be consistent with the industry standards.

C. Fuel Cell System Components and Subsystems

A PEM fuel cell system is made up of unique and specific components. To achieve cost and performance goals, each of these components must be optimized for the automotive application. This section reviews these components, their general function and technical status. The specific components reviewed are the PEM membrane electrode assembly, the fuel cell stack and the supporting subsystems which include hydrogen, air supply, thermal management, and system control.

1. Membrane Electrode Assembly (MEA)

The most fundamental component of the PEM fuel cell is the Membrane Electrode Assembly (MEA). It is the prime contributor to the PEM fuel cell system performance, cost and life. The MEA is made up of three basic components that including the solid electrolyte and the anode and cathode electrodes. The anode and cathode electrodes utilize a platinum or platinum alloy catalyst to facilitate the electrochemical reaction. The catalyst generally consists of finely dispersed electrochemical grade platinum particles. This is typically achieved by supporting small platinum clusters on high surface area carbon. A gas diffusion layer may be part of the

MEA and provides a method of gas distribution across the electrode and current conductivity to the stack bi-polar plates.

The challenges associated with the MEA are to reduce cost while simultaneously increasing specific power, life, and durability. Other challenges include operating at higher temperature and recovery from freeze and abuse conditions.

To increase the MEA specific power (W/cm^2) requires a reduction in the ionic resistance of the membrane material and improved electrode-layer structures that more readily allow hydrogen and air to reach the catalyst while allowing the water by-product to be removed.

To give adequate ionic conductivity, conventional membranes absorb water from inlet gases and produce water. Thus, water management (membrane hydration) of the MEA is one of the primary factors in determining performance. Proton conductivity of the membrane is dependent on the water content. Alternatively, excess humidification leads to liquid water (flooding) in the cell which blocks the reactant gases and results in increased concentration polarization. As water is absorbed, the membrane volume increases resulting in mechanical stress. The water content in the membrane also changes during load and start-stop cycles. This mechanical cycling can lead to edge tears and pinholes.

Hydrogen starvation of the anode can lead to MEA failure. This condition can exist in the fuel cell during start-stop cycles. Before startup of the power plant, air is present on both the anode and cathode due to leakage from outside air and/or cross-over through the membrane. During startup, when the hydrogen is introduced to the anode, a condition is created where hydrogen occupies only part of the anode. This creates a high interfacial potential difference in the region where hydrogen is absent causing carbon corrosion and oxygen evolution at the cathode. A similar transition can occur during the shutdown procedure, when the air introduced to the anode from the outside or through the membrane, replaces the hydrogen. This mechanism is also possible during operation when localized hydrogen starvation occurs, even for a short time. The carbon corrosion weakens the physical platinum catalyst support. The platinum moves in location since it is no longer supported for electronic conductivity and becomes effectively inert.

MEA catalyst cost is a major contributor to overall fuel cell system cost. The reduction of the catalyst loading on the air electrode is the easiest means to reduce MEA cost. However, it must be balanced by higher utilization to maintain performance while achieving long life. The platinum catalyst activity can increase when alloyed with other lower cost noble metals such as ruthenium and iridium. Reducing the platinum loading by alloying with other transition metals is being actively researched. The alloying may modify the electronic structure to change the electrochemical potential at which platinum oxidizes which could increase the voltage for the adsorption of oxygen and potentially benefit the catalytic efficiency. State of the art catalysts for the oxygen side reduction are clusters of platinum alloyed with cobalt which are supported on very high surface area globular carbon (Pt-Co/C).

The use of a fluorine electrolyte membrane is limited by high temperature. Structural integrity is lost near 100°C which limits the typical working temperature to 80°C. At low temperatures (<5C°), there is high ionic resistance. New membrane technologies using an aromatic electrolyte are being developed. Compared to the conventional membrane, the aromatic electrolyte membrane maintains a structural integrity at or above 100°C and has a lower ionic resistance at low temperatures.

An increase in MEA operating temperature provides large system advantages including a

smaller and simpler vehicle thermal system as well as the reduction or elimination of humidification and water recovery. Operating at a higher MEA temperature, the fuel cell thermal system could be integrated with the electronic cooling loops and provide more effective cabin heating. Higher temperatures however, typically accelerate degradation mechanisms. Further, chemical degradation processes can be expected to increase exponentially with temperature since the rate of chemical processes typically doubles for every 10℃ increase in temperature. This characteristic adds further complexity to the trade-off of the MEA performance and life.

MEA progress in recent years includes:

- Improvements in applying and immobilizing the platinum catalyst
- Improvements in platinum support
- Improvements in composite membrane structures which increase the mechanical strength and improve dimensional stability
- Improved gas diffusion which allows > 1 amp/cm^2
- Reduced gas cross-over

Future work on high temperature membrane and low humidity requirements will allow higher stack operating temperatures

2. Fuel Cell Stack

The function of fuel cell stack is to provide all the conditions necessary for the MEA to operate. This includes mechanical support of the MEA, supply of reactants, removal of heat, and electricity. All PEM fuel cell stacks use a bi-polar plate configuration. The bi-polar plate is an electronic conductive plate that is sandwiched between successive MEAs. The bi-polar plates incorporate a complex series of manifolds to supply the respective reactants to the MEA and provide thermal management. The bi-polar plates are designed to be as thin as possible to reduce volume and mass while providing the lowest possible electronic resistance between successive MEAs.

The fuel cell stack must manifold six stream flows: air in and out, hydrogen in and out (due to the need for recirculation) and thermal coolant in and out. These flow streams must be kept separated and may include two phase flow. The design of the manifolds presents a complicated 3 dimensional engineering challenge.

Critical to the success of the fuel cell stack are the seals that are utilized between the bi-polar plates to prevent intermixing or external leaks of the flow streams. Further, the sealing must be done in such a way as to prevent electronic shorting between successive bi-polar plates. Significant advances have been made in stack sealing which have nearly eliminated external stack leaks and transfer leaks between internal manifolds. The issue of sealing during thermal cycling has been generally overcome. The bi-polar plates and associated seals represent a significant cost and are the main contributor to mass and volume of the fuel cell stack.

Historically, PEM fuel cells could not start from a frozen state (≤ 0C°) and had to be carefully monitored to operate in freezing conditions. The maximum power available at low temperature was insufficient to power the start-up functions and provide the heat required to warm the stack to the operating temperature. There were three basic reasons for this:

- the conductivity of hydrogen ion exchange membranes declines as the temperature decreases below 0°C.

- the contact resistance of carbon separators increases significantly as the temperature decreases below 0°C.
- carbon separators have a low thermal conductivity and take a long time to warm up.

This freezing problem has been overcome by:

- metal bi-polar plates, lower intracellular electronic contact resistance and flow field design,
- reduced stack heat capacity,
- improved water management at shutdown and startup, and
- improved and more robust MEA and gas diffusion materials.

The remaining stack challenges include the need for continued reduction of mass, volume and cost, and the development of volume production for the unique manufacturing requirements of fuel cell stacks.

3. Hydrogen Supply

The function of the hydrogen supply system is to provide hydrogen to the fuel cell stack and associated MEAs. The hydrogen flow is pressure regulated and recirculated. The recirculation rate is maintained at a flow rate greater than fuel consumption to prevent fuel starvation during rapid load changes, and to remove liquid water from the anode. Within the hydrogen supply system, inert gases (nitrogen and other gases) can accumulate due to cathode gas cross-over of the membrane and fuel quality. Occasional purging of the recirculation loop is used to control inert gases.

Re-circulation of the hydrogen flow stream requires a pump. This has been accomplished in the past by a venturi method but today a variable flow pump is generally used. This adds parasitic electrical load but is able to better manage the recirculation functions of liquid water control and fuel starvation. The hydrogen recirculation pump presents difficult design requirements that include the management of two phase flow.

4. Air Supply and Humidification

The primary function of the air supply and humidification system is to provide oxygen to the cathode side of the MEA in proportion to the fuel cell stack electrical load while maintaining membrane hydration. The system typically consists of an air filter, blower/compressor, humidification section and, in some cases, a pressure recovery device. The air supply system is the largest parasitic load on the fuel cell system.

The fuel cell stack requires a supply of excess air greater than the calculated stoichiometric value, typically 1.5 to 2.5 times that of the ideal mixture. As the air passes over the MEA, oxygen is consumed. The MEA material closest to the air inlet then experiences a higher oxygen partial pressure than does the MEA material closest to the air outlet.

The dynamic electrical loads on the fuel cell necessitate a rapid change in air flow in order to correctly supply a flow rate proportional to the electrical load. Inadequate electrical load following of the air supply can result in oxygen starvation, poor humidity control and MEA flooding.

Increasing the cathode air pressure by means of the blower or compressor improves the

reaction kinetics and water management. Typical operating pressures are 1 to 3 bar over atmospheric pressure. However, the parasitic power to provide the air compression is significant and results in a net loss in fuel efficiency. Exhaust pressure recovery to offset the blower or compressor's parasitic power is possible but adds cost and complexity to the system. The general development trend is to operate at lower air pressures, reducing parasitic power requirements and helps mitigate associated vibration/noise issues.

Water management challenges include gas humidification and anode/cathode flood control, as well as product water removal. Product water can create droplets in the bi-polar plate gas channels that must in turn, be forced out the air exit. This liquid water creates a flooding condition which blocks the gas passage and results in oxygen starvation. Indirect monitoring and management of the product water is critical to the fuel cell operation. Successful development of a high temperature MEA could significantly reduce or eliminate the need for water management.

5. Thermal Management

The function of the fuel cell thermal management system is to provide an optimum operating temperature for the stack and thus the MEA. Heat removal from a fuel cell stack is difficult due to the relatively low operating temperature of the MEA and the quantity of heat that must be removed. Unlike an internal combustion engine, the fuel cell exhaust carries little heat from the stack. The majority of waste heat from the fuel cell reaction (approximately 80%) must be removed by the thermal system. If the thermal system is inadequate, it will restrict the length of time the fuel cell can operate at full power.

A circulating liquid loop is typically used and is designed to minimize stack volume and to provide consistent thermal management for all the MEAs. A variable speed electric pump is used to circulate the coolant. The coolant must maintain dielectric characteristics or be stack voltage isolated. The coolant pump rate must be adjusted for warm-up (recirculation) and to reduce parasitic losses during normal operation.

FCEVs typically use two separate thermal systems, a low temperature loop for the fuel cell and a higher temperature loop for power electronics. The development of a high temperature MEA may allow for a common thermal system with significant cost savings.

6. Sensing and Controls

An automotive fuel cell system must meet a wide variety of operational requirements from freezing start-up conditions to high temperature desert hill climbing. The challenges associated with maintaining fuel efficiency, performance, durability and safety can be substantially mitigated by accurate sensing and control of the fuel cell operation. Following materials and system design solutions, control strategies are generally considered the tool used last by the designer to solve issues and improve performance.

Historically, fuel cell stack voltage and temperature monitoring was done at the single cell or small group of cells to avoid failures by voltage reversal. Other parameters monitored include gas pressure, flow rates, humidification etc. To be effective, the control and sensing system reliability must be higher than that of the fuel cell system. The design is challenging in that the fuel cell controls and associated wiring and sensors become overly complicated, use unique parts, and are costly to build and install.

State of the art fuel cell sensing and controls minimize the number of sensors required and utilize production hybrid vehicle components and engine controllers.

D. Automotive Fuel Cell System - Findings

1. Automotive Fuel Cell Developers

The Panel visited 10 companies that are actively pursuing the development and commercialization of automotive fuel cells. The following are the ZEV Panel findings regarding individual automotive developers, in alphabetical order. Summaries of the individual companies are provided only for those companies who gave prior approval of their specific summary, so as not to inadvertently release confidential information.

a) Ballard Power Systems

Ballard has been actively developing the PEM fuel cell for 20 years and is broadly recognized as a world leader in PEM fuel cell technology. They have protected a large number of key inventions through worldwide patents and have experience in a variety of fuel cell applications. Ballard has clearly defined their focus on the fuel cell stack. Located in Burnaby, Ballard has a purpose built research and development facility with state of the art test and reliability equipment and an aligned manufacturing facility. Hundreds of professionals, many of whom are long-term are employed at Ballard.

The Panel visited and toured Ballard's R&D, Product Engineering, Test & Reliability and Manufacturing facilities. The Panel observed activities ranging from customized research cell testing for water management, individual cell testing, environment testing (stack freeze start) as well as durability testing of commercial-size stacks for automotive fuel cell vehicles and buses. The Panel observed a well organized manufacturing facility using automated equipment that has been designed or modified to fit the needs of low volume fuel cell manufacturing.

Ballard is the exclusive supplier of automotive fuel cell stacks for two major automotive manufacturers, DaimlerChrysler and Ford. These automotive manufacturers hold ownership in Ballard at 19% and 11.4%, respectively. The relationship provides a joint funding arrangement that leads to shared research and field experience. Ballard develops, manufactures and sells the fuel cell stack and in turn, the automotive manufacturers provide the necessary subsystems, vehicle packaging and integration. The combined experience of Ballard and associated partners has resulted in a total of 130+ FCEVs, including buses and light duty vehicles that have operated a total of 3.3 million km. They have the largest number of vehicles and total driven km of any fuel cell Alliance or developer.

Ballard described that its automotive fuel cell development and commercialization activities have led to early success in non-automotive markets such as materials handling and residential cogeneration. Ballard pointed out that fuel cells and batteries are complimentary technologies. The combination of a fuel cell and batteries used in automotive and other applications results in improved fuel economy, fuel cell durability and reduced cost.

Ballard has made significant technical progress. Fuel cell stack power density exceeds 1500 W/kg. Freeze start has improved with start times of less than 90 seconds demonstrated at –25°C in R&D stacks, and –15°C in full 100 kW stack modules. Ballard has developed analytical tools that are fuel cell specific to assist in the technical aspects of cell/stack design and to provide the analysis of the trade-offs between variables that affect cost, performance, weight,

volume, heat rejection, fuel efficiency and durability.

Ballard described to the Panel a four phase automotive technology development plan to demonstrate commercial viability of fuel cell technology by 2010.

The technology demonstration phase (Mk902 stack) is now in DaimlerChrysler, Ford and Honda vehicles that in most cases, are part of the NREL monitored fuel cell fleet (data presented at the ARB September 2006 ZEV Symposium[4]). The customer acceptance phase (Mk1100 stack) is focused on improvements in manufacturability, power density, freeze start capability, robustness and durability. The cost reduction phase will continue the technical advances of the Mk1100, through significant reductions in the use of platinum metal, while substantially increasing volumetric power density and durability. The market introduction phase will pursue further cost reduction and increased reliability.

According to Ballard, cost and durability are the largest barriers remaining to the commercialization of automotive fuel cell stacks. The major cost component of the fuel cell stack is the MEA. The MEA cost issue is being addressed with a focus on the composite membrane material and engineered electrocatalyst layers. Durability is being improved through increased understanding of the key failure mechanisms and accelerated design iterations with improved modeling, tools and test methods. To reduce manufacturing cost, Ballard is developing a multi-step process with the ultimate goal of implementing continuous manufacturing methods.

b) BMW

The BMW Group is a manufacturer of premium vehicles. The BMW objective is to produce vehicles with power trains that exemplify "Efficient Dynamics" which equates to more power, less mass, less fuel consumption and lower emissions. In BMW's view, the combustion engine will remain the main source of automotive propulsion power as it benefits from maturity and optimum cost-efficiency for their target market, at least for the next decades.

BMW is developing small fuel cells for use as Auxiliary Power Units (APU). Both PEM and SOFC fuel cell types are being considered. In the long term BMW sees potential for fuel cells in the electrification and control of ancillary units such as air conditioning and power steering. Rather than being parasitic to the combustion engine, these electrified components will be powered by an APU fuel cell, independent from the ICE. The fuel cell reduces load from the hydrogen ICE for increased driving performance and leads to a greater overall fuel efficiency. New customer benefits are possible like electric air conditioning when the ICE is switched off and driving in pure electric mode within cities at low speed.

In addition to further improvements of the hydrogen ICE in terms of efficiency and NOx-emissions (< 10% of SULEV limit), the integration of the ICE and a small fuel cell in a hybrid power train offers a high power-to-weight ratio and dynamics at low cost (ICE) in combination with high efficient low-load-conditions at acceptable cost (small fuel cell).

The BMW PEM based APU development is in cooperation with UTC Power. BMW provides vehicle integration and, together with UTC Power, the system development. The SOFC based APU development is an in-house activity at BMW.

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[4] "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, Project Overview and fall 2006 Results" National Renewable Energy Laboratory. Wipke, K. & et. al.

The Panel visited the BMW Engineering facility in Munich and was shown a PEM APU fuel cell, and a research hydrogen ICE engine, both operating on the test bench. The Panel was given the opportunity to drive the hydrogen powered ICE 7 Series sedan (no fuel cell APU) and observe refueling of liquid hydrogen.

BMW described the key developments needed to facilitate a PEM fuel cell as:

- A membrane with low humidification demand for easy water management, lower amount of platinum for the catalyst, and longer life time.
- A higher power density to reduce weight / volume and an increased efficiency to reduce the cooling system size.
- Reducing cost by using cheaper materials for the catalyst and the bipolar plates and reducing system complexity.

The answers BMW provided to the ZEV Panel questionnaire describe that performance; durability and cost are conflicting issues in the development of the fuel cell APU. They also described that FCEV performance and cost parity with ICE vehicles was not possible. However, BMW pointed out the efficiency of an FCEV could be greater than an ICE vehicle. They believe that the FCEV cost will be significantly higher than that of a hydrogen ICE with a small fuel cell. Further, BMW is of the opinion that the small fuel cell APU approach is seen as an add-on solution and will help introduce fuel cells to automotive applications.

c) Daimler Chrysler

DaimlerChrysler (DCX) is part of a cooperative alliance with Ford and Ballard Power Systems. DCX holds an approximate 19% ownership in Ballard while Ford has 11.4%. There is also a joint venture between DaimlerChrysler and Ford called NuCellSys in Nabern, Germany. The NuCellSys venture is a 50%/50% relationship between DCX and Ford.

DCX started the development of FCEVs in the early 1990s and has demonstrated fuel cell powered cars, mini-vans and buses. The panel visited the fuel cell development center in Nabern, Germany. During this visit, the panel saw an impressive history display of the DCX fuel cell developments and vehicles,

DCX has over 100 FCEVs in world wide operation with over 2 million km of experience. Achievements that occurred from 1994 to 2004 include increased efficiency, reduced operational noise, improved performance and packaging. The technology road map for light duty vehicles being undertaken by DCX is as follows:

1. Technology Demonstration	2004 (Gen 1, Ballard Mk 902)
2. Customer Acceptance	2009 (Gen 2)
3. Cost Reduction	2012 (Gen 3)
4. Cost Reduction and Market Introduction	2015 (Gen 4)
5. Mass Production	2020 (Gen 5)

The DCX Gen 1 vehicles are currently part of the NREL monitored FCEV fleet. The challenges that DCX sees in the immediate future for Gen 2 include fuel cell system mass reduction, increased reliability and durability, the ability to withstand freeze starts, and thermal management. The Gen 2 stack is currently being developed by Ballard in collaboration with DaimlerChrysler and Ford. The Gen 3 and 4 fuel cell stacks are now at the research phase.

To achieve the technological advances necessary for market introduction (Gen 4), the fuel cell system requires further mass and size reduction with increased power. The system complexity needs to be reduced by component optimization and elimination with a significant reduction in cost. It is expected there will be a high level of power electronic integration. DCX sees that conventional hybrid developments had supported some of the electronic component developments. Mass production (Gen 5) will require further optimization and significant cost reduction, and technical achievements such as extreme cold start capability and hybridization.

DCX described that fuel cell system performance and cost targets can be achieved by eliminating and simplifying the components. The architecture can be met only if new fuel cell stack design developments can be accomplished. Hence, the level of development of the fuel cell stack ultimately determines the performance characteristics and cost of the fuel cell system.

DCX described that simultaneously reducing cost and improving performance and durability is the major challenge for stacks in Gen 3 and beyond. Gen 4 fuel cell stack innovations and inventions require flow field design, water management, corrosion resistant bipolar plates, improved catalysts (low loading, higher durability), and low cost gas diffusion material.

DCX described that the ultimate fuel cell drive train costs have the potential to be reduced considerably by a combination of technological improvements and economies of scale. Cost reduction approaching the level of conventional vehicles is possible. Sales in the range of 100,000 FCEVs per year can only be reached if the fuel cell component suppliers can expand accordingly. Onboard fuel storage and hydrogen infrastructure are also barriers to widespread introduction of fuel cell vehicles.

d) Ford

Ford is part of a cooperative alliance with DCX and Ballard Power Systems. Ford holds 11.4% ownership in Ballard while DCX has 19%. There is a joint venture between Ford and DCX called NuCellSys in Nabern, Germany. The NuCellSys venture is a 50/50 relationship between DCX and Ford. The technology sharing through these partnerships is essential to accelerate the development of these pre-commercial fuel cell technologies. Ford started the development of FCEVs in 1995 and has demonstrated fuel cell powered cars, and SUVs. Ford is increasing research and development activities of fuel cell systems and vehicle research despite corporate financial difficulties.

The panel visited the Ford FCEV development center in Dearborn, MI. During this visit, the panel was presented technical and cost data. The panel saw vehicle and research laboratories, and was given the opportunity to drive a demonstration vehicle based on the Ford Explorer. This technology demonstrator was purpose built within the constraints of the Explorer chassis. The Explorer FCEV utilized an under the hood position of the fuel cell system with centralized hydrogen storage in "drive shaft position". The vehicle was impressively smooth, responsive and quiet in operation. This is however, a purpose-built vehicle, not a production model.

The Ford Focus FCEV is part of the NREL monitored Department of Energy (DOE) Learning Demonstration fleet. It was purpose built within the constraints of the Focus chassis. The Focus FCEV utilizes a Ballard Mk902 fuel cell stack (440 cells) hybridized with a Sanyo battery pack. The fuel cell system provides a net peak power of 68 kW. The fuel cell balance of plant uses a screw type air compressor with a contact humidifier and a multi-stage jet pump for hydrogen recirculation within the fuel cell stack. The Focus FCEV has a city/highway fuel consumption

that is 55%/66% that of its non hybrid gasoline counterpart.

The Ford philosophy for commercialization of FCEVs is that it must have no customer compromise compared to other alternatives. Ford believes that until the technical and commercial challenges are overcome, the FCEVs will not be commercially viable. The no compromise characteristics include:

- Cost (initial and lifetime operational cost)
- Performance
- Reliability & Durability
- Vehicle Utility

The technical challenges that Ford is addressing for a fuel cell propulsion system include the stack and system useful life, durability, and robustness, and on-board fuel packaging and weight. Ford believes that preparing for high volume production detracts from advancing core fuel cell technology because it employs resources that could otherwise be used for research and development. Fuel cell system costs are a major concern for commercial viability because more than an order of magnitude reduction is required. Customer acceptance of new, unfamiliar, and expensive technology with limited fueling infrastructure also makes commercialization of this technology very difficult.
Ford emphasized that commercialization will require time and resources to overcome technical and commercial issues to attain the no customer compromise compared to other alternatives. Ford anticipated that between the years of 2015 to 2020, low volume government and/or commercial demonstration/development fleets are possible. Ford expressed concern about inadequate resources for research and development timelines if an early commitment to high volume FCEV production were to be made.

Ford described that fuel cell technology holds great promise to be a sustainable mobility option; however there are no clear winners. Ford also described their commitment to a portfolio of advanced environmental technologies, including E85 flexible fuel vehicles, clean diesel, hybrid electric vehicles, hydrogen internal combustion engines, and fuel cell vehicles.

e) General Motors

General Motors has a variety of fuel cell activites underway working toward the goal of developing an automotive competitive fuel cell propulsion system (FCPS). GM's fuel cell program started in the mid 1990s. The panel visited the GM fuel cell development centers in New York, Detroit, Torrance and Mainz, Germany. During these visits, the panel observed activities ranging from basic material development to the engineering of complete systems. These next generation designs have begun to incorporate manufacturing considerations and are now in validation. Additional generations with simpler designs, improved materials, and volume manufacturing processes will be required before fuel cell electric vehicles (FCEVs) can be produced on a large scale.

Where possible, GM is leveraging its conventional and hybrid development programs to support fuel cell development. An example is the engineering integration of high volume electronic control modules to GM fuel cell systems. GM noted however, that many of the fuel cell critical path components (stack, unique subsystems, and hydrogen storage) are not supported by conventional or hybrid development programs. These critical path components require development programs that involve substantial resources and time.

GM described the path to developing an automotive competitive FCPS and the subsequent introduction of vehicles into the marketplace as follows:

1) Advances in technology through material solutions, design and systems solutions.
2) Comprehensive strategies to mitigate the constraints associated with the introduction of a new technology at low initial volumes.
3) Extensive market development to avoid introducing the technology too quickly (immature) or too slowly (delayed benefit and higher cost due to inadequate volume).

GM has made significant technical progress from membrane electrode assembly development to vehicle packaging. GM is working on system power density, freeze durability, high ambient temperature operation, subsystem simplification and efficiency gains and believes these issues will be addressed. Issues of durability and cost remain as the most significant hurdles to the development of an automotive competitive FCPS.

GM's next generation of demonstration fuel cell vehicles (2007 to 2010) will incorporate some of these technical advances. The "Equinox" is based on a 4-passenger version of a Chevrolet crossover vehicle and is expected to meet all FMVSS and ZEV requirements. It is designed for freeze durability and a 50,000 mile operating life. The EPA city and highway combined range is 200 miles with hydrogen storage of 4.2 kg at 700 bar.

The GM goal for 2010 is to design and validate a fuel cell propulsion system that is automotive competitive. This means that assuming high volume manufacturing, the fuel cell propulsion system would have performance, durability and cost equivalent to today's internal combustion engine propulsion system (on a common functionality basis). In addition, substantial production and manufacturing process development will be required to execute the design solutions into marketable fuel cell vehicles.

GM has the most aggressive cost goals of any fuel cell automotive developer. It believes cost targets can be met with the current family of stack materials. Achieving the $50/kW fuel cell propulsion system cost target will require a progression of generational design simplification, materials thrifting and substitution, supplier engagement and manufacturing process development..

GM described that FCEV production will also require the development of a strategic supplier network for unique fuel cell system materials and components. The majority of current suppliers are not traditional suppliers to the automotive industry. Long term commitments and substantial resources will be required.

GM believes initial market entry of production FCEVs could occur sometime before 2015. Depending on external factors such as the availability of safe, convenient, and affordable hydrogen fueling and supportive government policies, larger volume production could occur sometime after 2015. Based upon current information it appears that the volume necessary for per unit breakeven (not cumulative cash breakeven) would be in excess of 500,000 FCEVs per year.

Substantial government assistance (at the federal, state, and local levels) will be required to overcome the near-term and longer-term business risks / costs associated with hydrogen refueling and FCEV market introduction and acceptance. This assistance needs to include at least the following elements:

- Implementation of a comprehensive and clear national energy strategy that focuses on

every sector, not just the vehicle.

- Sustained long-term financial incentives for automakers, suppliers, infrastructure providers and customers.
- Government as an early and ongoing fuel cell vehicle customer at meaningful volume levels.
- Support for uniform vehicle and infrastructure codes and standards.
- Actual implementation and deployment of a comprehensive fueling infrastructure and affordable hydrogen fuel to assure customer acceptance of FCEVs.

f) Honda

Honda has a large fuel cell development and commercialization program that was initiated in 1989 and significantly expanded in the mid 1990's. Honda first demonstrated their FCEV in 1999 using a Ballard Power System fuel cell stack. The use of Ballard stacks continued through 2004. In parallel, Honda developed its own fuel cell stacks and introduced them for early applications in the MY 05/06 FCX with cold start capability to -20C. Honda has delivered over 40 FCEVs (model years 03 to 06) to the US and Japan for customer evaluation.

At their fuel cell development center in Japan, Honda presented to the Panel, information about their automotive fuel cell technology development and gave the Panel a tour of the fuel cell development laboratory facilities.

Honda's plan for FCEV commercialization includes four major steps:

1.	R&D Demonstration	2005 (Gen 1)
2.	R&D Demonstration	2010 (Gen 2)
3.	Pre-Commercialization	2015
4.	Early Commercialization	2020

The R&D demonstration phases 1 and 2 include production of a limited number of FCEVs that are highly instrumented to permit rapid analysis and information feedback into development cycles. The pre-commercialization step will focus on increased durability, operation in temperature extremes, increased driving range and cost reduction. The early commercialization step is intended to further improve durability and reliability to match that of a conventional vehicle and reduce cost.

In Honda's view, the three major areas of fuel cell durability, driving range, and cost reduction require substantial improvement before commercialization can occur. Honda pointed out that there is a significant difference between laboratory durability results and real world experience. Honda is mitigating these degradation mechanisms through further development. The cost issues involve the fuel cell stack, the fuel cell system components, energy storage and electric drive. Fuel cell cost reduction will require additional material R&D and production process development. Specifically, reductions in the costs of the MEA and bi-polar plates are necessary. Honda noted that in order to reach cost targets for early commercialization, a catalyst breakthrough or alternate catalyst was necessary in addition to Honda's use of an aromatic hydrocarbon electrolyte membrane that permits higher temperature fuel cell operation for increased stack performance.

g) Nissan

Nissan has an advanced fuel cell development and FCEV commercialization program that started in 1996. During its visit of the Nissan fuel cell development center in Japan, the Panel observed activities ranging from basic material development to the engineering of complete systems. Also, the Panel had an opportunity to drive a demonstration FCEV vehicle based on an SUV chassis. The vehicle operation was smooth and responsive.

Nissan has 10 FCEVs in leased or customer vehicles in Japan and expects to have 8 customer vehicles testing by the end of 2007 in the USA. These vehicles will have a 90kW fuel cell stack and system developed internally at Nissan. The fuel cell system is hybridized with a Li Ion battery and has a 7.2 second startup time.

The Nissan research and development effort is focusing on resolving issues in two key areas:

- Durability and reliability
- Assurance of low temperature starting ability

The durability of the PEM fuel cells must be improved to meet the operating life of more than 5,000 hours under normal automotive driving conditions. Operating at a near constant load, the fuel cell can exceed 5,000 hours. This is however, significantly reduced to 1000-2000 hours under the dynamic electrical loads of an automobile. Nissan is addressing degradation mechanisms associated with system start/stop, electrical load cycling, and thermal cycling. They are also developing new materials for the catalyst layers and the solid polymer membrane and technologies for suppressing their degradation. To address the low temperature start-ability, Nissan is developing methods to prevent product water from freezing or quickly liquefying on cold start.

The durability of the PEM fuel cells must be improved to provide an operating life of more than 5,000 hours under normal automotive driving conditions. Operating at a near constant load, the fuel cell can exceed 5,000 hours but life is reduced to 1000-2000 hours under the dynamic load cycles imposed by automobile operation. Nissan is addressing degradation mechanisms associated with system start/stop, electrical load cycling, and thermal cycling. They are also developing new materials for the catalyst layers and the solid polymer membrane as well as techniques to suppress their degradation. To address the low temperature starting ability, Nissan is developing methods to prevent product water from freezing or quickly liquefying on cold start.

Nissan emphasized the need for drastic cost reduction for the FCEV commercialization, including:

- Cost reduction of the MEA
  - Reduction of the amount of Pt in catalyst
  - Reduction of membrane cost
- Simplification of the fuel cell system
  - Innovation of stack materials
  - Elimination of BOP (examples: external humidifier; hydrogen pump)

Nissan estimates that based on materials cost alone, the cost of a fuel cell system is still several times higher than that of an ICE. In order to lower the cost, it is necessary to simplify the balance of plant and to reduce the quantity of platinum used in the MEA. No time estimates for commercialization were provided.

h) Toyota

Toyota has had an automotive fuel cell development program since 1992. Visiting the Toyota fuel cell development center in Japan, the Panel toured engineering laboratories and was given an opportunity to drive a demonstration FCEV vehicle based on an SUV chassis. The vehicle operation was smooth, quiet and responsive. Toyota has demonstrated fuel cell technology in mini-cars, cars, buses, fork lifts and stationary applications. Demonstrations of Toyota FCEVs started in 2001 in the USA and there are now a total of 25 Toyota FCEVs in California.

Toyota is independently developing a 90kW fuel cell stack and balance of plant. The specific technical issues that they indicated need to be addressed include:

- Fuel cell durability,
- Start and operation in low and high ambient temperatures,
- Need for higher efficiency
- Hydrogen embrittlement of components
- Hydrogen storage technology

Toyota has reduced the fuel cell durability problems by developing improvements in the physical and chemical stability of electrolyte membranes. They have demonstrated a hybridized FCEV start-up period of one minute from a starting temperature of -30°C and consider hybrid technology important to the fuel cell system. Toyota indicated that a further reduction of the start-up time and improvements to the drive performance will be necessary for commercialization. Regarding efficiency, Toyota indicated that vehicle fuel cell efficiency (km/kg) during on-road driving was dramatically reduced when compared to dynamometer testing (10:15 mode). Further, air conditioning and average speed significantly influence fuel consumption and vehicle range.

In order to achieve commercialization, Toyota estimates fuel cell system cost will need to be reduced to 1/100 of the cost of current prototypes. Cost reduction by a factor of 10 is projected for innovations in design and materials. Another 10-fold reduction will have to be achieved through the efficiencies and economies of mass production. Specific targets for cost reductions include reduction of platinum catalyst loadings to 10% of the current values; membrane cost reduction, as well as changes in the design of manufacture technology and of the manufacturing processes themselves.

Toyota noted that the FCEV is still in the R&D phase with additional development and more time needed before commercialization is possible. Technical development targets, cost and vehicle range as well as adding appeal to the product are considered key challenges. Toyota did not provide dates for commercialization but indicated the general progression from small demonstration fleets through small scale production (e.g., 1000 per month) to larger volume production.

i) UTC Power LLC

UTC Power is a division of United Technologies Corporation, a $47.8 billion company that provides high-technology products and services to the building and aerospace industries. A full-service provider of environmentally advanced power solutions, UTC Power has nearly 50 years of experience. The company is a world leader in developing and producing fuel cells for on-site

power, transportation, space and defense applications, and a developer of other innovative combined cooling, heating and power applications in the distributed energy market. It has been a supplier to BMW, Hyundai, Nissan and numerous fuel cell bus programs. Since 1997, UTC Power has been actively developing automotive PEM fuel cells and the company has developed unique intellectual property in the area of bi-polar plates that use a porous, hydrophilic material to facilitate water management. Specifically, the process humidifies inlet gas streams to maintain saturation of the membrane.

The panel visited and toured the UTC Power manufacturing and development facilities and observed activities ranging from engineering development to cell and stack durability testing.

UTC Power believes that the key to fuel cell performance and durability is water management. By proper humidification of the membrane, a high conductivity and long life is possible. By efficiently removing product water, gas transport is maintained and local fuel starvation is avoided. UTC Power presented to the panel the durability data of a 20-cell stack load cycle which performed 100,000 cycles in 3000 hours without failure. The success was attributed to the unique method of water management.

UTC Power is focusing on increased system power density by reducing the volume of the fuel cell stack and system balance of plant simplification. The projected fuel cell system power density for 2007 is greater than 0.5 kW/liter and is predicted to be 0.65 kW/liter. Advanced fuel cell stack power densities, projected to be greater than 1.4 kW/liter in the near future, are consistent with the system power densities projected above. UTC Power has done laboratory demonstrations of 20-cell stacks doing freeze starts from -20°C with no performance degradation, as well as -40°C parts survivability. In-vehicle verification of the advances made in durability, power density and freeze capability are ongoing.

UTC Power described the obstacles to widespread adoption and commercialization of automotive fuel cell systems to be: 1) continued support for development, scale-up, and vehicle integration, 2) cost 3) on-vehicle hydrogen storage and 4) hydrogen fuel infrastructure.

2. Fuel Cell System Performance Estimates

The performance of fuel cells has dramatically improved in recent years. Stack power densities in excess of 1 kW per kg are now common. Figure 5-8 provides an estimate of automotive fuel cell stack and system peak power density as a function of time. The figure presents the cumulative data from developer's estimates in comparison to the FreedomCAR fuel cell system goal. The peak power density of the fuel cell stack is expected to be substantially higher than the system goal to accommodate the mass of the balance of plant.

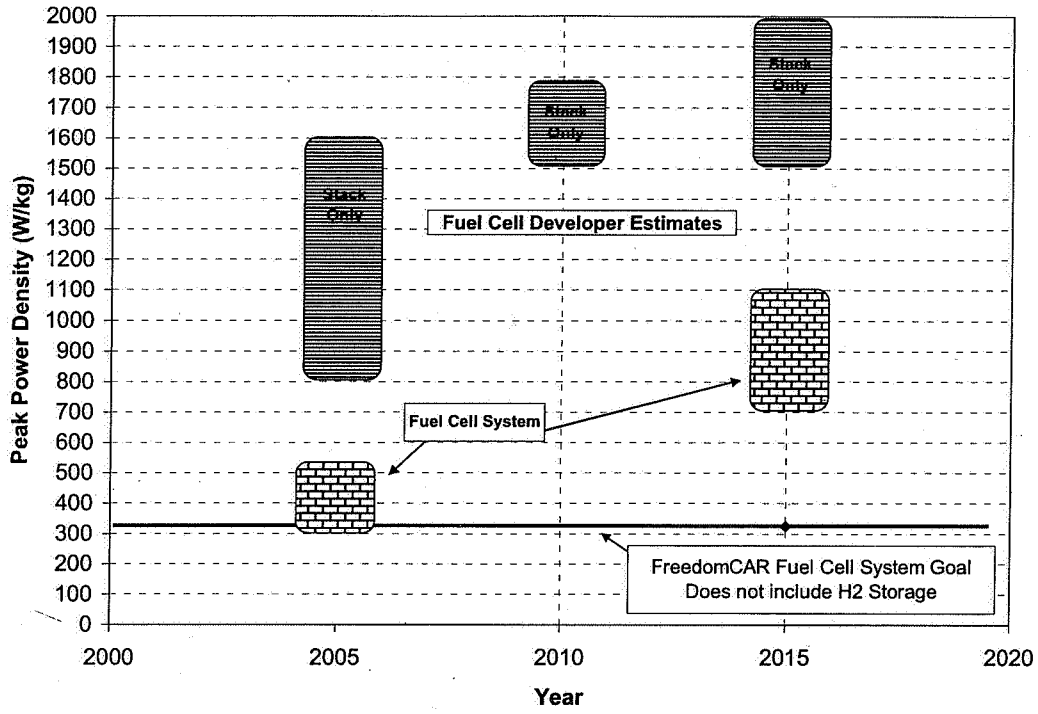


Figure 5- 8: Fuel Cell Stack and System Power Density Development

As shown in Figure 5- 8, the 2005 fuel cell stack peak power density ranges from a low of 800 W/kg to a high of 1600 W/kg. This broad range is likely the result of the timing of different development programs and represents technology over a number of different years. Further increasing the stack peak power density will be achieved by a combination of higher specific power MEA and lighter bi-polar plate materials. Comparing estimates of 2010 and 2015 shows only a relatively small change in stack power density.

The system power density in 2005 is approximately equal to the FreedomCAR goals and by 2015 fuel cell systems are estimated to exceed the goals. The panel did not receive any estimates of system power density for 2010.

The fuel cell system life is vital to its commercial success and can be based on hours of use, years of typical service, kWh of energy produced and so on. The FreedomCAR goals are generally considered to be greater than 5000 hours of use in a 15 year period. The following Figure 5-9 provides developer's life estimates in comparison to the FreedomCAR fuel cell system goal of 15 years.

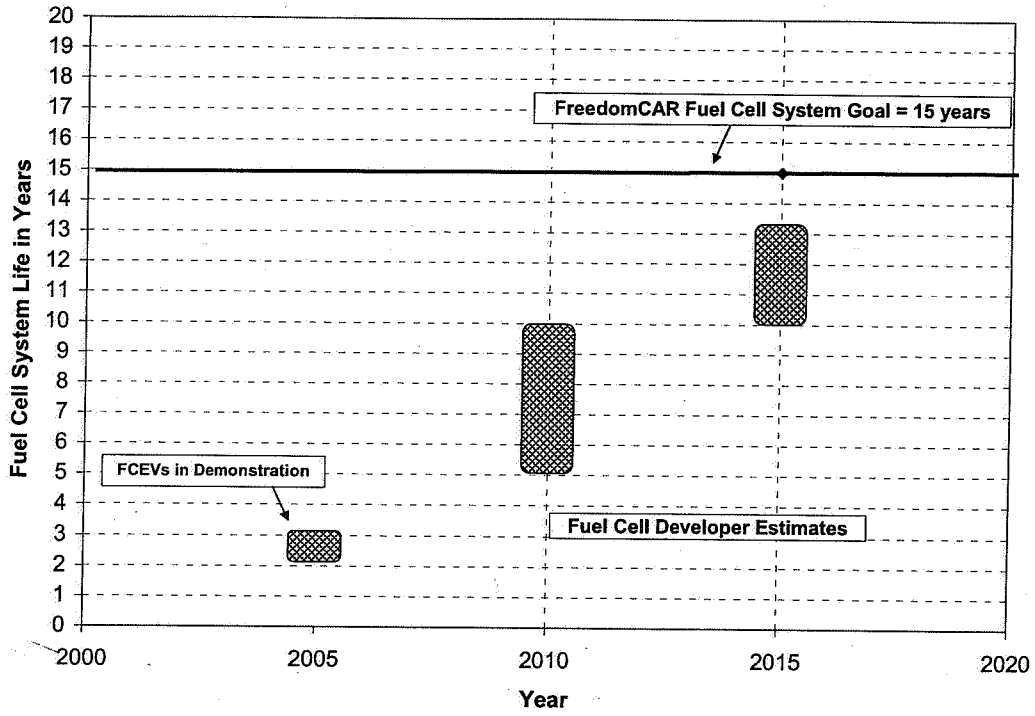


Figure 5- 9 Fuel Cell System Life in Years

Figure 5-9 indicates that in 2005, the fuel cell system life is significantly less than the goal. The issue of durability is considered a major challenge by the developers as there are many possible failure mechanisms. Understanding of failure mechanisms is paramount and the use of improved materials, controls and statistical control of manufacturing are expected to improve the fuel cell system life.

Developers are optimistic that the life issue can be improved but indicate it will be difficult to reach the 2015 FreedomCAR goal. Accurate accelerated testing procedures are still being developed to realistically age the fuel cell system over a shorter period of time. Demonstration fleets are currently the only available means of characterizing real world performance and durability for the fuel cell system.

Some fuel cell developers view hybridization and associated fuel cell load management as a significant method to improve fuel cell durability and to lower the overall system cost. In battery dominated hybrid applications such as fork lifts and buses, fuel cell life has been significantly greater than in light duty vehicle applications. Hybridization will improve vehicle efficiency by brake energy recovery but will not reduce the overall vehicle cost for the same continuous power (trailer towing application). If full power is not needed to be continuous, then energy storage can reduce the overall system cost. In this case, the goal of the power train designer would be to install the smallest fuel cell possible to meet vehicle performance requirements.

Platinum used in a fuel cell MEA has been and remains a fundamental impediment to automotive commercialization. The need for a high specific MEA power combined with low cost makes the automotive application particularly difficult to meet. The MEA platinum loading (total mg/cm^2) has been on a steady decline as methods of preparation, application and support have

improved. However, the rising cost of platinum necessitates significant further reduction. The following Figure 5-10 presents a composite of developer estimates of platinum loading as a function of time, as well as those estimated by US DOE contractors TIAX and Directed Technologies Inc.

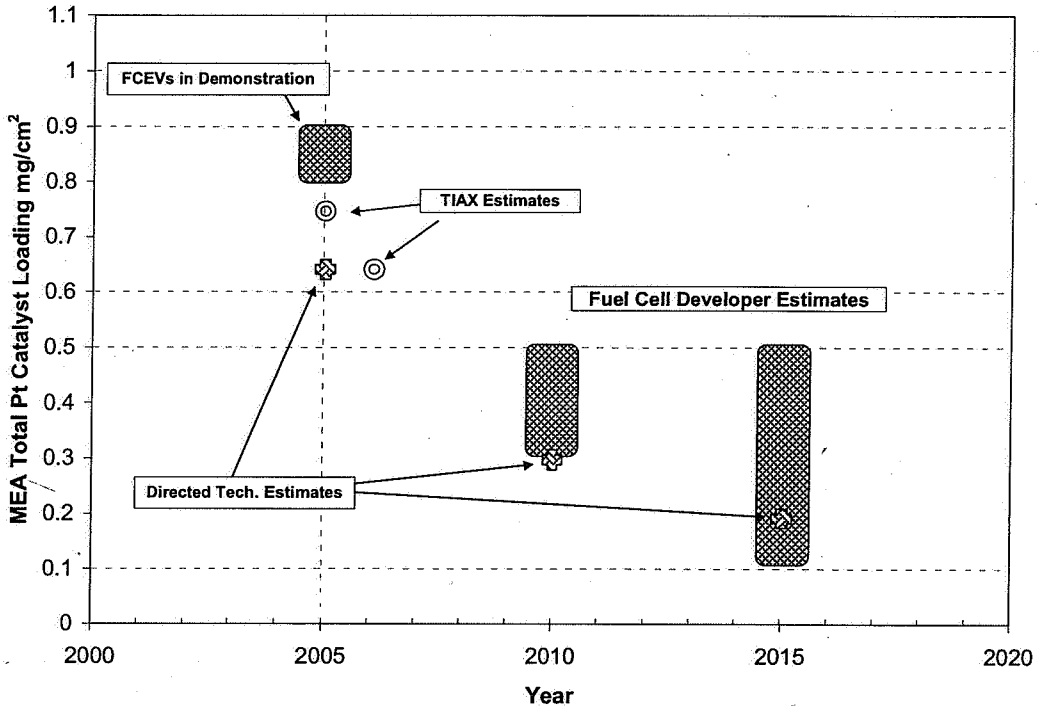


Figure 5- 10 MEA Platinum Loading Estimates

Figure 5- 10 indicates that fuel cell developers are predicting a sharp decline in MEA platinum loading between 2005 and 2010. Between 2010 and 2015 some developers predict a further significant decline while others feel that due to life and durability considerations, the Platinum loading will not significantly change. The lowest value in 2015 (and beyond) was estimated to be 0.1 mg/cm^2.

Platinum is a world wide commodity and is valued for jewelry and its catalytic properties. It is the rarest and the most expensive of the three "precious metals" (Ag, AU, Pt) Platinum is physically harder than gold and silver and has a higher melting point. These attributes make it more difficult to alloy and prepare as a fuel cell catalyst. In the past 6 years there has been a significant increase in the commodity cost of platinum as shown in Figure 5- 11 (Johnson Matthey price data). The actual cost of fuel cell grade platinum is higher than commodity cost due to preparation.

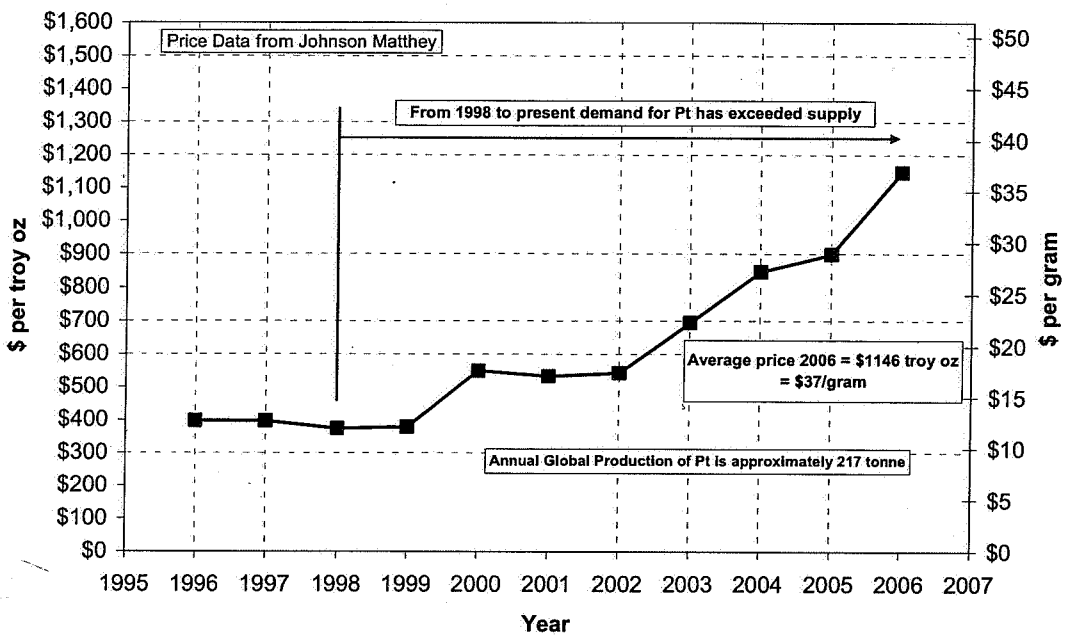


Figure 5-11 Average Annual Platinum Cost 1996 to 2006

Developers are working to mitigate the increasing costs of the platinum catalyst by a combination of:

- Reduced platinum loading (See Figure 5- 10)
- Platinum replacement by alloying
- Higher platinum utilization by increased MEA specific performance (See Figure 5- 12)
- Reduced catalyst preparation cost

The specific power of the fuel cell MEA is increasing. A higher MEA specific power allows a given fuel stack to produce more power and thus achieve a lower $/kW. Nearly every stack cost factor, for a given voltage, decreases in inverse proportion to MEA specific power. A higher MEA specific power is accomplished by lower resistance and improved electrode-layer structures to ensure voltage at a higher operating current density.

The following Figure 5-12 presents developer's MEA specific power estimates as a function of time, as well as those estimated by US DOE contractors TIAX and Directed Technologies Inc.

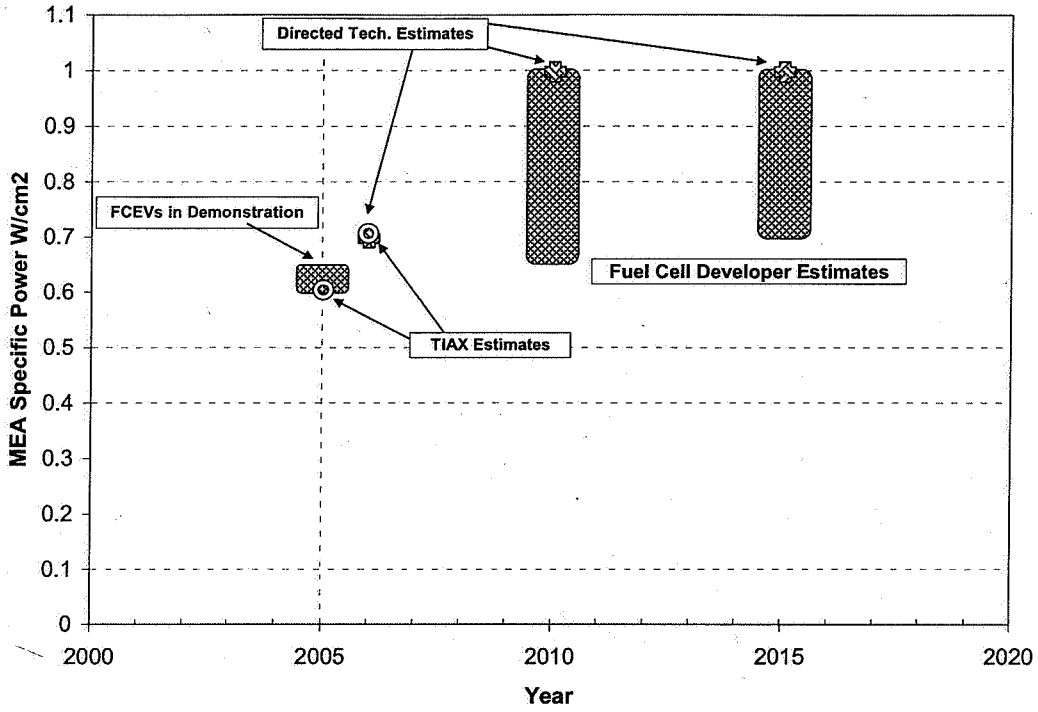


Figure 5- 12 MEA Specific Power Estimates

The figure indicates that developers anticipate an increase in MEA specific power by 2010. By 2015, the estimated maximum specific power will not have further increased but the lower value within the estimated range has increased. The highest foreseeable specific power is 1 W/cm^2. This will require operating the MEA at approximately 1.5 Amps/cm^2 and a cell voltage of 0.66.

3. Fuel Cell System Cost Estimates

Fuel cell system cost remains high with developers estimating that several generations of technology development will need to occur prior to volume production. System cost estimates are confidential to the individual developers and the panel received limited cost data on a relative and absolute basis. Figure 5-13 presents the US DOE relative percentage cost estimates for the major components of a fuel cell system in 2006. The fuel cell stack is the major component of this cost almost 60%.

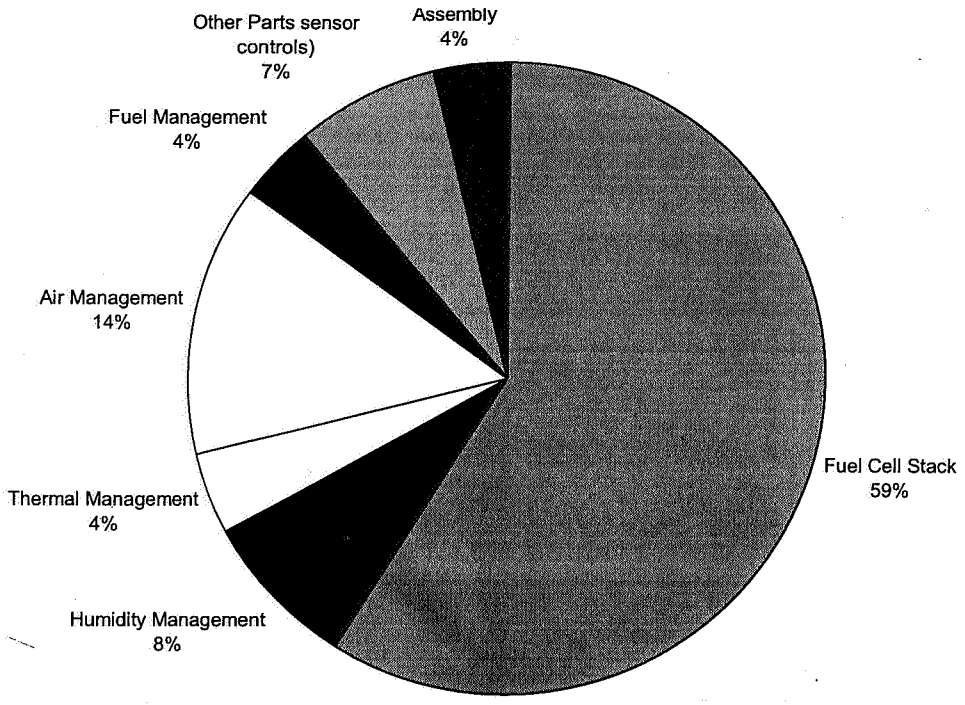


Figure 5- 13 Fuel Cell System Cost Estimate -TAIX

The relative cost values presented in Figure 5- 13 were compiled based on the limited data provided to the Panel by the developers.

The $/kW cost of a fuel cell system in volume production is dependent on the level of design maturity, material cost assumptions, and manufacturing method. The limited data provided to the Panel was not consistent in assumption of design, material cost and level of volume production. The following Figure 5-14 presents a composite of developer estimates of fuel cell system cost as a function of time, as well as those estimated by US DOE contractors TIAX and Directed Technologies Inc.

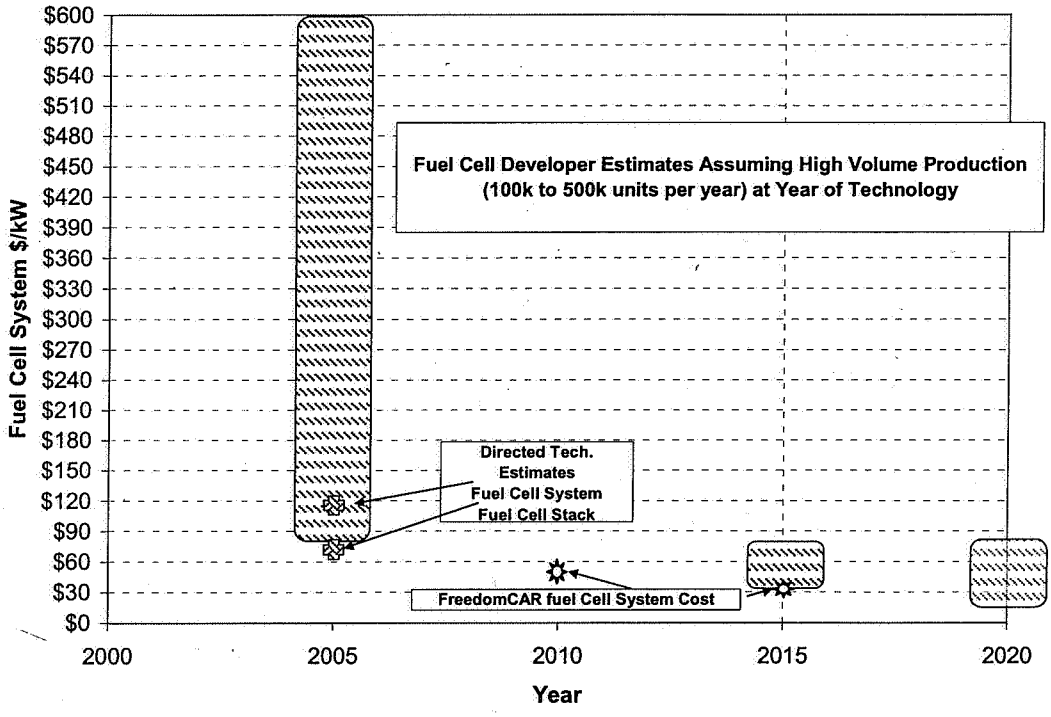


Figure 5- 14: Volume production Fuel Cell System $/kW

As shown in Figure 5-14, the developer cost estimates vary widely for volume production of 2005 technology. The reason for this wide variation in the composite data is the relative confidence in the maturity of the technology and assumptions on materials and volume production (10 to 500 k units per year). The estimated values for 2015 converge to values that range from the FreedomCAR goal to 2.5 times that goal. The Panel was also given some long term projections of cost (indicated at the year 2020) that indicate the $/kW ranging from less than the FreedomCAR goal to 2.5 times that goal.

Continuing development will likely increase the performance and decrease the cost of the stack. Some developers estimate that cost reduction by technical innovation could reduce the prototype fuel cell system cost by a factor of ten while manufacturing could possibly further reduce cost by another factor of ten.

a) Fuel Cell Stack Cost Estimates

The fuel cell stack dominates the cost of the fuel cell system, see Figure 5- 13. Individual developers consider stack cost estimates confidential and therefore the panel received limited cost data on a relative and absolute basis. Figure 5-15 presents the US DOE percentage cost estimates for the major components of a fuel cell stack in 2006. The MEA and gas diffusion layer material account for approximately 88% of the total stack cost.

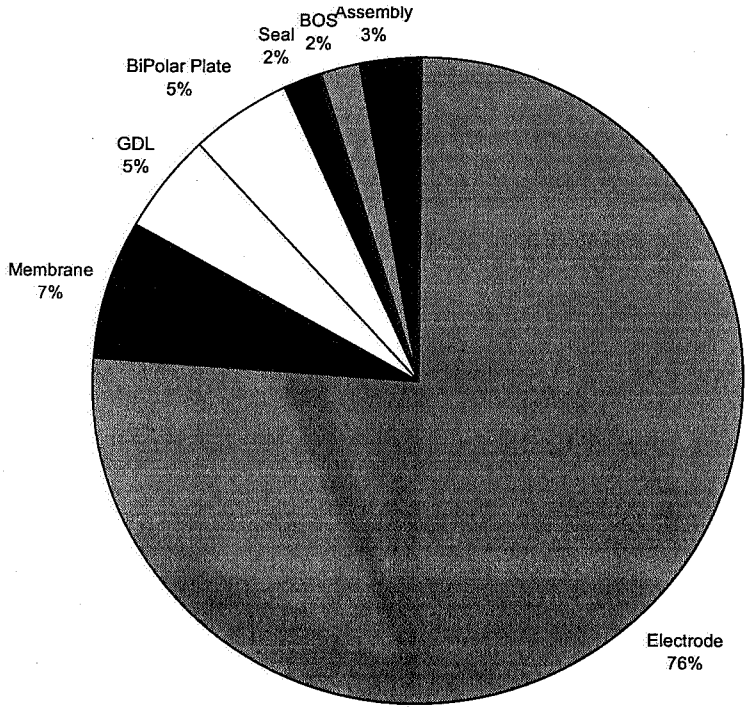


Figure 5- 15 Fuel Cell Stack Cost Estimate - TIAX

As noted earlier, in the past 5 years there has been a significant increase in the cost of platinum. As a result, the fuel cell stack cost is dominated by electrode costs as illustrated in Figure 5-15.

b) Recycling of Fuel Cell Stack materials

The recycling of the fuel cell MEA may be necessary to create a sustainable supply of platinum. The membrane materials are also sufficiently expensive that some form of reuse could have economic benefits for fuel cells. US DOE sponsored research has shown it is possible to recycle platinum and the membrane materials. The platinum will need to be removed from the MEA in a way that does not emit hydrofluoric acid as occurs with conventional combustion processes. Although platinum recovery from fuel cells appears feasible, the recovery costs for large scale recycling is unknown. Early data indicates that MEAs made from recycled materials can deliver performance essentially equivalent to that of an MEA made from virgin materials. Stack and balance of plant materials may be recycled but hold a lower strategic value than MEA platinum and membrane materials.

4. Fuel Cell Efficiency

The lifetime operating efficiency of a fuel cell system is fundamental to its successful application as an automotive power plant. Efficiency is important to the achievement of acceptable range within the constraints of the on-board hydrogen storage and, it directly impacts the vehicle operating cost, while indirectly impacting the re-fuelling infrastructure (more efficient FCEVs require less hydrogen generation).

A DOE project awarded in April 2004 has created four integrated auto and energy company teams to validate hydrogen fuel cell vehicle and infrastructure technologies in different geographic and climatic conditions. The data collected through these projects will help identify new research needs and evaluate technology readiness for the commercial marketplace. The teams are:

- GM/Shell,
- Chevron/Hyundai/Kia,
- Ford/BP
- DaimlerChrysler/BP.

As of the 4th quarter in 2006, there are 63 vehicles in the project, approximately ½ of the total expected number of vehicles. The vehicles are at somewhat different development stages, but generally represent the state of the art FCEVs for model year 2005. The vehicles are being operated in Southern and Northern California, Michigan, Florida, Washington, D.C. and New York until 2009. Operational data is being submitted by all teams to the Hydrogen Data Center at The National Renewable Energy Laboratory (NREL). The data is being analyzed and periodically published in an agreed composite format. For example, each make/model will only generate one data point for on-road fleet average hydrogen consumption.

Recent NREL data presented at the ARB September 2006 ZEV Symposium[5] provided fuel cell system efficiency and in-vehicle fuel consumption for participating vehicles. The limited data indicates net in-vehicle fuel cell system efficiency ranges of 52.5% to 58.1% at 25% of system net power ranges. These values can be considered idealized and actual in-use efficiency values will be less.

The NREL data also provided dynamometer measurements (SAE 2572) of on-road fuel economy as follows:

Dyno City/Hwy	50 to 67 miles/kg	(0.93 to 1.24 kg of H_2 per 100 km)
On-Road*	31 to 45 miles/kg	(1.38 to 2.00 kg H_2 per 100 km)

*Note: on-road data excludes trips of less than 1 mile.

The dramatic difference between the dynamometer City/Hwy values and the on-road values (62% and 67%) may be explained by a combination of aggressive driving, use of air conditioning and dynamic operation of the fuel cell system.

The Efficiency of a fuel cell system is influenced by:

- Cold start/ freeze start
- Average power – High speed driving inherently raises the operating power and lowers efficiency. Alternatively, if the power requirements are very low the efficiency declines.
- Parasitic losses of the Balance of Plant
- Load Dynamics – during rapid electrical load changes, hydrogen purging occurs more frequently and there are limitations of the air supply to maintain an optimized condition in the stack
- Outside load factors such as air conditioning

[5] "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, Project Overview and fall 2006 Results" National Renewable Energy Laboratory. Wipke, K. & et.al.

The fuel cell developers provided some net fuel cell efficiency estimates to the Panel. The provided estimates are not directly comparable due to differences in assumptions e.g. constant 25% net power and type of driving cycle. Figure 5-17 presents a composite of the developer net fuel cell efficiency data and the NREL data.

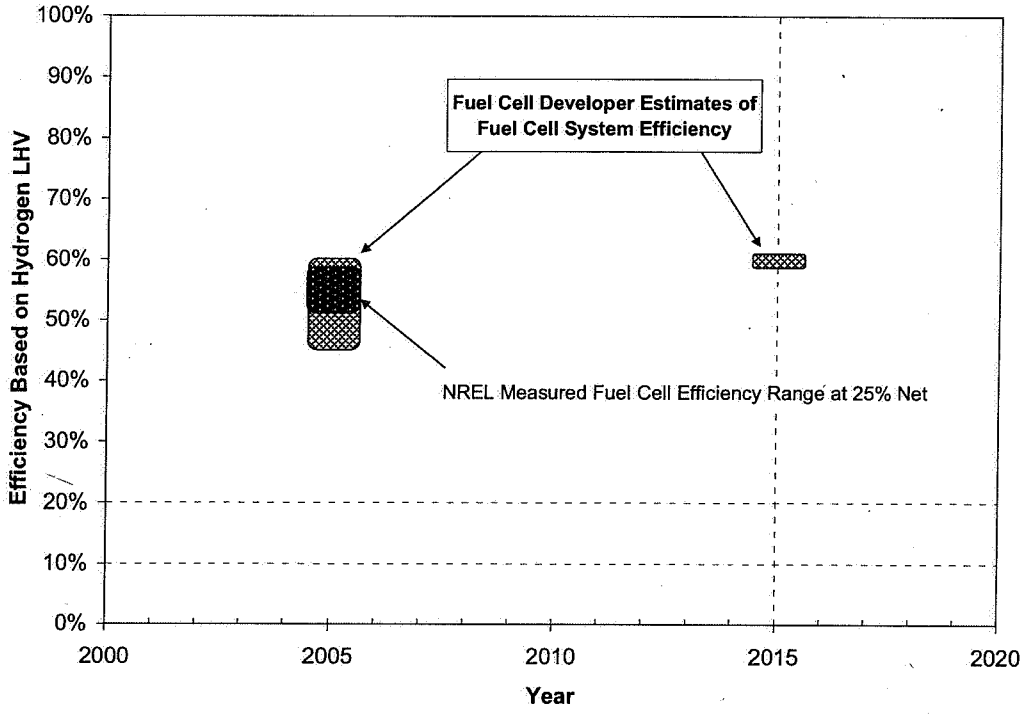


Figure 5- 17 Fuel Cell System Efficiency

Figure 5- 17 shows that the 2005 estimate of net fuel cell efficiency and the NREL measured values coincide. It would be expected that the NREL values would be high in the composite data as they represent net efficiency under near idealized conditions. The developers expect the fuel cell system to marginally increase in peak efficiency. The 2015 values provided to the Panel were virtually all the same. It is not clear that this is a realistic expectation.

Toyota presented on-road fuel consumption data at the EVS 22 conference, October 2006 in Yokohama Japan, se Figure 5-18. The data compares the fuel economy of a Toyota FCEV on the Japanese 10-15 mode driving cycle, simulated results, and actual values on public roads.

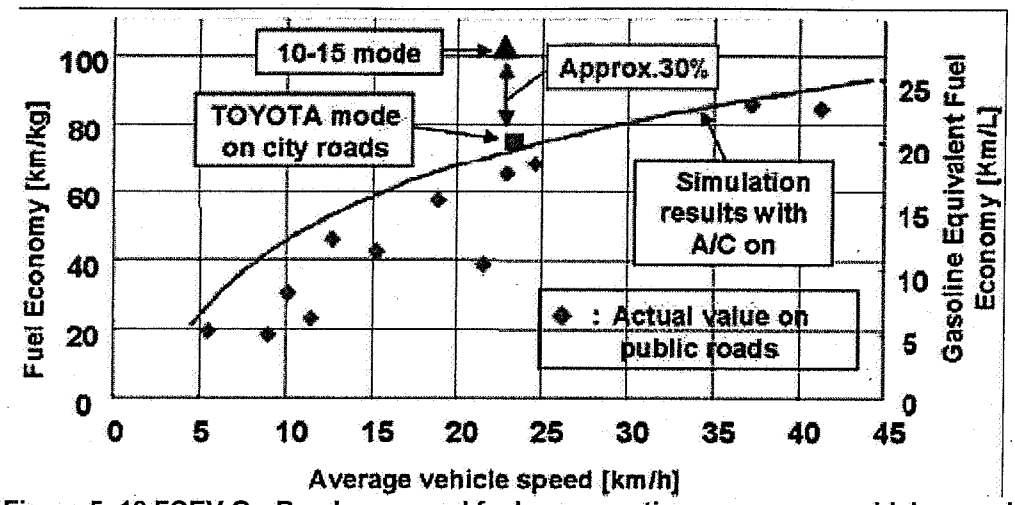


Figure 5- 18 FCEV On-Road measured fuel consumption vs. average vehicle speed

Note: The 10-15 Mode Urban driving cycle is currently used in Japan for emission certification of light-duty vehicles.

The measured Toyota data indicates significantly lower fuel economy when compared to the 10-15 mode and even the simulated results with the air conditioner on. The date suggest that the fuel economy at low speed on public roads is surprising low and that the system is not yet optimized for this driving condition.

In general, the developers indicate a high fuel cell system efficiency of 50% to 60% is possible with some qualification for start-ups and dynamic operation. The effect of dynamic load on efficiency was calculated as being small. The developers did not have an explanation for the difference in NREL data.

To reduce hydrogen consumption, developers felt it was less expensive to optimize the hybridized power train, use light weight components and improve aerodynamics to decrease the fundamental vehicle energy needed than to further increase the fuel cell system efficiency. A plug-in FCEV was also described as a method of reducing operational cost.

Fuel Cell system developers are working to improve the fuel cell system efficiency in the vehicle by optimizing:

- Sizing and hybridization of the application
- Idle condition fuel consumption
- Fuel use during normal start up and shut down (hot start)
- Fuel use during normal start up and shut down (cold start, freeze condition)
- Inert purging and flood control
- Transient load response
- Reduced balance of plant power requirements
- Hydrogen Purging requirements

E. Panel Assessment and Conclusions

The Panel concludes that automotive fuel cell technology continues to make substantial progress but is not yet proven to be commercially viable. Technological and engineering advancements have improved, simplified and even eliminated components of the fuel cell system. Prototype FCEVs now have functionally viable fuel cell systems that are freeze capable,

relatively quick to start, quiet, and satisfying to drive.

Progress made since the 1998 ARB fuel cell report include large improvements in the MEA and fuel cell stack. The Balance of Plant has a reduced number of components and now uses some parts that are of automotive quality and cost. The fuel cell system has a reduced start time and, in-vehicle start-up from a frozen condition has been demonstrated. Great strides have been made in the science of materials and operational characteristics of fuel cells. This increase in fundamental understanding shows promise for solving life, abuse and durability issues of fuel cells.

Fuel cell technology has advanced, but not in the manner or at the rate expected in the 1998 ARB report. Switching to on-board hydrogen as the designated fuel reduced the complexity of the fuel cell system but effectively increased the need to maintain a high net conversion efficiency to achieve range goals.

The largest challenge for the developers is to continue increasing performance of the MEA while reducing overall system cost and increasing system life. The consensus among the majority of fuel cell developers is that in order to achieve commercialization there are simultaneous requirements for:

6) Higher MEA specific power (goal of 0.8 to 1.0 W/cm^2)
7) Reduced MEA catalyst cost (goal of total MEA loading <0.1 to 0.5 mg Pt/cm^2)
8) Longer fuel cell system operating life and increased durability (goal of >5000 hours of customer use)
9) PEM materials that are stable and can operate at a higher temperature (above 100°C)
10) Engineering advances

The increase in MEA specific power allows a given fuel cell stack to produce more power and thus achieve a lower $/kW. Nearly every stack cost factor, at a given voltage, decreases in inverse proportion to MEA specific power. The higher MEA specific power can be accomplished by lower resistance and improved electrode-layer structures to ensure voltage at a higher operating current density. Increased MEA specific power has been accomplished at the cell level with some stack experience.

The MEA catalyst cost is related to the price of platinum. The price of this noble metal is rising due to world wide demand exceeding supply and it represents a significant barrier to automotive fuel cell commercialization. A reduction in the MEA catalyst cost can be achieved by reducing the amount used (higher utilization) and alloying. Low platinum catalyst loading has been demonstrated at the cell and stack level but further reductions of approximately 2X will be required to achieve cost goals. Platinum alloying has been tested at the cell level with improved cycle life at high current densities. Platinum recovery from fuel cells appears to be feasible although the recovery costs for large scale recycling is unknown. In order to be directly ICE cost competitive, a new non-platinum catalyst invention may be needed.

The life and durability of fuel cells in automotive applications is not yet proven. A life of 5000 + hours in a light duty vehicle type load cycle has not been demonstrated at the cell or stack level. A factor of at least 2X increase in life is required. The correlation between laboratory life testing and customer use life is not fully understood and the 5000+ hour life requirement may need to be increased to simulate actual customer use.

High temperature membranes (100°+C) have only been demonstrated at the cell level. This development can potentially reduce the size and complexity of the FCEV thermal system and may possibly eliminate the need for stack humidification. This significant change can reduce the cost and improve the life of the fuel cell system. The Panel is optimistic about these developments but cautious because the rates of chemical degradation can be expected to increase exponentially with temperature.

Engineering advances and innovation are focused on materials, stack design, and balance of plant to reduce cost and increase life. This includes the simplification and where possible, the elimination of subsystem components. Manufacturability, vehicle packaging, serviceability, net fuel efficiency, noise and vibration are all being optimized.

Overall, the Panel concludes that at this time no fuel cell developer has achieved the necessary requirements for automotive fuel cell commercialization. The developers are relying on future technological improvements to meet both cost and life goals. Achieving these goals creates some contradictory requirements for the fuel cell system. The Panel believes that these requirements are difficult to achieve separately and because they are interrelated, even more difficult to solve simultaneously. These technological improvements include the development of MEAs that use significantly less catalyst material, operating at high specific power and temperature over a longer system life. To simultaneously increase performance and life at a lower cost will likely take ingenuity and invention.

Each of the developers believes that the simultaneous requirements can be met but on different time schedules. For example, one major developer's objective is to compete with the "upper" segment of ICE vehicles in the year 2020 at volumes of 100,000 units per year. Another major developer's assessment is that a commercially viable fuel cell system would be available in 2010, given a production rate of 500,000 units per year. Many developers believe that the FreedomCAR cost goals are not possible and the time schedule too ambitious.

At this time, large conventional automotive suppliers are not active in fuel cell development and are taking a wait and see attitude. If the market develops, it is conceivable that they will rapidly acquire the technology. A small number of non-automotive fuel cell applications are now being commercialized (higher $/kW and shorter life applications). This commercial activity may start to establish a supplier base that could grow to meet automotive demands.

The Panel remains cautiously optimistic for fuel cell system commercialization. There are large technical barriers that can be solved but there are other issues that are beyond the control of any single auto manufacturer. Wide spread deployment of FCEVs will require continuous strong support from government agencies. This support must include a clear message of long term commitment to fuel cell FCEVs. These include adequate and affordable hydrogen refueling, as well as a host of sustainable financial incentives to help minimize the capitalization risks of all key stakeholders during the initial transition years. Ultimately, consumer knowledge and willingness to buy these vehicles in high volume is required.

6. Vehicle Integration – Automotive Manufacturers

This section considers the status and prospects of vehicle integration of zero emission vehicles (ZEVs) by ten major original equipment automotive manufacturers (OEMs), and a few examples of smaller, automotive manufacturers, as well as their advanced technology vehicles (ATVs) that could have synergistic benefits supportive to the introduction of ZEVs. It uses the outcomes of the detailed analysis in the sections above that address the goals, status, major issues and potential of three key ZEV enabling system technologies, the vehicle energy storage system (VESS), vehicle hydrogen storage system (VHSS) and vehicle fuel cell system (VFCS). In addition to vehicle technical considerations, vehicle business considerations (e.g., manufacturing cost, capital investment, marketability, etc.) also are addressed, as the ARB requested the Panel to forecast the future prospects, introduction timing, and volume milestones of the ZEV and ATV technologies.

The ZEVs considered include full performance battery electric vehicles (FPBEVs) and fuel cell electric vehicles (FCEVs). ATVs considered are those that share technologies with ZEVs and include neighborhood electric vehicles (NEVs), utility electric vehicles (UEVs), city electric vehicles (CEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), hydrogen internal combustion vehicles (H2ICVs), and fuel cell auxiliary power unit vehicles (FCAPUVs).

Both ZEVs and ATVs, in combination with the off board infrastructure required to produce the various fuels used by these vehicles, have the capability to provide important societal benefits - improved air quality, reduce greenhouse gas emissions and increase energy independence. However in this report, emissions, fuel consumption and greenhouse gas are considered only from the vehicle perspective ("tank to wheels"). At the request of ARB, infrastructure ("well to tank") and overall ("well to wheels") energy perspectives were not part of the scope of the Panel's study and report. Apparently, ARB will be handling infrastructure separately. For the purposes of this study, energy infrastructure is addressed only from the customer's vehicle experience and satisfaction level, a necessary and important consideration in attempting to predict volume milestones.

A. Zero Emission Vehicles (ZEVs)

Zero emission vehicles (ZEVs) have zero exhaust emissions of hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx) and particulate matter (PM), which are the main contributors to air pollution. Moreover, emissions of ZEVs do not change with age or improper maintenance and an increase in total fleet mileage does not increase vehicle emissions. Conversely, exhaust emissions of conventional vehicles are not zero, so increased fleet mileage increases vehicle emissions, and the emissions increase with time, due to normal mechanical wear and aging of materials. Deterioration of conventional vehicle exhaust emissions can be especially severe if the owner fails to properly maintain his/her vehicle.

Only two types of motor vehicles have been successfully demonstrated as true ZEVs – battery electric vehicles (BEVs) without fuel fired heaters, and fuel cell electric vehicles (FCEVs) that consume hydrogen fuel.

1. Full Performance Battery Electric Vehicle (FPBEV)

A battery electric vehicle (BEV) receives electric energy from the electric grid, usually overnight, stores the energy in electrochemical batteries, and uses the stored electric energy the next day to power the vehicle with an electric motor propulsion system. BEVs without fuel fired heaters have zero exhaust emissions, and on a vehicle basis do not directly consume any hydrocarbon based fuel (gasoline, diesel, compressed natural gas (CNG), propane, ethanol, etc.) and create carbon dioxide (CO2), which is the main greenhouse gas.

For this report, BEVs have been divided into two main categories – (1) full performance battery electric vehicles (FPBEVs) of all sizes and driving ranges, and (2) all other, less than full performance, battery electric vehicles, including neighborhood electric vehicles (NEVs), utility electric vehicles (UEVs), and city electric vehicles (CEVs). This distinction is relevant when considering the practicality and likelihood of high volume BEV substitution for conventional vehicles and the associated societal benefits. FPBEVs are not performance limited (i.e., acceleration and top speed) compared to conventional internal combustion engine (ICE) powered vehicles and are fully capable of U.S. urban freeway driving. This is an important consideration given that driving conditions and practices in most U.S. urban areas include a significant amount of freeway driving.

As discussed below (see 6. B. 1.), the California ZEV regulation uses "common description" terms of "Full Function EV" for BEVs with 100+ miles of driving range and "City EV" for those with 50 to 99 miles of driving range, but this range criteria has not been used here for the definition of a FPBEV.

a) Manufacturers/Vehicles/Specifications/Performance

In the past, several major attempts to commercialize FPBEVs have been conducted.

In the United States, eight FPBEVs were produced by six major OEMs. These were the General Motors EV-1, first introduced as the GM Impact concept vehicle at the January 1990 Los Angeles Auto Show, and the others that were developed primarily in response to the September 1990 California ZEV mandate; Chevrolet S-10 EV, Chrysler EPIC, Ford Ranger EV, Ford Postal Van EV, Honda EV Plus, Nissan Altra, and Toyota RAV4 EV.

The specifications and performance of these vehicles are shown in Appendix J. Although they are almost 10 years old, and this is not new information, it is useful to consider them, as they provide the only large body of comparable data from the major OEMs from which to draw some conclusions about FPBEVs. It represents a significant case study of a major effort to try to commercialize advanced technology vehicles – without the enabling system technologies being ready (primarily battery cost) and without fully considering mass-market customer expectations and preferences. This was a comprehensive attempt to commercialize FPBEVs, consisting of, (1) six of the world's largest automotive competitors with independent technical teams, (2) a wide variety of types and sizes of vehicles, and (3) three different battery types from eight different battery suppliers. The results were disappointing; (1) limited driving range, (2) very low volumes, and (3) lack of commercial success. On the other hand, most of the technology developed for these vehicles, and the general realization of the benefits of electric propulsion systems, has led to commercialization of NEVs and HEVs, a major industry effort now underway to try to commercialize FCEVs, and a growing level of interest in PHEVs.

Range of the previous generation of FPBEVs varied from 30 miles to 122 miles per overnight charge. This variability is primarily due to different battery technology, battery system size and vehicle size, weight and design, but, climatic conditions, terrain, load, and driver diversity

(driving style) also significantly affect real world driving range of individual vehicles.

Energy consumption results were obtained in both sets of testing and varied about 300% from best to worst in both cases. Again, these vehicles had significantly different payloads, performance, size and weight, different types of batteries, and the ambient temperatures during charging varied significantly. The Panel expects that technology available today would reduce this variability and achieve better energy consumption results.

In Europe, several BEVs were produced in the mid 1990's, including the Peugeot 106 and Partner, Citroen AX, Saxo and Berlingo, Renault Clio Electrique, and Fiat 600 Ellettra. These vehicles could achieve driving ranges of about 80 to 100 km (50 to 60 mi) and maximum speeds of about 100 kph (60 mph). They were intended for use in European city centers, and not for freeway driving, so in the sense that they could meet the customer's performance requirements, they can be considered "full performance" BEVs for that specific application.

Recently a few small companies have developed FPBEVs and are offering them to retail customers. Two examples are the Tesla Motors' Roadster and AC Propulsion's conversion of the Toyota Scion xB to the AC Propulsion eBox. The specifications and performance of these vehicles are shown below:

Table 6-1: FPBEV Specifications[1]:

Vehicle	**Platform**	**Motor**[2] (kW)	**Battery** (kWh – Type)	**Curb Weight** (pounds)
Tesla Roadster	Tesla	50/185	50 Li Ion[3]	~2,500
AC Propulsion eBox	Scion xB	50/120[4]	35 Li Ion[3]	3,050

1. Source: manufacturer, ZEV Symposium, and press releases
2. Continuous power rating/peak power rating
3. See Appendix J for discussion
4. Governed to limit battery current, 120 seconds

Table 6-2: FPBEV Performance[1]:

Vehicle	**Payload** (pounds)	**0-60 mph** (seconds)	**Driving Range** (miles)	**Consumption** (AC kWh/mile)
Tesla Roadster	>300[2]	~ 4	250[3]	0.204[3]
AC Propulsion eBox	>750[4]	~ 7	150[5]	0.250[5]

1. Source: manufacturer, ZEV Symposium, and press releases
2. Payload not available, based on 2 passengers and FMVSS minimum payload of 150 pounds per seating position
3. HFET
4. Payload not available, based on 5 passengers and FMVSS minimum payload of 150 pounds per seating position
5. "Road test result using driving routes and speeds typical of the Los Angeles area including freeway speeds up to 75 mph, congested freeway driving, and urban and suburban driving at local speed limit, all with heater and A/C off."

As can be seen from this data, Li Ion batteries can provide a significant improvement in energy storage capability, performance and driving range. It also appears that advancements in charging system efficiency and vehicle electric drive efficiency have been made.

Compared to the average U.S. price of about $26,500 for a light duty vehicle, these FPBEVs are expensive, the Tesla Roadster price is about $100,000 and the eBox is quoted at $55,000, plus about $15,000 for a customer supplied Scion xB conversion vehicle. As discussed in Appendix H, the batteries for these vehicles alone are likely to cost between $18,000 and $36,000, and their life is uncertain. Tesla has a 5 year, 100,000 mile warranty and eBox has a 1 year warranty on the conversion components.

Automotive News reported that at the recent National Automobile Dealers Association convention in Las Vegas, Miles Automotive showed their Javlon XS500 electric car. The article stated that the four dour sedan designed by Pininfarina will have a 150 mile driving range, a top speed of 80 mph, and a price of about $32,000.

In France, The Société de Véhicules Electriques (SVE) – Groupe Dassault is converting 30 Renault Kangoos to FPBEVs, using both SAFT Li Ion and ZEBRA NaNiCl2 batteries for testing in the Cleanova II program. The Société de Véhicules Electriques (

b) Units in Operation

Plug In America estimates 5600 FPBEVs were leased or sold nationwide and Electrifying Times estimates that 2,300 were placed in California between 1997 and 2002. Plug In America estimates about 1280 remain on the road nationwide.

Solar Energy International estimates there are 4,000 Electric Vehicles operating in the United States.

In France, about 10,000 FPBEVs with NiCd batteries were produced as part of the mid 1990's program and many are believed to be still in operation, primarily in the vehicle fleets of Electricitè de France (EDF).

EDF estimates the total number of BEVs in the world is about 30,000, or about 0.004 % of the total number of light vehicles (~800 million).

c) Technical Issues

Architecture ("Conversion" vs. "Ground Up")

As demonstrated by the vehicles listed in Appendix J, FPBEVs can be either conversions of existing vehicles or new dedicated vehicle platforms (a.k.a. "ground up"). Conversions have the advantage of starting with the platform of a volume based conventional vehicle but usually have payload restrictions due to the added battery weight, or packaging compromises due to the volume necessary to package the battery system. Achieving the increased range the customer wants makes this conversion issue even more challenging. Dedicated vehicles minimize these technical compromises but require much greater capital investment.

Battery Performance and Life

A detailed discussion of the status, major issues and future potential of the vehicle energy storage system (VESS) technologies is presented in Section 3, with emphasis on NiMH and Li Ion batteries. One conclusion of that discussion is that the performance of high energy NiMH battery technology of the type used in past FPBEVs has not progressed significantly in the past five years. NiMH gravimetric energy density, in particular, remains marginal or inadequate for FPBEV applications and is likely to remain so. On the other hand, Section 3 makes clear that Li Ion battery technology has advanced very substantially, driven not only by the rapidly growing market for consumer products but by the emergence of power tools and HEVs as potential applications. Of particular relevance to FPBEVs is that cycle and calendar life, considered inadequate 5-6 years ago, are improved to the point that automotive applications are considered feasible. However, no Li Ion battery technology designed for full size FPBEVs has become

available or seems to be under development. One likely reason is that the prospective costs of Li Ion (and NiMH) batteries in the capacities required for full size FPBEV applications remain high, even if these batteries were mass-produced (see Tables 3-13 and 3-14 and the discussion below).

Battery Temperature

FPBEVs must be able to be parked unplugged during the day in a cold environment, such as is experienced in the northeastern U.S., yet their batteries must still provide enough energy and power for safe vehicle performance. Li Ion (and NiMH) batteries cannot meet this requirement at temperatures below approximately -20 to -30 ℃ (-4 to -22 °F), depending on the specific Li Ion technology. In addition, battery powered electric resistance heaters can significantly reduce driving range in cold weather. Although the use of fuel fired heaters for ZEVs is allowed below 40℃ under the present regulations, they result in a FPBEV that is not a true ZEV and they require the customer to refuel them separately. Batteries also need to be able to be charged and operated when FPBEVs are parked and operated in high ambient temperatures, such as is experienced in the southwestern U.S. Under these conditions, battery cooling may be required, again with expenditure of battery energy and loss of vehicle range. Control of battery temperature within limited ranges is required also to maximize battery cycle and calendar life, as discussed in the VESS section above.

Battery Safety

The original design verification process and experience of the past decade with several thousand FPBEVs propelled by NiMH batteries has shown that NiMH batteries do not present significant safety issues. However, concerns about safety and the need to develop robust systems that prohibit or safely contain failure modes are among the major factors that have delayed the introduction of Li Ion batteries in automotive applications. Recent well publicized incidences with laptop computer battery fires, and widespread Li Ion battery recalls, has made the general public aware of the potential issue of Li Ion battery safety. Fortunately, as reviewed in the VESS section, more than 200 prototype FPBEVs and HEVs have been operated on public roads worldwide without significant safety incidents. Technological advances in battery chemistry, design and management have enhanced every aspect of automotive Li Ion battery safety, and continuing advances can be expected to further reduce the already small safety risks. The current use of a small Li Ion battery for the start-stop function of the Toyota Vitz mini-car, use of Li Ion batteries in several small FPBEVs planned for Japan (described below), and the plans to introduce Li Ion batteries in HEV applications within the next few years, indicate that technical progress has improved Li Ion battery safety to the point where it is now considered acceptable by several OEMs.

d) Commercial Issues

Vehicle Cost

Historically, FPBEVs have cost substantially more to manufacture than their counterpart ICE vehicles because of the high costs of the electric propulsion systems, including the electric drive system, electric accessories, and, in particular, the battery system. With the rapid proliferation of models and market growth of hybrid electric vehicles (HEVs), as well as major efforts underway to develop fuel cell electric vehicles (FCEVs), discussed later, substantial progress is being made in lowering costs for the high voltage electrical systems – drive motors, power electronics and accessories (e.g., electric power steering and electric air conditioning). Although not yet at

levels necessary to be fully competitive with conventional ICE technologies, the costs of these systems in mass production are not considered to be a major issue. Thus, the major commercial issue for FPBEVs continues to be the battery system's initial and life cycle cost.

A battery system with a rated capacity of 40kWh would provide a medium sized family sedan FPBEV with a maximum driving range of about 125 miles, assuming 0.250 kWh/mile DC energy consumption and 80% DOD. Based on the cost projections developed in the VESS section, a comparison of the cost goals and status for a 40kWh battery system with a 10 year life is shown below:

Table 6-3: 40 kWh Battery System Goals / Present Status / Projected Status

Battery System[1] (40kWh)	**Long-term goals** (2005-2008)[2]	**Present Status** – Best Case[3]	**Projected Status** – Best Case[4]
Type	n/a	NiMH	Li Ion
System Price ($)	6,000 – 3,000	15,360 – 11,430	13,680 – 8,395
System Price ($/year)	600 – 300	1,536 – 1,143	1,368 – 839

1. The battery system includes the battery modules, module support structure, battery management system and software algorithms (full or partial), wiring, thermal management sub system, and enclosure. For interfacing with the vehicle, the battery system also includes a high voltage DC connector, CAN bus connector, thermal management connection (liquid or air) and mounting brackets.
2. Source: Table II-5 (page 14), U.S. Advanced Battery Consortium Goals for Electric Vehicle Batteries, 2005 Annual Progress Report, Energy Storage Research and Development, FreedomCAR and Vehicle Technologies Program, U.S. Department of Energy, January 2006. Price of 150 $/kWh (desired to 75 $/kWh) is supplier selling price at volumes of 10,000 40 kWh units/year.,
http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/2005_energy_storage.pdf
3. Source: VESS, Table 3-14, price range reflects 12,500 – 100,000 40 kWh units/year
4. Source: VESS, Table 3-13, price range reflects 12,500 – 100,000 40 kWh units/year

As can been seen above, the battery pack's life cycle price is much higher than the USABC goals, even considering up to 10 times higher volume over which to spread fixed costs and take advantage of automated manufacturing processes.

When customers consider the purchase of an alternative fuel vehicle (e.g., a diesel passenger car), they often want to know whether or not their potential fuel cost savings will offset the incremental price of the vehicle. Some may do their own calculations, but many potential customers rely on calculations or estimates done for them by others, such as the automotive press and other media. It may be reasonable to assume a FPBEV *without a battery* could be offered on a commercially viable basis, if mass produced by a manufacturer, at the same price as a comparable conventional vehicle, and that the incremental cost of the battery would be the incremental cost of the vehicle. Using the battery system prices from above, the chart below shows the price of gasoline that would be necessary for a customer to recover his/her cost for the battery system over a 10 year period on a simple payback basis, assuming he/she would be willing to pay the manufacturer's incremental cost of the battery:

Table 6-4: Gasoline Price ($/gallon) Required for Customer Breakeven[1]

Electricity Rate ($/kWh)	**Long-term goals**[3] ($600 – 300 /year)	**Present Status**[3] ($1,536 – 1,143 /year)	**Future Status**[3] ($1,368 – 839 /year)
0.04	1.75 – 1.05	3.85 – 2.95	3.50 – 2.30
0.06	1.90 – 1.20	4.05 – 3.15	3.65 – 2.45
0.08	2.05 – 1.35	4.20 – 3.30	3.80 – 2.60
0.10[2]	2.20 – 1.55	4.35 – 3.45	4.00 – 2.75

1. assumptions: 10 year life, 12,000 miles/year, 27.5 mpg (combined) ICE vehicle, 0.300 kWh/mile AC basis for FPBEV; costs not included: scheduled maintenance, battery markup and warranty cost not recovered by OEM, time

value of money, inflation, value of vehicle at end of 10 years
2. 2006 average U.S. residential rate ($0.0973)
3. Source: Table 6-3

Gasoline prices of $3.00 to over $4.00 have been experienced in 2006, which if they continue in the future, make battery cost much less of a barrier to commercialization of FPBEVs than in the past when gasoline was under $2.00/gallon. Since the USABC cost goals of 150 $/kWh (desired to 75 $/kWh) were developed about 10 years ago, when gasoline was much less expensive, the Panel expects that these goals may be revised upwards to be consistent with the expected higher prices, or possibly increased taxation, of gasoline. For reference, in August 2006 the Japanese Ministry of Economy, Trade and Industry (METI) published a 2015 CY battery cost goal of 40,000 ¥/kWh (336 $/kWh @ 119 ¥/$) for 1,000,000 packs/year.

However, if the "costs not included" in footnote 1 were included, with the exception of scheduled maintenance, the gasoline price payback threshold would be higher. In addition, the following cautions concerning this analysis are important to consider.

In the above example, it is assumed that the customer drives the national average of about 12,000 miles per year, or an average of 33 miles per day, every day (or commutes 46 miles per day, 5 days a week). This is an aggressive assumption for a FPBEV that is not capable of long trips. For a customer who drives less, the fuel savings would not be as much. If the customer drove half as much, the gasoline prices for customer breakeven would be significantly higher than those prices shown in Table 6-14 (e.g., for a $1,536/year battery and $0.10 electricity rate, the breakeven gasoline price rises from $4.35 to $7.90; or for a $839/year battery and $0.04 electricity rate, the breakeven gasoline price rises from $2.30 to $4.20).

OEMs in total are probably not likely to commit to very high annual volumes of battery systems, given their recent experience with FPBEVs. Furthermore, a battery system is usually unique for each new vehicle program, and it is highly probable that the various OEMs would not all use the same cell suppliers, further reducing volume and increasing unit costs for individual battery system suppliers and cell manufacturers.

An analysis of FPBEV fuel cost savings potential based on the net present value (NPV) of the customer's future energy cost savings is included in Appendix I. It varies annual mileage (10,000 to 14,000 miles), gasoline price ($2.50 to $4.00/gallon), conventional vehicle fuel economy (27 to 36 miles/gallon), electricity price ($0.06 to $0.12/kWh), and vehicle energy economy (3 to 4 miles/kWh). For four combinations of assumptions it shows NPVs of $4,055, $7,056, $7,239, and $10,933. Assuming the customer pays for the battery, these values can be compared to his/her battery system cost shown above that range from $8,395 to 15,360, depending on type and volume (Table 6-3). Only in the case of high volume Li Ion and the most optimum vehicle assumptions does the NPV exceed the initial cost of the battery.

In France, the commercial goal of the Cleanova II program is to both (1) demonstrate the feasibility of producing a FPBEV that fully meets the customer's requirements and is priced – *excluding the battery* – equivalent to a conventional vehicle, while still achieving a positive profit margin for the vehicle manufacturer – and (2) produce a battery system that is priced low enough, while still achieving a positive profit margin for the battery manufacturer, such that the customer's fuel savings over the life of the vehicle recovers the customer's cost of the battery system (possibly on a lease basis) over the life of the vehicle. Fueling in France with inexpensive "clean" electricity vs. expensive gasoline/diesel, combined with relatively low speeds and short daily driving distances, should provide an optimum scenario for FPBEV

commercial success.

Battery Business Case Alternative

Because of the prospective high cost of FPBEV batteries, business models other than straight ownership of FPBEVs and their batteries by customers deserve consideration as a way of capturing the substantial propulsion energy cost savings of BEVs that could be realized. Electric utility ownership of batteries and lease-back to customers is one such model that has been proposed and discussed. Several business models have been proposed that go beyond utility ownership of batteries and include use of these batteries to provide specific utility functions that may have sufficient value to offset part of battery ownership costs. These include (1) availability of the power and energy delivery and acceptance capacity of batteries connected to the electric grid through the BEV-charger interface, to provide functions such as spinning reserve (i.e., energy system production capacity that is "idling", or is ready and available to accommodate an rapid surge of demand), voltage regulation, emergency power, and peak shaving/load leveling on a local and system basis, and (2) use of batteries no longer meeting BEV requirements as distributed energy storage subsystems on the electric grid to provide some or all of the functions listed under (1). The analysis of the cost and economic feasibility of every one of the many possible configurations and functions is very complex since they are dependent on the values of these different functions which will be different for different utility systems. Moreover, for each utility system these values change as a function of time-of-day, over historic time, and as a function of system "saturation" with battery storage. Overlaid over this fundamental complexity are uncertainties regarding statistical availability of the batteries and of customer behavior, issues for which there are neither experience data nor credible models. However, because of the potential attractiveness of one or more of these applications, the Panel encourages this type of analysis.

Customer Acceptance

Major OEMs with FPBEV experience have found that customer acceptance of FPBEVs varies considerably, ranging from very high to very low, due to a complex combination of vehicle characteristics and societal norms. Many customers who rate them highly do so because of their beliefs in the electric vehicle's cutting edge technology that leads to important societal benefits – pollution reduction, greenhouse gas reduction, and energy independence. Most customers are interested in the direct FPBEV attributes – lower fuel cost, smooth quiet operation, reduced maintenance requirements, fueling at home, "instant" heat, and/or fun to drive because of high torque at launch. Customers who rate the FPBEV low do so because of real or perceived inconvenience factors: limited driving range (especially in cold weather), the need to plug in at night, fear of forgetting to plug in, fear of running out of fuel/energy, long recharging time, limited availably of public charging infrastructure (including incompatible connectors), and/or the high cost of the battery system (if not subsidized by manufacturers or governments).

Based on market research studies of early BEV users and potential users, some OEMs have concluded that FPBEV requirements for real world driving range, reflecting all of the conditions mentioned above, is a minimum of 100 miles per overnight charge, with acceptable range of about 150 miles and preferred range of at least 200 miles. Although General Motors indicated that from their experience with the EV-1, 150 mile range was not acceptable for a mass-market vehicle. Others have found that for mass-market retail customers anything less than the typical 300 to 350 mile range of a conventional vehicle implies a functional degradation and an expected reduction in vehicle price, despite the fuel cost savings.

Ideally, the size of a FPBEV battery should not be any larger than necessary in order to keep the vehicle as affordable as possible. The Panel's perspective is that for people willing to consider a FPBEV, refueling frequency must be taken into account when making range comparisons, although this does not seem to be widely understood or accepted by mass-market customers. When plugged in every night, an EV driving range of 100 miles provides 350 miles per week, using, on average, just half the available range of the EV per day – 50 miles. This allows the EV driver flexibility to drive nearly double an average daily distance of 50 miles when necessary – thus providing day to day driving range flexibility similar to, but not as great as, that of a conventional ICE vehicle. This range and flexibility is comparable to a 350 mile range conventional ICE vehicle, which is typically refueled not more than once a week. Also, one must realize that when plugged in daily an average of 50 miles per day could provide a generous 18,250 miles/year.

While 100 miles daily driving range should be considered adequate for most urban usage, it is not sufficient for occasionally taking long trips, and thus the vehicle will have limited practicality for many customers. This limitation is especially critical for customers who have only one vehicle available to them.

Charging Infrastructure

The Panel considers charging infrastructure to be a major factor in customer acceptability – and therefore the potential commercial viability of FPBEVs. High power fast charge (e.g., 40 to 80% SOC of rated energy capacity in 15 minutes using an off board DC charger) provides an opportunity to extend driving range for unanticipated or long trips, and if fast charge infrastructure were convenient and widely available to the public, could improve the customer acceptability of FPBEVs. It could allow downsizing the battery more toward the average daily driving range and thus reduce the customer's battery cost and improve his payback rate.

However, several issues would have to be overcome before fast charge could become widely available. Electricity rates in many places are much higher during peak hours of the day, when most fast charging would take place, so FPBEV drivers would be encouraged to use fast charging only in an emergency or when taking a long trip. Special electricity rates for fast charge infrastructure could help mitigate the FPBEV range issue and possibly encourage the use of more FPBEVs but are not known to exist. Moreover, fast charging equipment is expensive, so the owner of the equipment would need to add on a significant cost premium to the electricity rate to recover his investment. Coupled with limited use by the customer, because of the resulting high cost per kWh, the business case for installing fast charge equipment becomes very difficult, unless it is intended to support a dedicated fleet operation or is subsidized by a broader utility plan to encourage FPBEVs and the associated sale of night time electricity. Finally, some battery technologies are less capable of fast charge than others (for example, some lithium systems cannot accept fast charge), and there is very little deep discharge life cycle test data of battery systems subjected to both normal overnight and (randomly used) fast charging.

e) Prospects for Advancement

Mitsubishi has announced they are developing a mini-car sized FPBEV in Japan – the 4 passenger, 1080 kg, "i MIEV", with a 16-20 kWh Li Ion battery and 47 kW motor, and that they plan to bring an EV to the U.S. in the future. Subaru is also investigating a Li Ion version of their R1 mini-car in Japan. Nissan recently announced that they plan to launch a "test" electric

vehicle early in the next decade. No other major OEM is producing, or known to be developing, a FPBEV. The reasons these automakers give for either not developing FPBEVs, or proceeding very cautiously, are primarily high battery system cost and additional battery issues associated with deep discharge cycle life, robustness, gravimetric energy density and volumetric energy density, and their concerns about limited driving range and customer acceptance of FPBEVs.

Based on their past experience, and the inherent limitations of FPBEVs, most major OEMs seem convinced they will not become accepted by the mass-market and thus consider them to be niche market products with limited volume potential. Vehicles with lead acid battery packs had very limited driving range (especially in cold weather), and short battery life, and vehicles with more advanced batteries, including NiMH and Li Ion, had very high battery costs, resulting in high vehicle prices and/or unsustainable manufacturer subsidies. Long battery recharge times, and lack of convenient public fast charge infrastructure, made FPBEVs impractical for unanticipated travel or long trips. While acknowledging that they are closely monitoring energy battery developments, with a focus on cost and life improvements, most of the ten automakers that the Panel visited have not disclosed that they are actively developing next generation FPBEVs.

The major barrier to commercially viable FPBEVs is the energy battery system's high initial and life cycle cost. Volumetric and gravimetric energy densities are also concerns, although Li Ion promises gravimetric energy density meeting or approaching vehicle requirements. With the exception of the Li Ion batteries for Mitsubishi, Subaru and Nissan mentioned above, the Panel has found very little effort underway at the present time to advance the technology of batteries for FPBEV applications; however the potential for the introduction of PHEVs, discussed below, could stimulate efforts to develop and improve energy batteries that would benefit battery technology for FPBEV applications (as discussed in the VESS section (3. C) above). Relatively small FPBEVs with Li Ion batteries are most likely to be successful, due to cost issues.

Several small companies, have recently introduced, or plan to introduce, FPBEVs in very low volumes as discussed in the two examples above. Although prices are very high, these vehicles make capable retail products available to enthusiasts, and their development could help advance FPBEV technology. Also, they may help familiarize and educate the public on the various benefits of an electric vehicle and how drivers might adapt to the range limitation issues. Moreover, it will be important to track progress and market acceptance of the recently announced Javlon FPBEV from Miles Automotive, given it's expected price ($32,000).

Europe and Japan's significantly higher fuel prices, shorter driving distances, and in many cases little or no urban freeway driving requirements, provide easier hurdles for successful commercialization of small FPBEVs. If the technical and commercial goals of the Cleanova II program are met, the French Post Office may buy a substantial number of FPBEVs in 2008. If this happens, it could be the start of a commercially viable FPBEV program -- without using direct subsidies from either manufacturers or governments. Mitsubishi's "i MIEV" project, Subaru's R1e, and Nissan's recently announced plan to launch a "test" electric vehicle early in the next decade will be important to monitor.

f) Introduction Timing

Given current market conditions, combined with the high cost and other issues associated with batteries, most major OEMs do not see a viable business proposition in the next 5 to 10 years to produce FPBEVs for the U.S. market.

In the U.S. FPBEVs have achieved pre-commercialization (1,000s/year) but the Panel's projection is that they will not reach early commercialization (10,000s/year) until energy batteries that approach the DOE/USABC goals become commercially available and/or the price of gasoline increases substantially. With very little work presently underway to develop improved energy batteries, availability of suitable FPBEV batteries is not foreseen within the next 5 years. However, if energy battery development for PHEVs (discussed below) is successful, advanced energy batteries could become available after that time. Once a major OEM concludes that a battery is technically capable for the intended application, the purchase price is deemed to be acceptable, and there is sufficient long-term market demand to support a business case, it will take them another 3 or 4 years to design, develop and validate a truly commercial FPBEV. Thus early commercialization (10,000s/year) of FPBEVs in the U.S. is probably at least 8 or 9 years away at the earliest.

On the other hand, the outlook for small FPBEVs in Japan and Europe may be more promising. Nissan's outlook is that the development of battery technology indicates continued and promising progress in obtaining a future cost effective electric powered vehicle. These vehicles are likely to be introduced in limited fleet tests in the 2010 timeframe while cost reduction and performance gains continue. Test markets are expected to include both Japan and Europe based on green electric power generation, high petroleum prices, government support, and compatible usage patterns.

2. Fuel Cell Electric Vehicle (FCEV)

A fuel cell electric vehicle (FCEV) is similar to a FPBEV in that it contains an electric motor propulsion system and electric accessories, but instead of an electrochemical storage device – a battery, it stores a gaseous or liquid fuel onboard, and converts the fuel into electric power with an electrochemical conversion device – a fuel cell system. Some FCEVs also have a regenerative brake system, like FPBEVs, to capture kinetic energy during braking and deceleration, thus improving overall vehicle efficiency, and in this case they also have a small high voltage battery.

FCEVs that use hydrogen fuel have zero exhaust emissions, and on a vehicle basis do not consume any hydrocarbon based fuel (gasoline, diesel, CNG, propane, ethanol, etc.) that would create CO2 emissions.

a) Manufacturers/Vehicles/Specifications/Performance

Most major OEMs are actively engaged in fuel cell vehicle research and development and many of them are making very major financial and resource commitments. In addition to many "one-off" prototypes, FCEV fleets from seven OEMs that have been introduced or publicly announced are:

Table 6-5: FCEV Specifications[1]

Vehicle	**FC System** - stack developer - system power[2] (kW)	**Hybrid System** - type - power[3] (kW)	**Fuel System** - type - capacity[4] (kg)	**Curb Weight** (pounds)
DaimlerChrysler F-Cell	Ballard 68/72	NiMH 15/20	CH2 – 350 bar 1.8	3307
Ford Focus FCV	Ballard 68/n.a.	NiMH n.a./20	CH2 – 350 bar 4.0	3527
Ford Explorer TDV2	Ballard 68/n.a.	NiMH n.a./40	CH2 – 700 bar 10	5645
General Motors HydroGen3	GM 94[5]/94[5]	n/a 60/60	CH2 – 700 bar 3.1	3505
General Motors HydroGen3	GM 94[5]/94[5]	n/a 60/60	LH2 4.6	3505
General Motors Equinox	GM 93/93	n/a 90/100	CH2 – 700 bar 4.2	4431
2003 Honda FCX	Ballard 78/78	Ultra capacitor n/a	CH2 – 350 bar 3.3	3704
2006 Honda FCX	Honda 86/86	Ultra capacitor n/a	CH2 – 350 bar 3.6	3682
Hyundai Tucson FCEV	UTC Power n/a/80	Li Ion n/a/n/a	CH2 – 350 bar n/a	n/a
KIA Sprotage FCEV	UTC Power n/a/80	Li Ion n/a/n/a	CH2 – 350 bar n/a	n/a
Nissan X-Trail FCV	Nissan 90/90	Li Ion n.a./25	CH2 – 700 bar 3.6	4101
Toyota FCHV	Toyota 75/90[6]	NiMH n.a./25	CH2 – 350 bar 3.2	4145

1. Source: manufacturer data, most recent version deployed
2. Net continuous power/net maximum power
3. ETS continuous power/peak power
4. Actual customer usable capacity
5. Fuel cell stack power
6. Gross power

The performance of these FCEVs is shown below:

Table 6-6: FCEV Performance[1]

Vehicle	Payload (pounds)	0-60 mph (seconds)	Range (miles)	Economy[2] (mi/kg H2)	Consumption[3] (kWh/mi)
DaimlerChrysler F-Cell	705	13.8	110[10]	58[10]	0.520/0.440
Ford Focus FCV	605	17.2	191[6]	48/53	0.624/0.490
Ford Explorer TDV2	600	18	350[9]	35[9]	0.950[9]
General Motors HydroGen3[4]	792	16.0	168[9]	54	0.610
General Motors HydroGen3[5]	792	16.0	249[9]	54	0.610
General Motors Equinox	750	12.0	200[9]	48	0.700
2003 Honda FCX (Ballard stack)	n/a	15.0	170[0]	51/48	0.588/0.541
2006 Honda FCX (Honda stack)	n/a	13.0	210[0]	62/51	0.483/0.509
Hyundai Tucson FCEV	n/a	n/a	186[0]	n/a	n/a
KIA Sportage FCEV	n/a	n/a	n/a	n/a	n/a
Nissan X-Trail FCV	783	14.0	234[7]	58/53	0.513/0.492
Toyota FCHV	n/a	11.8	193[7]	52/46	0.574/0.565

1. Source: manufacturer data
2. City label (FTP x 0.9)/highway label (HFET x 0.78)
3. FTP/HFET dynamometer vehicle consumption "tank to wheels", hydrogen LHV: 33.3 kWh/kg
4. CH2 version
5. LH2 version
6. FTP
7. UDDS
8. HFET
9. Combined unadjusted
10. Combined adjusted
0. Footnote 6, 7, 8 or 9 N/A

It can be seen from the tables above that some of these OEMs have introduced or announced successive generations of FCEV on-road test fleets, and the successive generations are demonstrating continuous performance improvement. Unlike "one-off" prototypes or concept vehicles typically seen at auto shows, the vehicles in these fleets are very similar to production vehicles in that they are fully engineered and tested to ensure they will perform well, will display a high level of feature comfort and function, and will be safe and reliable in the hands of the general public when driven on public roads. Achieving all of these attributes is not only very costly, but it requires dedicating a large number of highly skilled technical employees. Development of the vehicles shown in Table 6-6 thus is a good indicator of the OEM's' conviction regarding the future potential of FCEV technology and the seriousness of their commitment.

The National Renewable Energy Laboratory (NREL), in Golden, Colorado, is continuing to collect key FCEV data from the DaimlerChrysler F-Cell, Ford Focus FCV, General Motors HydroGen3, Hyundai Tucson FCEV, and KIA Sportage FCEV. This data includes stack durability, vehicle fuel economy (dynamometer and on-road), vehicle range, fuel cell system efficiency, maintenance and safety events, vehicle performance (maximum speed, acceleration, grade climbing capability), maximum power and time at 40°C ambient conditions, freeze start capability (time and energy required), and continuous voltage and current from FC stack,

motor/generator, battery and key auxiliaries (dynamometer and on-road).

The individual vehicle test data is confidential; however, NREL has published composite data for 63 first generation vehicles which reflects efficiency and fuel economy results:

Table 6-7: FCEV National Renewable Energy Laboratory Fall 2006 Results[1]

Attribute	DOE Target – 2015[2]	Fleet Status
In-Vehicle Fuel Cell System Efficiency (%)	60 [4]	52.5 – 58.1 [5]
Fuel Economy – Dynamometer (miles/kg H2)		49 – 67 [6]
Fuel Economy – Window Sticker (miles/kg H2)		42 – 57 [7]
Fuel Economy – On-Road (miles/kg H2)		31 – 46 [8]
Vehicle Range – Dynamometer (miles)		125 – 225 [6]
Vehicle Range – On-Road (miles)	300	80 – 155 [8]
Range of Ambient Temperature (°C)		-15 – 47

1. Source: Hydrogen Learning Demonstration Project: Fuel Cell Efficiency and Initial Durability, presented at Honolulu, Hawaii Fuel Cell Seminar, Nov 15, 2006, http://www.nrel.gov/hydrogen/proj_tech_validation.html
2. Source: Figure 3 (page 10), Technology-Specific 2010 and 2015 Research Goals, FreedomCAR and Fuel Partnership Plan, U.S. Department of Energy, March 2006
3. Unused
4. Peak power
5. Dynamometer data at ~25% net power
6. Unadjusted combined city/highway per SAE J2572
7. adjusted combined city/highway (label)
8. Excluding trips <1 mile, calculated from FC stack current or mass flow readings

Due to the lack of complete public availability of the NREL information, it is not possible to explain the large reduction from adjusted dynamometer results ("label", "window sticker") to on-road results, which for the data shown in the chart above ranges from 19 – 26%. Since this is consolidated data taken from four different vehicle designs, four different fuel cell system designs, at least four different hybridization levels, and three types of hydrogen storage systems, it is not clear whether this is representative of all of the vehicles or just some of the vehicles. Furthermore, all of these vehicles are at early stages of system design maturity.

The on-road data is taken from a wide variety of uncontrolled drive cycles. Factors which can degrade fuel economy include a high frequency of severe operating conditions typical of demonstration vehicles, such as drive cycles with excessive idling (more than 18% of time) that require significant amounts of hydrogen purging for water management, abnormally high number of passengers/heavy payload, aggressive "full throttle" driving, many starts and stops, and many short trips. Also, use of the climate control system, which has a more severe impact on a high fuel economy powertrain, cold weather operation, unrefined dynamometer test procedures for fuel cell vehicles (the highly accurate conventional carbon emission method cannot be used), unrefined measurement of road fuel economy by calculation from stack current or mass flow readings, and hydrogen boil off from the liquid hydrogen fueled vehicles in the fleet.

The Environmental Protection Agency (EPA) has issued a new standard for fuel economy labels

(5-cycle method), which will be used in vehicles from model year 2008 onwards[6], which tries to account for higher speeds, more aggressive driving (higher acceleration rates and higher top speeds), the use of air conditioning, and the effect of cold temperature. By using EPA's "mpg method" of adjusting FTP/HFET dynamometer data to obtain 5-cycle label values, a range of 49 to 67 mpg on the dynamometer equates to 5-cycle labels of roughly 36 to 47 mpg[7]. This would lower the reduction from labels to on-road results from 19 – 26% with the present method to 2 – 14% using the new method. This remaining lower reduction could be due to the higher frequency of severe operating conditions typical of demonstration vehicles explained above.

No fundamental safety problems with the vehicles have been encountered. Future NREL reports will include fuel cell durability and cold start up times.

b) Units in Operation

The number of FCEVs in operation is shown below:

Table 6-8: FCEV fleet vehicles in operation[1]

Vehicle	California	North America[3]	Europe	Asia	Other	Global
DaimlerChrysler F-Cell	--	--	--	--	--	64[5]
DaimlerChrysler Sprinter FCEV	--	--	--	--	--	3[5]
DaimlerChrysler Bus FCEV	--	--	--	--	--	33[5]
Ford Focus FCV	8	26	4	0	0	30
Ford Explorer TDV2	0	3	0	0	0	3
General Motors HydroGen3	2	8	1	3	0	12
General Motors Equinox[4]	n/a	n/a	n/a	n/a	n/a	n/a
Honda FCX	22	26	0	14	0	40
Hyundai FCEV	n/a	n/a	n/a	n/a	n/a	n/a
KIA FCEV	n/a	n/a	n/a	n/a	n/a	n/a
Nissan X-Trail FCV	16	16	0	23	0	39
Toyota FCHV	25	25	0	37	0	62
Total	varies	varies	varies	varies	varies	286+

1. Source: manufacturer data, includes company test vehicles in 2006
2. Includes vehicles planned to be deployed in 2007
3. Includes California
4. 1 engineering development vehicle currently deployed in California. Fleet of over 100 will be deployed beginning in September 2007, with approximately half in California.
5. For DaimlerChrysler, vehicles have been moved among all the areas listed including Australia and South America.

These vehicles are being deployed in a wide variety of locations to gather data from different climatic conditions, road conditions and customers.

[6] Final Technical Support Document, Fuel Economy Labeling of Motor Vehicle Revisions to Improve Calculation of Fuel Economy Estimates, U. S. EPA, December 2006; http://www.epa.gov/fueleconomy/420r06017.pdf

[7] Detailed FTP/HFET NREL data is not available to the public, precluding a more precise calculation.

c) Technical Issues/Goals

Vehicle Fuel Alternatives

All OEMs are now focusing on hydrogen fuel for FCEVs. In the past, methanol and gasoline fuel cell vehicles were developed by several OEMs, due to the significant fuel infrastructure advantages relative to hydrogen. However, most, if not all, manufacturers have abandoned these efforts because of major problems with system complexity, efficiency, and cost. Reformer system transient response during rapid and unpredictable changes in propulsion system load requirements and contaminants in the reformer product hydrogen also made achieving durability goals challenging. Other factors contributing to abandonment of hydrocarbon fuels for automotive fuel cell systems included increasing emphasis on petroleum independence and CO2 emissions, concerns about methanol toxicity, and the fact that these vehicles were not ZEVs.

Fuel Cell System

Major technical issues with fuel cell systems are associated with cold start performance, gravimetric power density, volumetric power density, durability and cost. Many companies are working on this technology, and have different priorities in terms of meeting challenging goals, such as power density, below freezing start capability, and durability. Usually advanced technology engineers first develop a design that can meet the key functional objectives, and, if judged successful, then work on revising the design to meet the cost objectives. At this early stage of development, while one company may be further along on one of these aspects, others may be further along on other aspects, so it is hard to determine if all of the goals can be reached simultaneously.

However, some of the leading developers of fuel cell systems expect that the technical issues will be resolved by the 2010 time frame, which could support volume production by the 2015 time frame. A detailed discussion of the goals, status, major issues and future potential of vehicle fuel cell systems is discussed in section 5.

Onboard Hydrogen Storage

Most OEMs are convinced that high pressure gaseous storage is the only practical solution for onboard hydrogen storage for the next decade. Beyond that, some manufacturers say that the only promising long term storage technology appears to be a combination of hydrides and pressure.

The major vehicle technical issues with the onboard hydrogen storage system are high cost, low volumetric energy density, and low gravimetric energy density. Low volumetric energy density makes it difficult to find a suitable location in the vehicle for the large tank(s) needed to achieve acceptable driving range (300 to 350 miles), and low gravimetric energy density makes it difficult to accommodate the weight of the tank in the vehicle. A detailed discussion of the goals, status, major issues and future potential of vehicle hydrogen storage systems is contained in section 4.

Architecture ("Conversion" vs. "Ground Up")

Most FCEVs have been conversions of existing vehicles, in order to conserve resources and focus efforts on developing the fuel cell propulsion system technology, but conversions are

difficult because of the large volume and weight of the present generation fuel cell systems and hydrogen storage systems. This has resulted in passenger and cargo space compromises, driving range compromises, and expensive weight reduction actions (e.g., carbon fiber composites, titanium, aluminum, etc.).

Heat rejection in a FCEV has been a major design constraint. Although current PEM fuel cell systems are more efficient than a conventional ICE, they (1) reject about 80% of their waste heat into the cooling system as opposed to about 33% in an ICE, and (2) to achieve acceptable stack durability operate at a lower fuel cell stack and coolant temperature than an ICE, typically about 75 to 90 °C (167 to 194 °F) versus an ICE's 120 °C (248 °F), which reduces the rate of heat transfer to the ambient air. This means that a FCEV must have a much larger radiator than a similar size ICE vehicle, and, since space is usually limited in the vehicle, especially in the case of conversions, the radiator size can constrain the maximum continuous power of the fuel cell system in the vehicle. Although the coolant temperature can be allowed to rise for a short period of time, this constraint is most critical on long steep hill climbs, at full payload, with full accessory load, in high ambient temperatures. Dedicated vehicle architectures and higher fuel cell system operating temperature are some approaches to help overcome this issue.

Present generation FCEVs typically are about 500 lbs heavier than similar sized conventional ICE vehicles, primarily due to the fuel cell system, hydrogen storage system, and large radiator and increased amount of coolant. This added weight reduces fuel economy and vehicle performance, and in the case of derivative platforms, requires a combination of weight reduction measures and vehicle upgrades to meet requirements for safety (e.g., barrier crash performance) and vehicle dynamics (e.g., braking and handling performance).

In the pursuit of cost and volumetric energy density goals, fuel cell systems are being simplified and downsized as next generations are developed. By the 2015 timeframe some systems are expected to be packaged under the hood, along with the traction motor and power electronics, within the same space as conventional front wheel drive ICE powertrain systems.

However, even next generation 700 bar compressed hydrogen storage systems capable of providing vehicle driving ranges greater than 300 miles will still require a large space within the vehicle. Some manufacturers consider a promising solution to be an under hood FC system and electric drive with a single hydrogen cylindrical tank mounted in the vehicle tunnel area (FCEVs do not require a conventional rear wheel drive transmission and driveshaft, and the FC exhaust system runs much cooler). Using a single tank instead of multiple tanks is likely to be less costly, as duplication of expensive parts is eliminated. Also, extending the length of a single cylindrical tank is a cost effective way to increase storage capacity of a compressed H2 tank.

Two examples that demonstrate progress in dealing with the challenge of onboard vehicle Hydrogen storage, are the next generation FCEVs from Ford and Honda, which have driving ranges that approach customer expectations of 300 to 350 miles,.

Ford unveiled their next generation fuel cell fleet vehicle, which is based on a modified Explorer, at the December 2006 Los Angeles Auto Show. It seats 6 passengers and has an under hood FC system and electric drive motor, and a separate rear wheel electric motor to provide all wheel drive. A large 700 bar compressed hydrogen tank is mounted in the tunnel. The tank contains 10 kg of hydrogen and at 35 mi/kg (combined, unadjusted), provides 350 miles of driving range.

Honda has announced that their next generation FCX will start limited marketing in both Japan

and the U.S. in 2008 – and it will have a driving range of 270 miles (combined, adjusted). They say the range increase of about 30% versus the prior FCX is attributed to improved system efficiency and replacement of ultra capacitors with a Li Ion battery system. This is a new dedicated vehicle which seats 4 passengers and has no obvious package compromises. It packages the FC system in the tunnel, and has an under hood mounted electric drive motor and two wheel motors in the rear to provide all wheel drive. Two hydrogen storage tanks are placed laterally between the rear wheels. It maintains the prior generation FCX storage pressure of 350 bar, which can utilize the Honda Energy Station III home-based hydrogen production and refueling system, while awaiting deployment of a hydrogen infrastructure. The Panel notes that if this vehicle were modified to use 700 bar storage tanks, packaged in the same outer envelope as the 350 bar tanks, and if the additional weight of the tanks (~50% more) could be accommodated, the driving range could be increased by about 50% – to 400 miles (combined, adjusted). (Sources: Honda, 9/25/06 Press Release; Dutch Mandel, Autoweek, 10/23/06 Honda FCX Review; and VHSS; 4 G i)

Other Technical Issues

Many FCEVs are configured as HEVs, incorporating a power battery (or ultra capacitor) to store regenerative brake system energy for improved efficiency and to supply supplemental power for improved performance and to lessen the severity of load transients on the fuel cell system for improved durability. However, fuel cells do not achieve their highest efficiency at high loads as ICEs do, so the battery assist strategy is different than for "full" HEVs which lug the ICE powertrain to achieve more efficient operation. In addition, the present generation of FCEVs does not yet take advantage of start-stop capability, which is standard on virtually all conventional HEVs.

d) Commercial Issues

Vehicle Cost

As part of the FreedomCAR program, the U.S. Department of Energy (DOE), in collaboration with the U.S. Council for Automotive Research (USCAR) partners (DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation), has published goals for the three most challenging FCEV systems – the electric propulsion system, the fuel cell power system (including hydrogen storage) and the hydrogen storage system. These include goals for commercial viability in 2015 as well as interim goals and are intended to achieve costs comparable to conventional ICE systems. The Panel focused on the fuel cell power system and the hydrogen storage system as the most difficult of the three. Ongoing development of HEVs will drive down the cost of the electric propulsion system and the Panel reviewed some excellent progress in this area. The costs for the remainder of the vehicle systems are not considered to be a major issue at high volumes, and the electric accessory systems and power batteries are expected to decline in cost as HEVs continue to mature.

The goals and status of the fuel cell power system, which also includes the hydrogen storage system, are:

Table 6-10: FreedomCAR Fuel Cell Power System[1] Goals and Status

Fuel Cell Power System Parameter[1]	**FreedomCAR Goals** – 2010/2015[2]	**Present Status** – Best Case[3]	**Forecasted 2015 Status** – Best Case[3]
Type		PEM	PEM
Life (years)	15	2 – 3	10 – 13
Peak Efficiency (%)	60	50 – 60	60
Gravimetric Power Density[4] (W/kg)	325	300 – 500	700 – 1100
Volumetric Power Density[4] (W/l)	220	n/a	n/a
Cost[5] ($/kW)	45/30	75 – 600	30 – 75

1. Consists of the fuel cell stack, the fuel cell stack auxiliary sub-systems (e.g., sub-systems for air supply, fuel supply, thermal management, and any other necessary functions, such as water management), the hydrogen storage system, the high voltage energy storage system (if used), and all enclosures and connections.
2. Source: Figure 3 (page 10), Technology-Specific 2010 and 2015 Research Goals, FreedomCAR and Fuel Partnership Plan, U.S. Department of Energy, March 2006, http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/fc_fuel_partnership_plan.pdf
3. See VFCS (section 5) for detailed discussion and Figures 5-8, 5-9, 5-13, and 5-18
4. Excluding hydrogen storage
5. Direct material/labor and production facility costs. Indirect costs, marketing and profit not included. Design level assuming 250,000 units per year

The data shown above in Table 6-10 is a highly condensed summary of the material contained in the VFCS section (5). The Panel considers the forecasted status data to be a best case scenario, since much of the data shown in this table was derived from cell level testing, with limited full system level testing. Also, the Panel questions whether the status levels shown can all be achieved simultaneously, as discussed in detail in the VFCS section.

The goals and status of the hydrogen storage system are:

Table 6-11. FreedomCAR Hydrogen Storage System Goals and Status:

Hydrogen Storage System Parameter[1]	**FreedomCAR Goals** – 2010/2015[2]	**Present Status** – Best Case[3]	**Forecasted 2015 Status** – Best Case[3]
Type		Compressed, 350 Bar	Compressed, 700 Bar
Gravimetric Energy Density - (kWh/kg) - (weight %)	 2.0/3.0 6/9	 1.1 to 2.2 6 to 6.7	 1.9 to 2.1 6 to 6.3
Volumetric Energy Density (kWh/l)	1.5/2.7	0.6 to 0.8	0.9 to 1.3
Fill Time[4] (minutes)	2.5	<6	n/a
Cost[5] ($/kWh)	4.00/2.00	10.00 to 12.00	13.00 to 15.00

1. Based on usable hydrogen capacity, the hydrogen storage system consists of all sub-systems from the vehicle fuel inlet to the connection for the fuel cell system supply line, as well as all enclosures and connections
2. Source: Figure 3 (page 10), Technology-Specific 2010 and 2015 Research Goals, FreedomCAR and Fuel Partnership Plan, U.S. Department of Energy, March 2006, http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/fc_fuel_partnership_plan.pdf
3. Sources: VHSS Tables 4-4 and 4-7, see VHSS (sections 4 F and 4 H) for discussion
4. For >300 mile range (status assumes 5 kg)
5. Assuming 250,000 units per year

As discussed in the VHSS section, gravimetric energy density of both 350 and 700 bar

compressed storage can meet the 2010 DOE target of 2.0 kWh/kg and 6% weight fraction, but cannot meet the 2015 targets of 3.0 kWh/kg and 9%. For volumetric energy density, 700 bar compressed storage can approach the 2010 target of 1.5 kWh/l but cannot meet the 2015 target of 2.7 kWh/l (350 bar cannot come close to either target). Cost for either type of system is significantly higher than the DOE targets by factors ranging from to 2.5X for a 350 bar system compared to the 2010 target up to 7.5X for a 700 bar system compared to the 2015 target. Unfortunately, without a major breakthrough, no major improvement in these cost levels is foreseen at this time.

Customer Acceptance

From a purely vehicle perspective, there appear to be no expected issues with customer acceptance of fuel cell vehicles, if they can meet the FreedomCAR goals and become available at prices competitive with comparable conventional vehicles. Several manufacturers expect future generations of vehicles to meet all their technical objectives, including 15 year life, 300/350 miles driving range and -30/40°C cold start capability. Assuming that all of these goals and expectations are met, these FCEVs should provide essentially equivalent functionality with conventional vehicles, with no compromises, and will have added advantages in smoothness, quietness and a positive environmental image.

As has been the experience with other "alternative" fuels, customer acceptance will be highly dependent on the availability of reasonably priced, conveniently located, easily accessible, simple to operate hydrogen fueling stations, that are not dissimilar from conventional self service gasoline stations. In addition, the customer must perceive hydrogen (hydrogen fuel, hydrogen fueled vehicles and hydrogen refueling) to be as safe as gasoline, which is likely to require consumer education programs.

Hydrogen Infrastructure

Many OEMs say that the most significant issue with fuel cell vehicles is the lack of a hydrogen infrastructure, and the lack of a firm commitment to deploy a hydrogen infrastructure. They have had generally bad experience in trying to deal with the very difficult "chicken and egg" problem associated with "alternative" fuels, and have said that energy companies and/or governments must take a strong leadership role in making the case for hydrogen as an automotive fuel, and in the planning and deployment of a hydrogen infrastructure – otherwise it will not happen.

Even if OEMs are able to successfully develop a technically viable and cost competitive FCEV, they will not be able to develop a viable business case for, nor commit to, volume production of FCEVs without a hydrogen infrastructure, or a firm commitment to deploy one.

ARB has indicated that the hydrogen infrastructure issue will be addressed in more detail in a separate report.

e) Prospects for Advancement

Almost all major OEMs appear to be in agreement that hydrogen fuel cell powered vehicles will eventually replace a portion of conventional light duty ICE vehicles, and many of them have invested heavily, for ten or more years, in a major effort to develop commercially viable fuel cell vehicles. The primary motivation is ensuring the long term success of providing light duty personal transportation on a global basis – which is their core business.

These companies see hydrogen fuel cell vehicles as the best known technology to simultaneously solve the three challenges of (1) zero exhaust, evaporative and greenhouse gas emissions, (2) high efficiency, and (3) diversification of automotive fuel supply in the long term – with minimum customer compromises versus conventional ICE vehicles. To achieve these goals, hydrogen must be produced on a sustainable basis, with no greenhouse gas emissions or use of fossil based feedstock.

Many automotive companies continue to commit hundreds of engineers, large well equipped dedicated facilities, and budgets approaching hundreds of millions of dollars per year – all devoted to developing commercially viable hydrogen FCEVs. In addition to the vehicles identified above, most of them are researching and developing next generation fuel cell propulsion systems and vehicles.

At some OEMs, there is a concern about the time between the introductions of successive generations of fuel cell propulsion system technology and vehicles. It takes several years after finalizing a design concept to fully engineer the vehicle systems, build prototypes, complete validation testing, build the production tooling, and launch the vehicle. If the design concept for a next generation vehicle program must be finalized before the present generation has been evaluated by customers, and not enough improvements leading toward the technical and cost goals have been identified and validated to make the next generation worthwhile, inefficiencies are incurred that waste precious resources and slow the overall rate of progress. Advanced engineering organizations normally consider that achievement of a major portion of the shortfall of current status below the goals (often 50%) is necessary to make a next generation vehicle program worth not only the time and cost, but also worth dedicating a large number of scarce technical employees who possess the necessary qualifications and skills.

Several of the leading major OEMs who have massive efforts underway note that FCEV technology has been progressing at a rapid rate and they do not foresee any insurmountable technical barriers. In their view, it is only a matter of the time needed to develop several more generations of fuel cell system technology until the vehicles become commercially viable.

Some of the major OEMs have said they are responding to global customer concerns and are likely to first introduce FCEVs wherever support for them and the associated hydrogen infrastructure materializes.

Some OEMs have said that substantial government assistance will be required to overcome the near term and longer term business risks/costs associated with FCEV market introduction, including financial incentives for OEMs, suppliers and customers, fleet purchases at meaningful volume levels, and support for uniform vehicle codes and standards.

In the Panel's view, sustaining the high level of effort underway by many of the major OEMs to develop commercially viable FCEVs will be dependent on whether they can continue to make acceptable progress in overcoming the technical, cost and fuel availability problems, and to what extent the general public becomes more knowledgeable, interested and concerned about issues of pollution, greenhouse gas emissions and energy independence.

As discussed in the VFCS section (5), the Panel is concerned that the FreedomCAR $30/kW fuel cell power system cost goal may not be feasible, given the difficulty of simultaneously achieving adequate FC stack durability with lower MEA catalyst loading, higher current density and the upward trends in the price of platinum. Continued engineering innovation and additional scientific invention will be necessary to successfully reach commercialization, in the Panel's

opinion.

A major issue will be the availability of adequate hydrogen fueling infrastructure and hydrogen fuel at affordable costs, as discussed above. California's infrastructure efforts are a good start, but other states are not as far along. It may be that the first commercially successful hydrogen infrastructure will be developed outside the United States, especially given the high prices of gasoline in other countries, in which case the introduction of the first commercially viable FCEVs could occur outside the United States.

f) Introduction Timing

Several major OEMs have stated that the FCEV will be ready for volume production by 2015 but have serious doubts about the hydrogen infrastructure. They have indicated that as with other alternative fuels, there is a "chicken and egg" issue that must be resolved – and, as can be seen with today's far simpler ethanol or E85 availability issue, they have not been able to single-handedly resolve "alternative" fuel infrastructure issues.

Some major OEMs have suggested that there is very little technical or economic benefit associated with each of them building more than a few 10's of vehicles for engineering evaluation, or at most perhaps a few 100's of vehicles for market development, or public relations, until the goals are met. That is until FCEV technical maturity achieves the key goals for performance, durability, and cost (assuming high volume), and a firm hydrogen infrastructure plan is agreed to by all the key stakeholders. Producing larger numbers of pre-commercial vehicles could be counterproductive since it could require manufacturers to divert resources from the FCEV research, development and engineering urgently needed to attain the goals for commercially viable technology – thus slowing technical advancement and the eventual introduction of commercially viable FCEVs.

FCEVs have achieved demonstration volume levels (100s/year), and the Panel's view is that given the massive effort underway, are likely to reach pre-commercialization (1,000s/year) within the next 5 years, as long as the leading major OEMs and fuel cell suppliers continue to make substantial progress toward solving the technical and commercial issues, and can see a path toward availability of a hydrogen infrastructure. However, FCEVs will not reach early commercialization (10,000s/year) until achievement of the technical and cost goals is considered within reach at several OEMs and a suitable hydrogen infrastructure becomes available in some region of the world.

B. Advanced Technology Vehicles (ATVs) – Non-ZEV

The Panel also investigated five types of Advanced Technology Vehicles (ATVs), which utilize advanced technology also used in FPBEVs and/or FCEVs. Besides helping to accelerate the introduction of FPBEVs and/or FCEVs, these ATVs are playing or could play a significant supporting role in attaining the environmental and energy-strategic goals addressed by ZEVs.

Although not discussed in detail in this report, ICE vehicles that run on compressed natural gas (CNG) also provide some of these benefits. The extensive experience gained by OEMs in developing and producing CNG vehicles over many years has made important contributions to both ZEVs and ATVs. From a vehicle standpoint, CNG technology was used in developing onboard gaseous hydrogen storage systems (FCEVs and H2ICVs) and in developing ICE modifications necessary for running on hydrogen (H2ICVs). In addition, experience with gaseous fuel infrastructure has been gained that is applicable to a hydrogen infrastructure.

1. Neighborhood/Utility/City Electric Vehicle (NEV-UEV-CEV)

Several types of BEVs have been developed that have limited performance compared to conventional vehicles, allowing smaller motors and inverters and less powerful batteries in order to achieve lower manufacturing costs and better customer affordability. In particular, they have slower acceleration and lower top speed compared to conventional vehicles, making them marginal for safely or comfortably operating with conventional vehicle traffic on high speed roads that require those capabilities. They are not suitable for use on all roads and thus have limited ability to serve as a replacement for a conventional vehicle.

California ZEV classifications of BEVs are based on driving range, and not on performance. These classifications are NEVs (neighborhood electric vehicles), Utility Electric Vehicles (UEVs), City Electric Vehicles (CEVs) and Full Function Electric Vehicles as shown below:

Table 6-12: California ZEV Definitions[1]

ZEV Tier	Common Description	ZEV Range[2]
NEV	NEV	no minimum requirement
Type 0	Utility Electric Vehicle	< 50 miles
Type I	City Electric Vehicle	50 – 99 miles
Type II	Full Function Electric Vehicle	100 + miles
Type III	Fuel Cell Electric Vehicle	100 + miles[3]

1. Source, page 89, The California Low-Emission Vehicle Regulations, January 1, 2006, http://www.arb.ca.gov/msprog/levprog/cleandoc/cleancompletelev-ghgregs11-7.pdf
2. Urban dynamometer driving schedule
3. Also must be capable of refueling in <10 minutes (95% of rated energy capacity)

Some NEVs are similar to an electric golf car but can achieve top speeds between 20 and 25 mph. Vehicles that can travel 20 mph or faster are considered motor vehicles and are subject to federal regulations. In 1998 the National Highway Traffic Safety Administration (NHTSA) established a new classification for low speed motor vehicles, to (1) eliminate conflicts between local, state and federal regulations for these types of vehicles, and (2) standardize requirements for manufacturers and therefore encourage efficient production of small vehicles (including BEVs) for use in controlled locations (e.g., planned communities, college campuses, etc.) as well as certain public roads.

In about 45 states NEVs can operate on public roads with posted speed limits of 35 mph or less if they meet Federal Motor Vehicle Safety Standard 500[8] (FMVSS 500) for low speed vehicles. FMVSS 500 defines low speed vehicles as those that have 4 wheels, are capable of 32 km/hr (20 mi/hr), are speed limited to 40 km/hr (25 mi/hr), and have a Gross Vehicle Weight Rating (GVWR) less than 1,361 kg (3,000 pounds). The standard requires that these vehicles be equipped with headlamps, turn signal lamps, tail lamps, stop lamps, reflectors, rear view mirrors, parking brake, automotive windshield, seat belts, and VIN number.

In this section, all BEVs with lower performance (i.e. acceleration and top speed) than conventional vehicles are considered to be either NEVs if they meet FMVSS 500 or CEVs if they have a maximum speed of over 25 mph. CEVs can operate on all public roads and must meet crash requirements and all other Federal Motor Vehicle Safety Standards (FMVSS), but

[8] Source: NEV; http://www.nhtsa.dot.gov/cars/rules/rulings/lsv/lsv.html and http://avt.inl.gov/pdf/nev/changes.pdf

compared to FPBEVs, they may be smaller, have less driving range, and/or fewer features and passenger comforts. As the name suggests, they are intended for urban driving and are particularly well suited to European and Japanese city centers. They are not well suited to freeway driving due to their performance limitations.

a) Manufacturers/Vehicles/Specifications/Performance

Examples of NEVs include Club Car Pathway, Columbia Par Car, Dynasty IT, Frazer-Nash City Car, TH!NK Neighbor (Ford Motor Company), and GEM (Global Electric Motorcars, DaimlerChrysler). Several recent NEV entries into the US market are the ZX40 and ZENN. The ZX40 is being imported from China by the Miles Automotive Group. It is available in either 2 or 4 passenger versions. The specifications and performance of many of these vehicles are shown in Appendix K.

The manufacturer's suggested retail price (MSRP) for the GEM ranges from $6,795 for the standard e2 two-passenger model to $12,495 for the standard e6 six-passenger model. The MSRP for the ZX40 is $14,800 and the ZX40s is $16,500. The MSRP for the ZENN is between $12,500 and $14,995. For reference, some of these NEV prices approach the price of a Honda Civic Coupe, which has a MSRP of $15,610, achieves 30 mpg city/40 mpg highway labels, and is a full function vehicle meeting all FMVSS requirements (Sources: manufacturer's websites, Automotive News, NADA Price Guide).

Drivers who can use NEVs for short trips instead of conventional vehicles reduce exhaust emissions significantly. This is because a conventional vehicle cold start contributes a very large proportion of the total exhaust emissions on a short trip. On a vehicle basis NEVs do not consume any hydrocarbon based fuel (gasoline, diesel, CNG, propane, ethanol, etc.) and create CO2. However, their limited performance means that they are not likely to be driven as many miles and thus the improvement in fuel consumption and CO2 production is not as great as the improvement in exhaust emissions, since fuel consumption and CO2 production are nearly proportional to mileage (e.g., if they substituted for half of the trips of a conventional vehicle, they would have half as many cold starts, and therefore almost half the exhaust emissions, but they would be more likely to be used for the short trips and not for the long trips, and thus the NEV probably would be driven much less than half of the mileage of the substituted conventional vehicle).

NEVs use simpler electric drive technology than FPBEVs and are usually less efficient, but as can be seen by the excellent consumption results of NEVs compared to FPBEVs (see Appendices J and K, Tables J-2, J-3, and K-2) this lower efficiency is offset by lower road loads (i.e., less mass, lower speeds, slower acceleration), and lower accessory loads, and thus they consume less energy per mile driven than most FPBEVs.

CEVs include the previous Toyota e-Com, Nissan Hyper-mini, Honda City-Pal, and the Ford TH!NK City.

b) Units in Operation

Annual NEV volume surged in 2001-2003, during the time they could earn four ZEV credits (2001-2002) and manufacturers tended to subsidize the cost of the vehicles to earn credits, but volume fell back when credits for NEVs were significantly reduced. GEM estimates there are more than 15,000 NEVs on the road in California and that this fleet represents the largest concentration of electric vehicles in the world.

c) Technical Issues

NEVs and CEVs have no major technical issues. They have major performance limitations and lack features compared to conventional vehicles, but these limitations are inherent in the design concept of these types of vehicles, which is to limit performance and feature content in order to achieve low costs and an affordable vehicle for the intended use of the product.

d) Commercial Issues

NEVs have no commercial issues, and GEM appears to have successfully created a profitable business with this technology. Although barriers to entry into the NEV market are very low, there is not an over abundance of competitors, since many weaker entries have dropped out. This situation has enabled GEM to achieve an adequate volume to sustain and grow their business, as the market naturally develops and the technology matures.

CEVs have not been successful in the U.S. despite several attempts, such as the Ford TH!NK City, Honda City-Pal, Nissan Hyper-mini, PIVCO Citi, and Toyota e-Com. As with FPBEVs, relatively high manufacturing costs combined with a small base of interested customers are the most likely reason why these types of vehicles failed to become commercially viable.

e) Prospects for Advancement

GEM is the major manufacturer of NEVs in the U.S. and it has become a successful stand alone business. Their vehicles presently use PbA batteries but the company continues to evaluate more advanced battery types. However, the cost of advanced batteries is still too high for use in NEVs. GEM continues to refine the technologies in their products to remain competitive in the marketplace.

GEM supports the creation of a next level CEV FMVSS standard, similar in concept to FMVSS 500 for low speed vehicles, to encourage the development of commercially viable CEVs, possibly with a maximum speed of 55 mph.

The Panel's assessment of the advancement of NEVs is that they will continue to evolve and mature, but the rate of change will be paced by the cost of available electric vehicle technology. With the small size of the market for NEVs, there will not be much research and development funding available to support the advancement of NEV technology.

Given the difficulty of overcoming the cost challenges facing the development of commercially viable FPBEVs, as discussed above, the Panel agrees that the creation of standards, similar in concept to FMVSS 500, but applicable to CEVs, could help stimulate the development and introduction of CEVs. The Panel supports using a consensus standard process, ensuring all stakeholders have input. Possible ways to help keep CEV costs as low as possible, and therefore maximize the chance of achieving commercial success, are (1) restrict CEVs from operating on freeways and other high speed roads, (2) leave determination of an acceptable minimum driving range to the marketplace, and (3) encourage development of a standard that is universally accepted (maximum global harmonization).

f) Introduction Timing

NEVs have achieved early commercialization (10,000's per year), but probably will not achieve

mass commercialization (100,000's per year) until more low speed vehicle friendly communities are created, either "from the ground up" or by adapting existing communities.

CEVs might be reintroduced in the U.S. if the projects to commercialize limited performance city cars in Europe and Japan are successful, but this could be 10 or more years away. If a FMVSS for CEVs were developed, along the lines of the suggestion above, it might help stimulate interest in CEVs, but this process could take a long time.

g) Significance to ZEV Commercialization

DaimlerChrysler considers NEVs to be potentially significant relative to the commercialization of full performance FPBEVs for several reasons; (1) NEVs are sustainable – they are a commercially viable product without requiring manufacturer or government subsidies, although as with any new technology introduction, incentives would help to expand the market, (2) NEVs are conditioning customers – to learn to accept limited range and the requirement to plug the vehicle in, and (3) NEVs could lead to successful CEVs – as more sophisticated vehicles are demanded by customers and battery technology and cost gradually improve.

NEVs are helpful in solving the issues of emissions, greenhouse gas, and energy independence, but they use very simple technology. Most NEVs have DC motors and lead acid batteries, and they are not full function vehicles, so they have little direct synergy with the advancement of FPBEV technology.

However, they are the highest volume battery electric vehicles on the road today, they are affordable, and they are commercially viable. Thus, they can serve to condition and educate the public on the attributes of BEVs, and possibly stimulate interest in PHEVs discussed below.

The Panel envisions that CEVs could be more helpful in solving the issues of emissions, greenhouse gas, and energy independence, and they use more advanced technology, in some instances including advanced batteries. However, CEVs are not likely to be developed soon and/or far enough in advance to help FPBEV technology within the next 10 years. Longer term, CEVs could serve as a viable alternative to FPBEVs, especially as environmentally compromised and restricted access urban areas become more widespread.

2. Hybrid Electric Vehicle (HEV)

Hybrid electric vehicles (HEVs) are important to consider in the context of ZEVs and ATVs because (1) they are the only electric drive vehicles being sold in significant numbers and (2) they could become a basis for early PHEVs. A HEV contains a battery or ultra capacitor RESS, in order to be able to store electrical energy created during driving and selectively use it at a later time, as well as a conventional liquid or gaseous fuel tank. Most HEVs improve efficiency and reduce fuel consumption, especially in stop and go, low speed driving, which is typical of urban conditions, and as a result they have reduced exhaust emissions and produce less CO2.

The addition of the RESS and electric motor/generator(s) allows achievement of the HEV's efficiency improvement by one or more of several primary methods; (1) stopping the ICE when the vehicle is stationary (and during low speed braking or deceleration with some systems) and rapidly restarting it when needed (stop-start system), (2) capturing kinetic energy during braking or deceleration for use later (regenerative brake system) (3) forcing the ICE to operate at a more fuel efficient load point (as well as speed point with some systems) by simultaneously making it generate electricity for use later, and/or (4) adopting a less powerful but more efficient

ICE (e.g., downsizing and/or Atkinson cycle). Depending on the complexity of the hybrid system, energy that has been stored in the RESS by methods (2) and (3) can be used to: (A) rapidly restart the ICE, (B) provide torque smoothing to allow fuel shut off during braking or deceleration with the ICE rotating, (C) provide power to a planetary gear set to stop the ICE during braking or deceleration, or operate the ICE at a desired speed, (D) operate electric accessories when the ICE is stopped (e.g., climate control system, electric steering, etc.), (E) provide electric drive power assist to the ICE when needed, (F) provide an electric drive reverse, and/or (G) provide limited range low speed electric drive propulsion with the ICE stopped (EV mode). A sophisticated hybrid control system is used to determine the optimum combination of the available operating modes listed above during driving in order to achieve maximum fuel economy and provide performance and smoothness equal or better than a conventional ICE powertrain.

There are a wide variety of HEVs, either on the road today, being developed, or invented, ranging from simple 14 volt belt driven alternator systems to complex ~300 volt power split systems[9] capable of a few miles of low speed electric drive propulsion ("full" hybrids). These different types of HEVs have been described by many different names, including Series, Parallel, Split, Integrated Starter Generator (ISG), Mini, Mild, Full, Power Split, Two Mode, Type A, B, C, D, E, etc..

a) Manufacturers/Vehicles/Specifications/Performance

HEVs are, by far, the most successful electric drive vehicle technology on the road today in terms of availability and customer demand and are presently being produced by Ford, General Motors, Honda and Toyota as summarized in Appendix L.

Some of these HEVs have been certified as California ATPZEVs, which means they have electric drive capability and have met the Super Ultra Low Emission Vehicle (SULEV) tailpipe standard which is 90% cleaner than the average new 2003 automobile. In addition, they have near-zero evaporative emissions and their emission control equipment has a 15-year/150,000 mile warranty.

b) Units in Operation

There are nearly 1,000,000 HEVs on the road today around the world.

In the U.S., HEV growth accelerated rapidly in the 2003 – 2005 time frame, as new entries were introduced and existing entries were improved, but growth declined significantly in 2006 as shown below:

[9] How an electric CVT power split hybrid works: http://eahart.com/prius/psd/

Table 6-13: HEV U.S. Sales[1]

Calendar Year	2003	2004	2005	2006
Ford Escape		2,566	18,797	19,228
Honda Accord		653	16,826	5,598
Honda Civic	n/a	25,586	25,864	31,253
Honda Insight	n/a	587	666	722
Lexus GS 450h[2]				513
Lexus RX 400h			20,674	20,161
Mercury Mariner			998	3,375
Toyota Camry[3]				27,336
Toyota Highlander			17,989	31,485
Toyota Prius	n/a	53,761	107,897	106,971
Total	47,525	83,153	209,711	246,642
Annual Growth	32%	75%	152%	18%[4]
Share of Industry	0.3%	0.5%	1.3%	1.5%

1. Sources: HEV volume, Electric Drive Transportation Association, http://www.electricdrive.org/index.php?tg=articles&topics=7, industry volume, Automotive News
2. Not including October – December 2006 sales
3. Not including December 2006 sales
4. 28% based on R.L. Polk & Co. data (254,545 vs. 199,148); source: Automotive News, March 5, 2007

Since the Panel was asked by ARB to forecast future volumes of ZEVs and AVTs, this successful real world experience of commercializing electric drive technology provides some interesting and relevant background.

Much has been written about the appeal of HEVs and what motivates a customer to pay a price premium to buy one, in addition to the usual factors involved in choosing a vehicle, such as brand reputation, perceived quality, status/image conveyed by ownership, dealer experience, appearance, comfort, features, safety, performance, utility and function. There seem to be several distinct HEV factors which can be involved in the purchase decision, besides the fact that there are no compromises versus a conventional vehicle. Depending on the views of the individual customer and the attributes of the specific vehicle being considered, these can include, (1) expected fuel cost savings (highly influenced by gasoline prices at the time of consideration, as noted in the next paragraph), (2) newness of the technology, (3) societal benefits (improved air quality, reduced greenhouse gas, and/or more energy independence), (4) tax incentives, (5) preferential treatment (HOV lanes, tolls, parking, etc.), and (6), ability of others to identify the vehicle as a HEV. Should these factors diminish or increase in importance, it remains to be seen how future HEV growth and market share will be affected.

Regarding the sensitivity of HEVs to fuel prices, CNW Marketing Research recently reported that a year ago (2005), when fuel prices were high, 30% of car shoppers considered buying a HEV and said they were willing to pay a premium of $2,500 over a conventional vehicle. In December 2006 consideration was only 12% and the price premium had dropped to only $1,153. Directionally consistent with this market research, HEV sales were 19,000 in November 2006, compared to 32,000 in August 2006 when gas prices nationally peaked. (Source: Rick Popely, Chicago Tribune, December 20, 2006).

c) Technical Issues

There are no technical issues that preclude HEVs from being an acceptable product for the

customer. However, most OEMs have said that cost must be reduced to make HEVs viable, or more viable, from a commercial standpoint.

Remaining issues are vehicle package constraints and the vehicle weight increases from adding the HEV battery, motor(s) and inverter. Although the present NiMH battery-based systems perform quite well, greater SOC operating range for a given battery capacity would allow use of smaller-capacity and thus lower-cost and -weight batteries. The higher gravimetric power density and "stiffer" discharge and charge power characteristics of the high power Li Ion batteries currently being evaluated for HEV applications is expected to enable advances in this area beginning within a few years (see the VESS section (3C) for a more detailed discussion.). Determining power battery calendar life when combined with cycle life is a complicated and challenging task that can vary considerably based on temperature.

Different types of HEV architectures tend to result in different costs, fuel economy benefits, towing capabilities, reverse grade climbing ability, and/or all electric drive capability/range. The leading manufacturers of HEVs are taking different approaches in attempting to optimize one or more of these attributes in their commercial and developmental HEV products.

d) Commercial Issues

Vehicle Cost

Despite widespread availability and initial success, cost is still a major issue facing commercialization of HEVs. Design maturity, increased component standardization and high volume manufacturing processes are expected to further reduce cost, but additional cost reductions are required to make HEVs cost competitive with modern fuel efficient ICE technologies (e.g., direct injection gasoline and common rail turbo diesel).

On an incremental unit cost basis, there are significantly different perspectives among the OEMs. For example, Toyota executives have stated that the Prius is profitable. Based on this, the Panel would have to conclude that Toyota's incremental cost (labor, material, and direct overhead) required to produce another Prius is less than their revenue from selling the Prius to the dealer. Many other OEMs who either produce HEVs, or have studied HEVs, say that this cost is equal or greater than vehicle revenue, and therefore HEVs must be sold at breakeven or a loss. In this case, the manufacturer may have to subsidize the loss on the HEV, as well as the lost profit on his conventional vehicles for which some portion of the HEVs substituted. The Panel envisions several possible explanations for this difference in perspective, including different volume assumptions (Toyota is the market leader), different technology, different suppliers, or favorable exchange rates (Prius' sold in the U.S. are made in Japan).

On a fully accounted basis, where all costs in addition to incremental costs are considered, including engineering design and development, manufacturing plant and equipment, and allocated company overhead, the Panel is doubtful that "full hybrids" provide a positive return to OEMs. This is a major reason cited in the past by some automakers and why some have been slow to introduce HEVs. However, the competitive nature of the marketplace, as well as the expected high cost of diesel technology (now popular in Europe and often compared with HEVs) that can meet future U.S. emissions regulations, is pressuring almost all manufacturers into introducing HEVs into the U.S. market. In addition to "full" hybrids, other types, such as mild and mini hybrids are being pursued by several manufacturers as less costly alternatives.

Limited Component Supply Base

Many OEMs have indicated that the supply base for the majority of unique HEV components is still immature, which means that normal levels of automotive supplier competition, which drives technology advancement and cost reduction, is lacking. This situation also can allow higher than normal levels of supplier profit mark up to exist.

As the number of product offerings and volumes grow, efforts are underway by the manufacturers to increase and geographically diversify the supply base. One example is Delphi's recent announcement that it will provide battery pack and cooling systems for the 2008 Ford Fusion Hybrid and Mercury Milan Hybrid.

e) Prospects for Advancement

With four major manufacturers presently offering HEVs (Ford, General Motors, Honda and Toyota), and several more who have announced plans to offer them in the near future, including BMW, DaimlerChrysler and Nissan, it is clear that this electric vehicle technology is advancing rapidly, despite the cost issue discussed above.

The large number of vehicles being produced and sold, by many different manufacturers, will encourage the automotive supplier industry to aggressively pursue advancements in technology and cost for all unique HEV components, including power batteries, electric motors, inverters, control modules with their software control algorithms, and supporting systems, such as regenerative brake, electric steering and electric climate control.

However, variable cost remains a major issue, and gasoline prices have a significant impact on HEV volume, so as additional HEV products enter and fragment the market, tax incentives expire, and gasoline prices remain at current levels, maintaining or achieving sustainable profitability levels of individual HEV entries could be challenging. If this situation continues, implementing the needed HEV cost reductions rapidly is critical to avoid choking off growth and limiting the positive benefits this technology can have on the total vehicle fleet.

f) Introduction Timing

After the initial December 1997 introduction of the Toyota Prius in Japan, HEVs offerings expanded and quickly achieved mass commercialization volumes (100,000s/year) by 2004. In 2005 over 200,000 units were sold in the United States (over 300,000 units worldwide). In contrast to FPBEVs, the Panel considers the reasons for this success to be due to two important factors; (1) existing battery technology capability and cost levels were more suitable for the application, and (2) the mass-market customer did not have to accept vehicle performance, functional or convenience compromises.

g) Significance to ZEV Commercialization

Not long ago, manufacturer's assessment of HEV technology varied greatly, ranging from Toyota's view that all vehicles will become HEVs in the not too distant future, to some manufacturers having said HEVs don't make sense and that other powertrain technologies are more cost effective, such as direct injection gasoline engines and common rail turbo diesels.

With more and more manufacturers developing HEVs, their assessment of the significance of HEVs appears to be getting stronger. Interestingly, at a speech given at the November 2006 Los Angeles Auto Show (the 100th anniversary), General Motors' CEO Rick Wagoner stated: "I

have no doubt that, when the L.A. Auto Show celebrates its 125th anniversary, it will look back at this time as a period of great change... and the formative years of the age of electrically driven vehicles."

The Panel believes HEVs are undoubtedly the most important bridging technology for ZEVs due to their success in the marketplace, besides providing rapidly growing environmental and fuel savings benefits. In the case of FPBEVs, they will contribute improvements in electric drive motors, power conversion electronics, electrically operated accessories and vehicle systems controls. They are likely to lead to plug-in hybrid electric vehicles, discussed next, which would also contribute to energy battery development. In the case of FCEVs, almost all of which are HEVs, they will contribute advancements in all areas of electric vehicle technology other than the fuel cell and hydrogen storage systems.

3. Plug-in-Hybrid Electric Vehicle (PHEV)

From the customer's perspective, a plug-in hybrid electric vehicle (PHEV) combines all the benefits of a BEV with all the benefits of a HEV. Compared to a HEV, a PHEV adds the capability to connect the vehicle to the electric grid while parked and charge an energy battery, similar to a BEV. It then depletes this stored energy during driving to displace the use of ICE fuel. The attributes of a PHEV could make it attractive to the mass-market customer – like BEVs, they can reduce fuel cost and be refueled at home, and like HEVs they can be used for long trips, they can be refueled quickly when necessary and "plugging in" is not required to operate the vehicle. Compared to a HEV, they provide reduced exhaust emissions, fuel consumption and CO2 production.

As is the case with HEVs, there can be several different types of PHEVs. The main differentiators from a customer's perspective are: (1) the quantity of electrical energy from the grid that can be stored on the vehicle, typically overnight, and be available the next day to displace the use of ICE fuel, (2) whether or not the vehicle can operate in electric propulsion mode (EV mode), similar to a BEV, and (3) for those vehicles having EV mode capability, whether EV mode has limited performance (i.e., acceleration and top speed), like "full" HEVs, or does not have performance limitations, like FPBEVs – or has performance somewhere between "full" HEVs and FPBEVs. In general, PHEVs that can operate in EV mode will have all electric range (AER) proportional to the amount of energy from the grid that can be stored in the battery system.

A PHEV with EV mode capability could function temporarily as a true ZEV if the trip length was within the vehicle's remaining AER. However, this would require that the vehicle has no performance limitations while in EV mode applicable to the trip being taken (e.g., either no freeway driving required or fully capable of safe freeway driving in EV mode) and the ICE did not start.

a) Manufacturers/Vehicles/Specifications/Performance

Presently, the only known PHEV that has been developed by a major OEM and is undergoing limited fleet testing on public roads by customers is DaimlerChrysler's Sprinter Van PHEV. EnergyCS and EDrive Systems have converted several Toyota Prius HEVs to PHEVs by replacing the original power battery system with an energy battery and adding an on board charger. Sacramento Municipal Utility District (SMUD) and Southern California AQMD are currently testing several converted Toyota Prius PHEVs. The New York State Energy and Research Development Authority (NYSERDA) is also testing various "one-off" PHEV

conversions by third parties, including Toyota Prius, DaimlerChrysler Smart, Honda Civic and Ford Escape.

Table 6-14: PHEV Demo Specifications[1]

Vehicle	**ICE** --Displacement --Power (kW)	**Battery Rated Capacity**	**Battery SOC** –Depletion Mode –Sustaining Mode	**Motor**[2] (kW)	**Curb Weight** (pounds)
Sprinter Van PHEV[3]	2.3 l 150	14 kWh[4]	100 – 35%[5] 45 -- 35%	70/90	5860
Prius PHEV[6]	1.5 l 57	9.9 kWh[7]	100 – 27%[8] 31 – 23%	20[9]/50	3200

1. Source: manufacturer data
2. Continuous power rating/peak power rating (e.g., 18 seconds)
3. DaimlerChrysler conversion
4. SAFT Li Ion (102 cells, 41 Ah, derated by 7%)
5. Usable energy of 11.2 kWh versus rated capacity of 14 kWh
6. EnergyCS conversion of 2006 model for ETA
7. See Appendix H for discussion
8. Usable energy of 7.2 kWh versus rated capacity of 9.9 kWh
9. Battery – traction motor controller DCDC link – governs power delivered by battery

The performance of these vehicles is shown below:

Table 6-15: PHEV Demo Performance[1]

Vehicle	**Payload** (pounds)	**Acceleration** (seconds, 0 to 60 mph)	**Electric Range** (test cycle)	**Fuel Economy Improvement** (test cycle)
Sprinter Van PHEV[2]	2690	~22	20 miles (NEDC)	20% (NEDC) 10 – 50% ("Real World")
Prius PHEV[3]	680	<12.5	Up to 29 mi	40 – 140% (city, highway and urban driving)[4]

1. Source: manufacturer data, unless noted
2. DaimlerChrysler conversion
3. EnergyCS conversion of 2006 model for ETA
4. SMUD testing, average trip length 14.8 miles

The results of these demonstration vehicle tests show significant potential for improved gasoline fuel economy using the PHEV architecture. However, unauthorized conversions by third parties voids the original OEM's warranty, as is typically the case with any significant vehicle modification.

b) Units in Operation

DaimlerChrysler has built six Sprinter Van PHEVs and EnergyCS has built 13 Toyota Prius conversion PHEVs.

c) Technical Issues (in addition to HEVs)

Energy Battery

The major technical issue with PHEVs is the ability of the energy battery to endure the large number of deep cycles the battery must deliver over the life of the vehicle. As discussed in the

VESS section, this number is substantially higher for PHEVs than for FPBEVs and thus represents a new dimension in deep cycling requirements. The gravimetric power density of a PHEV battery also needs to be higher than that of a FPBEV battery, but it does not need to be as high as the power density of a HEV battery. Gravimetric energy density, although still important for PHEV batteries, is not as critical as for FPBEV batteries.

A PHEV can operate the battery system in four main types of modes: (1) a grid charging mode, which occurs when the vehicle is parked, is plugged into the grid and is charging the battery (2) a charge depletion EV only mode, which consists of discharging the battery during driving after being charged by the grid from a full SOC to a predetermined low SOC, allowing regenerative brake charging but not ICE charging (the ICE does not supply power to the wheels -- similar to a FPBEV), (3) a charge depletion HEV mode, which consists of discharging the battery during driving after being charged by the grid from a full SOC to a predetermined low SOC, allowing regenerative brake charging but not ICE charging (the ICE does supply power to the wheels when needed – similar to a HEV), and (4) a charge sustaining mode, which consists of continuously varying the battery SOC between an upper and lower limit during driving, allowing both regenerative brake charging and ICE charging, the same as with a HEV, but around a much lower average SOC.

Battery cycle life when first operating in a charge depletion mode and then switching to operation in a charge sustaining mode around a relatively low average SOC is not completely known at this time. However, in the first laboratory tests, both NiMH and Li Ion medium energy/medium power batteries are approaching 2000 deep cycles when cycled in this mode. Because a PHEV has an ICE to meet a portion of the vehicle's range requirement and power demand, its battery can be smaller than a FPBEV, thus reducing the battery cost, weight and volume issues. However, because of their lower capacity, PHEV batteries are more likely to be fully discharged daily than FPBEV batteries, making cycle life requirements more severe, as discussed in Sections 3.B and 3.C.

Some testing of Li Ion and NiMH batteries on a simulated PHEV cycle developed by the Electric Power Research Institute (EPRI) has been conducted by Southern California Edison with encouraging results, as presented at the ZEV Symposium and discussed in the VESS section (3.C.2 and 3.C.5). However, additional battery testing will be required and will impact the introduction timing of PHEVs. As with all components and systems in a production vehicle, OEMs will want to ensure they have a PHEV battery system test cycle that has been validated to be representative of a wide range of actual driving and climatic conditions (typically at the 90th percentile) and that the test cycle has been proven to accurately detect failure modes. Since they are responsible for customer satisfaction and vehicle warranty, they will expect their battery system suppliers to conduct cycle life testing of PHEV battery systems using validated test cycles until the end of life, or, if that is not possible, a substantial portion of life with a conservative end of life projection. Calendar life is another concern, especially for Li Ion battery technology, and it requires a long evaluation period. Battery warranty exposure for today's HEVs is 8 years, and rises to 15 years in order to qualify as an AT PZEV. The Panel was not able to obtain actual warranty costs, but OEMs have described battery warranty as "costly and a great risk for OEMs".

Other issues with a larger energy battery are the ability to find acceptable package space and accommodate the weight increase in some existing vehicle architectures, most likely existing or planned HEVs, which already may be straining to package both the ICE and electric drive systems.

Unlike FPBEVs and HEVs, USABC technical and commercial goals for PHEV battery systems are not yet available, so it is challenging to accurately compare the status of the various battery technologies to the appropriate vehicle requirements. PHEV battery chemistry alternatives, cycle life, cost and other issues are discussed in more detail in the VESS section (3 C – E).

Other Technical Issues

PHEV definitions and standards for testing emissions and fuel economy will have a major impact on the design and performance of PHEVs. For example, the design of the PHEV will depend on whether or not EV mode is necessary, and, if so, the distance of AER that may be required to meet certain goals. Also, whether AER should be measured in EV mode only, or, alternatively, a "blended" operating strategy, similar to an HEV, which specifies the equivalent electric range, sometimes called "virtual" AER, associated with charge depletion mode (fully discharging the battery after being fully charged by the grid), before switching to conventional hybrid charge sustaining mode.

Test standards that require a PHEV to follow the UDDS trace in EV mode to measure AER implies that in actual driving the vehicle can start the ICE and switch to HEV mode if the power requirement is greater than was needed to follow the UDDS trace. The UDDS test cycle contains maximum acceleration rates of 3.3 mph/sec, which are not severe, due to dynamometer capability limitations when the cycle was developed in the late 1960's, and the vehicle's air conditioning system is not operating. Since both of these conditions are not typical of actual vehicle usage, it is likely to cause a discrepancy between "tested" AER and actual AER and result in customer dissatisfaction. Customer dissatisfaction associated with actual results being less than tested results is the main reason that the 5-cycle method to establish fuel economy labels will be required with 2008 MY vehicles. The 5-cycle method includes the US06 test with acceleration rates of 8.4 mph/sec and the SC03 test with air conditioning operating.

Initially, PHEVs could be derivatives of HEVs in order to keep the manufacturer's development cost and risk at an acceptable level, and, therefore, to stimulate introduction. AER test requirements that specify acceleration, such as the one described above to follow the UDDS drive trace in EV mode only, or similar requirements with more severe cycles such those found in the 5-cycle method, could result in some, or possibly all, PHEVs having to adopt a larger electric motor and inverter than the base HEV from which they could be derived. Similarly, requirements that completely preclude starting the ICE on driver demand by simply pressing down the accelerator pedal, such as an "EV only" mode switch, will necessitate larger motors and inverters than the base HEVs to insure vehicle safety in emergency maneuvers.

Several manufacturers have said that vehicle emissions will be a difficult issue to resolve if the internal combustion engine in the PHEV is forced to perform a cold start under high load, such as in the case of a PHEV being started and driven in EV mode and suddenly needing to start the ICE to insure vehicle safety in an emergency maneuver. Today's "full" HEVs start the ICE when the driver turns the key on and operates it at low rpm, under low load, and with high exhaust gas temperature to light off the catalysts. It has been suggested that a PHEV can use grid energy while plugged in to keep the engine coolant and catalyst warm (albeit at some loss of efficiency), but there is no guarantee that the driver will always plug in the vehicle. In most places, plugging in is also not possible for a driver who starts out in EV mode and makes short trips with long stops in between while away from home during the day.

Evaporative emissions are another issue that has been raised if EV mode AER is used. If the vehicle is plugged in every day, is driven only for short trips, and the ICE does not start up and

go into charge sustaining HEV mode, there is no purge method available.

A different PHEV approach is to utilize series hybrid architecture. Instead of a large ICE and relatively small energy battery in a parallel configuration, it uses a small ICE and relatively large energy battery in a series configuration. This concept, sometimes called a range extender hybrid, is basically a FPBEV with a small ICE powered generator (or fuel cell system) to periodically recharge the battery when necessary or to supply continuous power during long trips. Unlike parallel hybrids, the ICE has no mechanical connection to the wheels. In order to be capable of long trips and satisfy customers, the ICE/generator must be sized to provide adequate power output at the wheels for sustained cruising during maximum load conditions (e.g., 75+ mph speeds, strong headwind, higher altitude, air conditioning operating in high ambient temperature, etc.) plus some amount of battery charging to keep the battery adequately charged and allow battery assist when necessary for hill climbs and other temporary situations requiring greater power. This type of PHEV can operate as a full performance ZEV, during the times that the ICE is not operating, and can avoid the cold start emissions problem discussed above, but it requires a relatively large energy battery and a large, full performance, electric drive propulsion system, similar to a FPBEV or FCEV. Compared to a FPBEV, it can use a smaller, more affordable battery and it does not have the driving range limitation issues. Compared to a parallel PHEV, it can operate the ICE at the optimum combination of speed and load necessary to achieve maximum efficiency (except for a short time for warm up), however, this efficiency advantage is reduced to some degree by a combination of generator, battery charging, battery discharging, and electric drive system efficiency losses before reaching the wheels. Compared to some other parallel hybrid systems, it is probably not suitable for vehicles intended for trailer towing.

Agreed upon definitions and standards for testing emissions and fuel economy of PHEVs are likely to be complicated and do not yet exist. Ideally they will maximize commonality with existing standards and will need to be established before serious design and development of PHEVs can begin. In addition to modeling efforts underway, manufacturers will need to deploy PHEV demonstration fleets with a variety of operational characteristics to gather real world on-road customer data in order to provide meaningful input to proposed definitions and standards prior to being finalized. Furthermore, truly representative battery cycle life testing, which takes a long time to conduct, cannot be started until agreement is reached on definitions and standards for PHEVs.

d) Commercial Issues

Vehicle Cost

A PHEV battery must have a much higher energy capacity than a HEV, which makes the cost issue more challenging. As is the case with FPBEVs, battery system costs are the major issue; however, compared to a FPBEV the customer payback of the battery is improved significantly. This is due to (1) being able to use a smaller battery and (2) being able to discharge the battery fully, because of the capabilities provided by the ICE, which results in a higher proportion of the battery capacity being used every day to displace conventional fuel.

If vehicle operational requirements require a higher power electric drive system, such as to operate the vehicle safely in EV mode, without ICE assist, larger, more costly motors and power electronics than the base HEV from which the PHEV is derived, will be required. Also, fixed costs will increase due to the need for these unique components, a significant redesign of the vehicle to accommodate the larger system and the associated validation testing.

Commonality and standardization of components would help keep fixed costs down for PHEVs, such as commonality of motors and power electronics with the base HEV from which early PHEVs could be derived. A less likely, but significant, cost opportunity is energy battery standardization, at least at the cell level, which would allow much higher volumes per cell manufacturing facility and reduce battery costs.

Customer Acceptance

The Panel expects customer interest and acceptance of a PHEV to be good. Depending on the final label methodology, high fuel economy numbers are likely to get mass-market customer's attention, and this could be particularly effective coupled with the significant 2008 MY reductions in label values. Fuel costs can be reduced by plugging into the grid, and unlike FPBEVs, the vehicle does not have range issues and does not need to be plugged into the grid to be able to operate. Customers can also have the satisfaction of knowing they are helping to reduce exhaust emissions, petroleum consumption and the creation of CO2. Other advantages are fewer trips to the service station, and if the vehicle has EV mode, quiet electric drive and the security of being able to do some limited driving during a fuel shortage. Ultimately, however, vehicle price will be a major factor in establishing mass-market customer appeal and therefore market success of the PHEV.

The fuel economy improvement of a PHEV varies with trip length, and, as can be seen from Table 6-15, varies greatly. From the customer's standpoint a direct way to assess the fuel savings value provided by the PHEV, and enable him/her to determine how that relates to the price premium of the vehicle, is to compare the cost of electric energy stored overnight and used the next day with the cost of the petroleum fuel displaced in normal HEV charge sustaining mode.

As with fuel economy, there are too many variables involved to make it possible to determine precisely what results a particular individual will achieve, but it is useful to make some assumptions and give an example. Using the Prius PHEV data shown above as a baseline, 7.2 kWh of usable electric energy would provide about 29 miles of electric drive range. This would cost the customer about $0.55 for the electricity and save him/her about $1.85 in gasoline (assuming $3/gallon) for a net fuel cost savings of about $1.30 per day or about $475 per year, assuming the battery is completely discharged every day.

From Table 3-13 in the VESS section, a 30 Ah cell Li Ion battery for PHEVs having a 10 year life and rated capacity of 9.9 kWh is projected to cost about $7,300 at a reasonable initial vehicle introduction volume level of about 14,000 vehicle batteries/year. Assuming comparable vehicle volume, a 10 year, 2 kWh, 7 Ah cell Li Ion HEV battery is projected to cost about $4,400. Adding a provision of $200 for other vehicle components (e.g., added onboard charger, upgraded thermal management system, etc.), the incremental cost of the PHEV at these volumes is therefore about $3,100. Assuming no additional profit mark up from the OEM to recover incremental development, warranty, and marketing costs, the customer payback would be about 6+ years. The payback is highly sensitive to the price of gasoline; at $2/gallon the payback period increases to 12+ years, and at $4/gallon it declines to 4+ years. This analysis assumes that the electric drive system does not need to be upgraded for increased power to achieve AER, as discussed above.

A major unanswered question is how many customers would actually pay the full $3,100 incremental cost of the PHEV in this example versus a HEV. There would need to be enough

paying customers for the OEM to achieve a viable business case. Although the per mile fuel cost savings is much greater on a PHEV than a HEV, given the price premium resistance of HEVs over comparable conventional vehicles discussed in the HEV section above (6. B. 2. b.), this could be a major issue. If the customer is not willing to pay the full incremental cost over the base HEV, the OEM would have to absorb the remaining portion of the cost difference and this would make the manufacturer's business case for a PHEV program less viable than what may already be a marginally profitable HEV program. This may be acceptable to the automaker for an initial low volume marketing or public relations effort, but it is not likely to be acceptable at higher volumes, nor is it sustainable.

Average customers will need to be educated on how a PHEV differs from a HEV and many are likely to be confused for a while. Communications efforts by manufacturers to convince potential HEV customers that HEVs do not need to be plugged in will be complicated by the existence of PHEVs.

Charging Infrastructure

The charging infrastructure requirements for PHEVs are much simpler than for FPBEVs because the AER (either actual or virtual) will be significantly less than the range of a FPBEV. Standard 120 volt, 15 amp circuits could provide about 30 to 40 miles AER with batteries capable of being completely charged in 6 to 8 hours. However, this would require circuits which are dedicated, or see only minor additional loads, and these are not always available. Since the PHEV, like a HEV, has an ICE and associated rapid fill fuel tank, high power fast charging infrastructure is unnecessary.

e) Prospects for Advancement

While acknowledging that PHEVs in principal have a high degree of synergy with FPBEVs, with respect to energy battery development and conditioning customers to plug in, many OEMs have been suggesting that the high life cycle cost of the energy battery, on top of the high cost of the base HEV, precludes commercial viability of both the PHEV and FPBEV in the foreseeable future.

These manufacturers' pessimistic views may be tied to an assumption that PHEVs will be required to have an EV mode in which the vehicle must provide both a long AER and full function performance capability. This assumption, in turn, may be based on the expectations being generated from statements such as the one President Bush made in an April, 2006 speech; "And we're pretty close to a breakthrough. We believe we're close to a technology that will make it possible to drive up to 40 miles on electricity alone. And then if you have to drive more than 40 miles, then your gasoline kicks in."

However, interest in PHEVs seems to be growing rapidly among major OEMs. DaimlerChrysler has deployed a small demonstration fleet of Sprinter Van PHEVs. Last year Ford, Nissan, and Toyota announced they are actively studying PHEVs, and General Motors announced at the December 2006 Los Angeles Auto Show that they will produce a Saturn VUE PHEV when advanced battery technology is ready.

At the January 2007 Detroit Auto Show, two interesting PHEV concept vehicles were shown. General Motors introduced the Chevrolet Volt, which uses series hybrid architecture with no mechanical connection from the ICE to the wheels. It consists of a full performance electric drive propulsion system, a Li Ion battery system, a battery charger for overnight charging, and a small

gasoline ICE powered generator, used to recharge the battery if necessary during driving. As with the Vue PHEV, General Motors said that production of the Volt PHEV will begin when battery technology is ready. Ford introduced the Airstream, which uses a fuel cell system from their Focus FCV and adds a Li Ion battery system and battery charger. It does not appear this vehicle is intended for production, but it is the first time Ford has shown a PHEV.

Ford also introduced a plug-in series hybrid drivable prototype, based on the Edge, at the February 2007 Washington DC Auto Show. It has a 130 kW Li Ion battery, a 120/240 volt onboard charger, a 35 kW fuel cell auxiliary power unit, a tunnel mounted, 350 bar, 4.5 kg, hydrogen tank, and a 4 wheel, 130 kW, electric drive system. They say that the powertrain reduces the size, weight, cost and complexity of a conventional fuel cell system by more than 50 percent and promises to more than double the lifetime of the fuel cell stack. They also mentioned that one of the benefits of this concept is that it can extend the time between hydrogen refueling, which is an important consideration during the early deployment of a hydrogen infrastructure.

The architectures of both the Chevrolet Volt and Ford Edge are envisioned by the respective manufacturers to be able to use a variety of ICE engines and fuels, such as gasoline, diesel, ethanol, or bio-diesel, as well as fuel cells, to generate electricity to recharge the battery.

The Panel considers battery cost the largest issue for successful introduction of PHEVs. As costs come down, and gasoline prices go up, PHEVs will become increasingly viable. However, several important issues will impact the future of this technology – AER probably the most important among them. Like FCEVs, OEMs are expected to need to conduct on-road customer fleet trials of demonstration vehicles to fully understand and address consumer acceptance, battery development and cost reduction.

As long as issues associated with AER, EV mode, and testing, discussed above, do not overly complicate vehicle operational requirements, force larger motors/power electronics, or require very large and costly energy batteries, the Panel anticipates that one or more OEMs may try to be the first to introduce a PHEV derivative of an existing HEV as a marketing competitive advantage.

Initial introduction and subsequent advancement of PHEVs will be highly influenced by the required battery capacities. Larger batteries are more costly, more difficult to package, and it is more difficult to offset the associated vehicle weight increase. A smaller battery, and consequently more affordable vehicle pricing, can increase the likelihood of early market introduction of PHEVs. The primary enabler of using smaller batteries is reducing or eliminating AER. This would help directly by reducing the usable energy storage required and indirectly by allowing manufacturers more flexibility in designing PHEV batteries and battery operation for shallower depth of discharge, to extend battery life and reduce warranty risk. From such a beginning, marketplace and technology competition, driven by the quest for customer satisfaction, are likely to eventually yield vehicles with greater AER (actual or virtual).

The Panel envisions that after demonstration fleets are deployed to gain real world information, definitions and standards are debated and agreed upon, and initial PHEV derivatives of HEVs with small energy batteries become available in the market, it is likely that as batteries improve and the market develops, vehicles with series hybrid architectures will eventually be introduced which have ZEV operating capability with 25 to 40 miles of AER, as demonstrated by the Chevrolet Volt and Ford Edge PHEVs.

f) Introduction Timing

Given the rapid success and increasing mass-market awareness of HEVs, the high level of national publicity about PHEVs, recent auto show PHEV concept and prototype vehicle announcements, and the need for OEMs to gain real world fleet experience in order to participate effectively in PHEV standards development, the Panel projects that demonstration level volume (100's/year) could be on the road within the next 5 years. A key requirement to enable successful introduction of PHEVs are definitions and standards developed through a formal process and consensus among the key stakeholders. Some manufacturers may introduce expensive and/or limited numbers of PHEVs within the next 5 to 10 years, probably as marketing or public relations initiatives. When a battery becomes available that is technically capable for the intended application and the purchase price is low enough, or gasoline prices rise significantly, or some combination of the two, mass commercialization (100,000's/year) is likely to be achieved within five years thereafter. Until then, however, volumes of PHEVs will not progress beyond the level of pre-commercialization (1,000s/year) or, at most, early commercialization (10,000s/year).

g) Significance to ZEV Commercialization

PHEVs have several desirable attributes from a customer perspective; they reduce fuel cost, they can be fueled at home (reducing the frequency of fueling at service stations), and they are not range limited. They also have several favorable attributes from a societal perspective (also desirable to many customers); they reduce exhaust emissions, and, including infrastructure, they reduce net petroleum fuel consumption and the associated production of CO2 and other greenhouse gases. PHEVs are making the news regularly and more OEMs have begun to evaluate them and publicly express a serious interest in their development.

If they become commercially successful, the Panel considers PHEVs to be an important technology for helping to enable FPBEVs, as they would stimulate more rapid development and commercialization of energy batteries, which are more similar to FPBEV batteries than power batteries for HEVs. Unlike FPBEVs, which must have large expensive batteries to achieve the customer's minimum acceptable 100 miles range, PHEVs are capable of starting out with much smaller, more affordable batteries because the ICE system gives them adequate range. In addition, they could serve to condition customers to plugging in, and to educate them on the advantages of using the electric grid, or homeowner supplied photovoltaic electric energy to help power their vehicle.

However, if significant AER and high performance while in EV mode are required in the early phases of PHEV development and introduction, the Panel is concerned that these initiatives and the required investments by potential manufacturers of batteries and vehicles could be slowed significantly due to cost issues. The key challenge is for the key stakeholders to encourage, guide, and carefully pace the introduction of PHEVs, consistent with the development of suitable energy battery life cycle costs.

If suitable batteries become available, PHEVs may support earlier introduction of FCEVs by providing a vehicle architecture solution to help resolve some of the most difficult fuel cell system challenges, such as meeting cold start, durability and cost objectives. A plug-in series hybrid FCEV with a relatively small fuel cell stack and a relatively large energy battery would allow the fuel cell stack to operate under more readily controlled conditions – those that have been found to be most ideal for simultaneously achieving higher efficiency and longer durability with lower catalyst loading (e.g., elimination of idling, constant power, gradual transients,

gradual cold start off-plug, coolant heaters on-plug, etc.). The fuel cell system could be simplified by requiring it to operate in only three steady state conditions; (1) off, (2) an optimum efficiency point for battery charging, and (3) an optimum power point for long distance cruising. Following dynamic vehicle loads would not be required, so transitions from one steady state to another could be highly controlled to optimize efficiency and durability.

Plug-in series hybrid FCEVs could also provide benefits supporting implementation of a hydrogen infrastructure, including reducing the quantity of hydrogen needed and making the customer's cost of hydrogen less of an impediment. A series PHEV with a fuel cell running on hydrogen is always a ZEV and would not need to be subjected to AER requirements. In this case the OEM might chose to establish one or more optimum battery sizes tailored to match the potential PHEV customer's expected daily driving range.

4. Hydrogen Internal Combustion Vehicle (H2ICV)

A hydrogen internal combustion vehicle (H2ICV) is basically a conventional ICE powered vehicle that has been converted to operate on hydrogen fuel, very similar to vehicles converted to operate on CNG fuel. Like CNG vehicles, some H2ICVs are "dedicated" (use only hydrogen fuel) and some are capable of operating on multiple types of fuel (e.g., bi-fuel – gasoline or hydrogen). When operating on hydrogen, H2ICVs have near zero exhaust emissions (primarily low levels of NOx), and on a vehicle basis do not consume any hydrocarbon based fuel (gasoline, diesel, CNG, propane, ethanol, etc.) and create CO2.

a) Manufacturers/Vehicles/Specifications/Performance

Only two major OEMs appear to be pursuing hydrogen internal combustion engine vehicles (H2ICV) at the present time – BMW and Ford. Some other manufacturers have studied this technology in the past but are not actively pursuing it at present.

BMW and Ford have announced limited volume demonstration fleets:

Table 6-16: H2ICV Specifications[1]

Vehicle	**Engine**	**Power** (hp/kW)	**Hydrogen Storage** (kg/type)	**Curb Weight** (kg)
BMW 7 Series – Bi Fuel	6.0L V12	256/191	~7.8 / liquid	2460
Ford E-450 Bus – Hydrogen	6.8L V10 (supercharged)	235/175	29 / compressed @ 350 bar	n/a

1. Source: manufacturer data

Table 6-17: H2ICV Performance[1]

Vehicle	**Emissions**	**Performance** (sec. 0-60 mph)	**Driving Range** (miles/km)	**H2 Consumption** (kg/100 km, cycle)
BMW 7 Series – Bi Fuel	ECE compliant	9.5	127/205 (hydrogen) 311/500 (gasoline)	3.6, NEDC
Ford E-450 Bus – Hydrogen	2010 Phase II Heavy Duty compliant	n/a	150/241 to 200/320	8.0 – 10.0, real world shuttle bus

1. Source: manufacturer data

BMW believes hydrogen is the energy carrier of the long term future and that it will play a major

role in resolving energy security and global CO2 issues. BMW is convinced that a solution for future sustainable mobility has to be defined on the basis of a technical standard fostering the competition between different technologies, in order to find commercially viable solutions fulfilling customers' needs. Therefore, BMW is focusing on H2ICVs and have developed a series of 100 units of 7 series hydrogen bi-fuel vehicles which they plan to loan to selected users in different countries starting in 2007. Compared to the SULEV II standard, the BMW hydrogen vehicle emissions are less than 1% of the NMOG and CO limits, and NOx is significantly lower than this standard, when operating on hydrogen.

Ford sees H2ICVs as a legitimate transitional product to move from today's fossil fuel dominated powertrains to a pathway that is powered by renewable fuels which have the potential to be environmentally benign. They have focused on high use shuttle vans which consume large quantities of hydrogen and thus help the business case for hydrogen fueling stations. They have developed a 12 passenger E-450 shuttle bus pilot/demonstration program which utilizes a 6.8L supercharged V-10 engine and 350 bar compressed hydrogen storage tanks holding 29 kg of hydrogen. The vehicle has a 150 to 200 mile driving range. In terms of regulated emissions, the E-450 shuttle bus is capable of meeting the 2010 heavy duty NOx standard with no after treatment and has significantly lower CO (3%) and THC (21%) compared to the standard.

For light duty H2ICVs, Ford has achieved the SULEV standard for NMHC and significant reductions in NOx (80 % below SULEV standard) and CO (500% below SULEV standard) with a lean NOx trap after treatment system purged by hydrogen.

b) Units in Operation

Until recently, there have been no fleets of H2ICVs, other than a few "one-off" concept vehicles. During the fourth quarter of 2006, Ford began leasing their E-450 hydrogen bus to customers and in the first quarter of 2007 BMW started production of their 7 series hydrogen bi fuel vehicles.

BMW plans to place up to 25 units in California and another 35 to 50 vehicles in Europe. Ford plans to deploy 30 E-450 H2ICV shuttle busses in 2006 – 2007.

c) Technical Issues

Onboard storage of hydrogen for use in an ICE is more difficult than with a FCEV. Although the efficiency of a H2ICV is about 15-20% better than a gasoline ICE, it is less than the FCEV, and thus for equivalent driving range, more hydrogen must be stored. BMW addresses this by using a liquid hydrogen storage system while Ford is developing large compressed hydrogen storage systems packaged in large shuttle vans.

A detailed discussion of the goals, status, major issues and future potential of onboard vehicle hydrogen storage is discussed in the VHSS section (4).

There are a number of powertrain issues remaining to be overcome in converting conventional engines to operate successfully and durably on hydrogen, however, they are steadily being resolved and none of them are seen by BMW or Ford to be barriers to the successful development of H2ICVs.

d) Commercial Issues

Vehicle Cost

Modifications are required to the ICE to operate successfully on hydrogen fuel and meet durability requirements. Also, direct injection, supercharging, turbo charging and hybrid electric systems are being investigated to offset the lower power output of a hydrogen ICE and improve efficiency. These are conventional automotive technologies and the associated costs are not considered to be an issue.

The cost of the hydrogen storage system is a major issue, as it is with FCEVs. For a more detailed discussion of hydrogen storage costs see section 4 above.

Customer Acceptance

From a vehicle perspective, there appear to be no expected issues with customer acceptance of hydrogen internal combustion vehicles, assuming they can achieve acceptable driving range and become available at prices competitive with comparable conventional vehicles. These vehicles would provide essentially equivalent functionality with conventional vehicles, with no compromises, and have added advantages of a positive environmental image.

Hydrogen Infrastructure

As with other "alternative" fuels, customer acceptance will be highly dependent on the availability of reasonably priced, conveniently located, easily accessible, simple to operate hydrogen fueling stations, which are not dissimilar from conventional self service gasoline stations. In addition, the customer must perceive hydrogen fuel as safe.

e) Prospects for Advancement

BMW and Ford are presently deploying first generation demonstration programs and are continuing to investigate H2ICV technology and possible next generation vehicles.

If a hydrogen infrastructure begins to be deployed on a large scale, before commercially viable FCEVs become widely available, it is possible that more OEMs will begin development of the less costly H2ICVs, especially if FCEV advancement slows due to unresolved technical or commercial issues, or significant government incentives for H2ICVs are introduced. The technology provides near zero exhaust emissions, does not rely on imported petroleum, and, compared to FCEVs, is less costly to develop. Questions of relatively low efficiency remain, however, and could preclude advancement.

f) Introduction Timing

With the BMW and Ford H2ICV fleets now starting production, demonstration (100s/year) will be achieved in 2007 or 2008. However, H2ICVs are not expected to be produced in much higher quantities until a suitable hydrogen infrastructure becomes available in some region of the world.

g) Significance to ZEV Commercialization

Despite the fact that conversion of their existing ICE manufacturing facilities to make H2ICVs is far less costly than ZEV alternatives, most manufacturers have said they are not pursuing

H2ICVs because FCEV technology is a better long term solution from an efficiency standpoint and that a FCEV is a true ZEV. Therefore, they say they are focusing their efforts on FCEVs and some of them are becoming convinced that FCEVs will achieve commercially viable by the 2015-2020 time frame. Although availability of a hydrogen infrastructure is a significant issue, it is necessary in either case.

Both BMW and Ford see H2ICVs as having high degree of significance on stimulating hydrogen infrastructure development, although the Panel questions how significant this can be based on the very low vehicle volumes and consumption expected from just two manufacturers. On the other hand, experience gained from both BMW and Ford's H2ICV demonstration programs could help in the effort to condition customers to accept hydrogen as an automotive fuel.

H2ICVs could help commercialization of FCEVs by development of onboard hydrogen storage systems. Although BMW is very active in developing onboard hydrogen storage systems for light duty vehicles, their vehicles utilize liquid hydrogen storage. Most FCEV developers have chosen compressed hydrogen over liquid hydrogen fuel storage systems and believe this will be the technology used by FCEVs for quite some time.

Some OEMs who are developing FCEVs, but not H2ICVs, have noted that if H2ICVs are given government incentives, and if that results in more availability of H2ICVs by their competitors, they could be forced to divert scarce R&D budgets away from their FCEV technology development to fund H2ICV development. In this case the synergy of H2ICVs with FCEVs would actually be negative.

H2ICVs have no known synergistic benefits for FPBEVs.

5. Fuel Cell Auxiliary Power Unit Vehicle (FCAPUV)

A fuel cell auxiliary power unit vehicle (FCAPUV) adds a small fuel cell to an ICE vehicle, primarily to produce electric power for electrically operated accessories. APUs can also be combined with an HEV system as an efficient supplementary power source under certain vehicle operating conditions. Some APU systems with reformers for use in petroleum fueled vehicles are being developed that also use the reformer's hydrogen rich gas for regeneration of particulate and NOx traps, primarily to meet future diesel emissions regulations.

There has been interest in APUs for heavy duty applications, such as long haul diesel trucks, to produce power for driver resting periods without requiring the ICE to idle for long periods of time. This type of application also makes sense for chauffer driven vehicles which spend a significant amount of time parked with the ICE running to power the climate control system and electronic accessories.

So called "fuel cell auxiliary power units" that are used in series hybrid vehicle architectures are discussed in the PHEV section above.

a) Manufacturers/Vehicles/Specifications/Performance

BMW is investigating a 5 kW United Technologies PEM fuel cell auxiliary power unit for their H2ICV. They are also investigating ways to use it as one option to capture the energy usually lost in the boil off hydrogen from the on board liquid hydrogen storage tank. The Panel knows of no other OEMs actively studying FCAPUVs at this time.

b) Units in Operation

There are no units in operation at this time other than a few engineering prototypes.

c) Technical Issues

Fuel Cell System Related

Fuel cell systems used in a FCAPUV do not have the same demanding start-up time and dynamic response requirements as in the case of a FCEV, which permits use of a wider variety of fuel cell technologies in addition to quick starting PEM, such as slower starting solid oxide.

To simplify vehicle fueling for the customer, these systems typically would be designed to use the same fuel as the ICE, and for gasoline or diesel vehicles, they require a reformer system to produce hydrogen for the APU's fuel cell stack. If the ICE uses hydrogen fuel, the small fuel cell or APU can be much simpler by avoiding the need for a reformer to produce hydrogen.

BMW's experience with the development of FCAPUVs is described in more detail in the FCS section (5. B. 1. b.).

Architecture Related ("Conversion" vs. "Ground Up")

In the case of a conversion of an existing ICE vehicle, there is usually no unused space to package the addition of a FCAPU, especially one which includes a high temperature reformer and its associated insulation and heat shielding. One solution is to package it in the spare tire well and adopt run flat tires. A FCAPU that runs on hydrogen is easier to package but the hydrogen storage system itself is a major packaging problem, as discussed in the H2ICV section.

d) Commercial Issues

Vehicle Cost

The Panel did not obtain any information on the cost of a FCAPU or a FCAPUV.

Customer Acceptance

A vehicle with an APU which uses the same fuel as the ICE will provide improved fuel economy and can eliminate long ICE idle time. It will be transparent to the customer and should require no compromises, except if it requires run flat tires and the customer does not want run flat tires. If the addition of an APU increases the price of the vehicle substantially, there will be customer resistance, especially in mass-market vehicles. A vehicle with an APU that uses a fuel different from the ICE will be difficult to market, due to the inconvenience of having to refuel with two different fuels.

e) Prospects for Advancement

BMW is studying FCAPUs for use with their H2ICV and is continuing their investigation. The Panel knows of no other OEM investigating FCAPUVs.

As BMW is the only known OEM pursuing FCAPUVs, therefore, prospects for advancement are

limited to BMW's plans.

Several companies now offer battery powered APUs for vehicles, which are fuel independent and serve existing customer needs for auxiliary power to avoid long periods of ICE idling. This commercially available competitive technology makes it more difficult to establish a market for FCAPUs.

f) Introduction Timing

BMW is considering adding an APU to their H2ICV in the future, but they have not made a decision on their next program. If they decide to proceed, demonstration level (100s/year) could be possible in 5 or more years. Volumes beyond that level are not possible to predict.

g) Significance to ZEV Commercialization

As BMW is the only OEM investigating FCAPUVs, and they apparently do not have a major effort in FCEVs underway, there appears to be little synergy between the two technologies at the OEM level. To the extent UTC Power is developing FC systems for both FCAPUs and light duty propulsion, there is some synergy possible.

The Panel has no assessment on FCAPUVs synergy with ZEVs. Although PEM APUs are similar to fuel cells in FCEVs, the Panel does not expect that FCAPUVs will have much synergy with FCEV technology. The units are usually small (e.g., 5 kW) and the duty cycle is significantly different than fuel cells used for vehicle propulsion. BMW is investigating hydrogen APUs, but their use is predicated on successful introduction of H2ICVs discussed above.

Some of the suppliers that were working on APUs in the past were focused on high temperature systems (e.g., solid oxide). This technology is suitable for use with petroleum fuels and therefore for use in conjunction with ICEs running on gasoline or diesel, but are not suitable for vehicle propulsion due to their long start up time.

C. Vehicle Integration Discussion

Customer demand, intense competition, stockholder expectations, and increasingly stringent global regulations force all automotive manufactures to improve their conventional powertrain systems and to diversify their powertrain offerings. Most automotive manufactures agree there is no single technology that solves all the issues. Advanced technologies such as E85 flexible fuel vehicles, CNG vehicles, common rail turbocharged diesels, direct injection gasoline engines, and dual-clutch, continuously variable, and 6 speed (or more) automatic transmissions must be developed and introduced at a rapid rate. These efforts require major engineering efforts and capital expenditures.

Major resources are also necessary to develop ZEVs and ATVs, but the payback on these investments is usually far longer and much more uncertain. Costs to produce larger than necessary for learning volumes of demonstration fleets with immature design levels (designs that still would not achieve competitive cost levels even if they were produced at high volumes) takes resources away from the basic research and development efforts necessary to advance the technology.

However, there are urgent and compelling reasons for ZEV and ATV technologies to be developed as rapidly as possible, and eventually to become commercially successful –

improved air quality, reduced greenhouse gas emissions and increased energy independence.

Electrification of mass-market light duty vehicles is steadily progressing, ranging from increased electrification of accessories on conventional ICEs to the introduction of more and different types of HEVs. With several PHEVs being announced at recent auto shows, the Panel contemplates an eventual convergence of advanced electric drive technologies – merging HEV and BEV technology to create PHEVs and merging PHEV and FCEV technology to create plug-in FCEVs.

D. Vehicle Integration Summary

In summary, significant progress is being made on ZEVs and ATVs, but there appears to be no agreement among the OEMs on whether and when the designs can mature enough to satisfy all the functional requirements and reach cost levels low enough to become commercially viable mass-market products and therefore achieve the societal benefits described above.

A brief summary of the ten major OEMs input is shown below:

Table 6-18: Summary of Major OEMs' and Suppliers' Input

	Present status of technology[1]:		**Range of assessment of potential:**	
Technology	**Function**	**Cost**	**Low**	**High[6]**
FPBEV	Major Issues	Major Issue	Not viable[2]	Promising for urban
FCEV	Major Issues	Major Issue	Not viable[3]	Commercial by 2015-18
NEV	No Issues	No Issue	Low volume	Commercial now
CEV	Some Issues	Major Issue	Not viable[2]	Promising for urban
HEV	No Issues	Still an Issue	Cost too high	Commercial now
PHEV	Still an Issue	Major Issue	Not viable[2]	Commercial by 2012-15
H2ICV	Minor Issues	Medium Issue	Not viable[4]	Promising
FCAPUV	Some Issues	Major Issue	Not viable[5]	Uncertain

1. Views of majority of automakers, detailed discussions of function and manufacturing cost (goals, status, issues and potential) is included in the report, along with minority views
2. Due to lack of an affordable battery in the foreseeable future
3. Due to lack of an affordable fuel cell system in the foreseeable future and hydrogen storage issues
4. Due to low efficiency, hydrogen storage issues and high cost
5. Due to dependency on H2ICV and high cost
6. "Promising" – manufacturer is investing in the technology but say it is too early to predict commercialization

Also, several manufacturers consider FCEV, H2ICV and FCAPUV technology "not viable" due to lack of a suitable hydrogen infrastructure in the foreseeable future.

7. Report Summary and Conclusions

In the Panel's scope of work, the ARB specifically requested that the Panel make projections as to when the various ZEV and ATV technology vehicles would achieve certain volume milestones.

Given the uncertainty surrounding the future of major factors that will contribute to the success, or lack of success, of these technologies, especially the cost and performance of the key vehicle systems (batteries, fuel cells and hydrogen storage), the price of petroleum, the mood of the general public regarding global warming and energy independence, the level of government incentives (e.g., fleet purchases, tax credits, ZEV credits, etc.), and the implementation of a

hydrogen infrastructure in the case of FCEVs and H2ICVs, it is not really possible to make predictions with a high degree of confidence.

However, since being formed, the Panel has reviewed a great amount of public information, and confidential information from many OEMs, automotive suppliers and others, most of whom were very cooperative and forthright, and the Panel is comprised of diverse individuals, with a wide variety of relevant experience and knowledge, so at this point in time, as a group, is willing to make an educated "best guess" projection.

The chart below reflects the Panel's consensus projection on global volumes, based on what they know today, including the present ZEV regulations, and barring any sudden and unanticipated major trigger events (e.g., scientific breakthrough, public and/or political outcry, increase in gasoline taxes (U.S.), petroleum supply destabilization, climate change, war, terrorism, etc.):

Table 7-1: Panel's Projected Achievement of Global Volumes (ARB defined milestones)

Vehicle Technology	**100s/year** (Demonstration)	**1,000s/year** (Pre-Commercialization)	**10,000s/year** (Early Commercialization)	**100,000s/year** (Mass Commercialization)
FPBEV	*1996*	*2002*	**2015**	**2030**
FCEV	*2004*	**2009**	**2020**	**2025**
NEV	*1998*	*2001*	**2010**	**2040**
CEV	*1998*	*2001*	**2010**	**2030**
HEV	*1998*	*1999*	*2000*	*2004*
PHEV	**2008**	**2010**	**2012**	**2015**
H2ICV	**2007**	**2020**	**2025**	**2030**
FCAPUV	**2010**	**2015**	**2030**	**2050**

Note: For years prior to 2006, the year when the technology achieved the stated volume is approximate and is shown in small italics.

The Panel suggests that these projections while probably not very confident in terms of the exact year of achievement carry somewhat greater confidence in terms of the relative timing of these technologies, for the reasons outlined in this report and briefly summarized here:

> *The Panel's projection is that PHEVs with modest energy storage capacity will be derived from HEVs and will proliferate rapidly, stimulating further development and cost reduction of energy batteries and leading to commercially viable PHEVs and, in the longer term, FPBEVs. While PHEVs will continue to grow rapidly, as they have no functional limitations, FPBEVs will grow more slowly due to customer acceptance of limited range and long recharge time. NEVs are commercially viable now and will continue to grow, but will grow slowly due to limited functionality. CEVs will become commercially viable in Japan and Europe in the not too distant future due to lower hurdles for BEVs to overcome. CEVs may be offered in the U.S. as energy batteries continue to mature, but growth will be slow due to functional limitations of BEVs in general, and the specific limitations of CEVs, especially urban freeway driving. The intense effort on FCEVs will result in technically capable vehicles by the 2015 to 2020 time frame, but successful commercialization is dependent on meeting challenging cost goals and the availability of an adequate hydrogen infrastructure. If that happens, FCEVs will grow rapidly, followed by some H2ICVs, and some H2ICVs with FCAPUs.*

The Panel's can envision as a long term outcome - plug-in hybrid FCEVs, powered by

sustainable electricity for shorter trips and sustainable hydrogen for longer trips.

8. Appendix A: Questions for Lithium Ion Battery Manufacturers

A. Company Views on HEVs, EVs and PHEVs; Company Battery Strategy

- How do you view the commercial prospects of hybrid electric vehicles (HEVs)?
- Is your company engaged in development of batteries for HEVs? In manufacturing of batteries for HEVs?
- How do you view the commercial prospects of battery-powered vehicles (EVs)? Does your company strategy include development of batteries suitable for EVs? Future manufacturing of EV batteries?
- How do you view the commercial prospects of plug-in hybrid electric vehicles (PHEVs)? Does your company strategy include development of batteries for PHEVs? Future manufacturing of PHEV batteries?
- If your company is not now engaged in EV or PHEV development, which events or developments might lead to your company becoming engaged?

B. Company Li Ion Technologies Suitable for EV Applications

- Has your company developed (or under development) Li Ion technologies in cell sizes suitable for EV applications (for example, 40-100 Ah)?
- If yes, in which state of development is this technology (laboratory R&D; laboratory prototype cells or modules; pilot production of cells or modules; manufacturing [on which scale?])
- What are the most important characteristics of the technology?
    - Cell chemistry (composition of positive electrodes, negative electrodes, electrolyte)
    - cell and/or module specific (pulse) power
    - cell and/or module specific energy and energy density (e.g.@c/3)
    - cycle life (e.g., at 80% depth of discharge; at which temperature?)
    - safety characteristics in abuse tests?
    - special characteristics unique to your company's technology?
- What are the most important technical problems that still need to be overcome to achieve commercial production of the technology? (Performance? Cycle and/or calendar life? Safety issues? Other?)
- What are the most important non-technical barriers to commercial production?

C. Company Li Ion Technologies Suitable for PHEV Applications

- Has your company developed (or under development) Li Ion technologies in cell sizes suitable for EV applications (for example, 15-50 Ah)?
- If yes, in which state of development is this technology (laboratory R&D; laboratory prototype cells or modules; pilot production of cells or modules; manufacturing [on which scale?])
- What are the most important characteristics of the technology?
    - Cell chemistry (composition of positive electrodes, negative electrodes, electrolyte)
    - cell and/or module specific (pulse) power
    - cell and/or module specific energy and energy density (e.g.@c/3)

- cycle life (e.g., at 80% depth of discharge; at which temperature?)
- safety characteristics in abuse tests?
- Special characteristics unique to your company´s technology?

- What are the most important technical problems that still need to be overcome to achieve commercial production of the technology? (Performance? Cycle and/or calendar life? Safety issues? Other?)
- What are the most important non-technical barriers to commercial production?

D. Cost of your company´s Li Ion technology for EV applications:
(cell size 30-100Ah, capacity 20-40 kWh)
Capacity, voltage and estimated cost of modules:
at maximum current production rate (please indicate that rate)
at 3,000 kWh per year
at 30,000 kWh per year
at 300,000 kWh per year
Cost of balance of battery system (BMS, case/tray, wiring, other hardware)
at maximum current production rate (please indicate that rate)
at 3,000 kWh per year
at 30,000 kWh per year
at 300,000 kWh per year

E. Cost of your company´s Li Ion technology for PHEV applications
(cell size 15-50Ah, capacity 5-20 kWh)
Capacity, voltage and estimated cost of modules:
at maximum current production rate (please indicate that rate)
at 3,000 kWh per year
at 30,000 kWh per year
at 300,000 kWh per year

F. Cost of balance of battery system (BMS, case/tray, wiring, other hardware)
at maximum current production rate (please indicate that rate)
at 3,000 kWh per year
at 30,000 kWh per year
at 300,000 kWh per year

G. Technology Improvement and Advancement Prospects

- Which technology advances are most likely to reduce Li Ion battery cost? When does your company expect these cost reductions to become part of commercially available technology?
- Which technology advances are most likely to increase Li Ion battery safety?
  - When does your company expect these safety increases to become part of commercially available technology?

9. Appendix B: Questions for Nickel Metal Hydride Battery Manufacturers

A. *Company Views on HEVs, EVs and PHEVs; Company Battery Strategy*

- How does your company view the commercial prospects of hybrid electric vehicles (HEVs)?
- Is your company engaged in development of NiMH batteries for HEVs? In manufacturing of batteries for HEVs?
- How do you view the commercial prospects of battery-powered vehicles (EVs)? Does your company strategy include development of NiMH batteries suitable for EVs? Future manufacturing of EV batteries?
- How do you view the commercial prospects of plug-in hybrid electric vehicles (PHEVs)? Does your company strategy include development of NiMH batteries for PHEVs? Future manufacturing of PHEV batteries?
- If your company is not now engaged in EV or PHEV battery development, which circumstances might lead to your company becoming engaged?

B. *NiMH Batteries Suitable for EV Applications*

- Has your company developed (or under development) NiMH technologies in cell sizes suitable for EV applications (for example, 40-100 Ah)?
- If yes, in which state of development is this technology (laboratory R&D; laboratory prototype cells or modules; pilot production of cells or modules; manufacturing [on which scale?])
- What are the most important characteristics of the technology?
    - Cell chemistry (composition of positive electrodes, negative electrodes, electrolyte)
    - cell and/or module specific (pulse) power ?
    - cell and/or module specific energy and energy density (e.g.at c/3) ?
    - cycle life (under which testing conditions were cycle life data obtained (charge/discharge profile, temperature, cell/module/pack)
    - safety features and cell/module/pack characteristics in abuse tests?
    - special characteristics and advantages that are unique to your company´s technology?
- What are the most important technical problems that still need to be overcome to achieve commercial production of the technology? (Performance? Cycle and/or calendar life? Other?)
- What are the most important non-technical barriers to commercial production?

C. *NiMH Batteries Suitable for PHEV Applications*

- Has your company developed (or under development) NiMH technologies in cell sizes suitable for EV applications (for example, 15-50 Ah)?
- If yes, in which state of development is this technology (laboratory R&D; laboratory prototype cells or modules; pilot production of cells or modules; manufacturing [on which scale?])
- What are the most important characteristics of the technology?

- Cell chemistry (positive electrodes, negative electrodes, electrolyte)?
- cell and/or module specific (pulse) power ?
- cell and/or module specific energy and energy density (e.g.at c/3) ?
- cycle life (under which testing conditions were cycle life data obtained (charge/discharge profile, temperature, cell/module/pack)
- safety features and cell/module/pack characteristics in abuse tests?
- special characteristics/advantages of your company´s technology?

o What are the most important technical problems that still need to be overcome to achieve commercial production of the technology? (Performance? Cycle and/or calendar life? Safety issues? Other?)
o What are the most important non-technical barriers to commercial production?

D. Cost of your company´s NiMH technology for EV applications:
(cell size 30-100Ah, capacity 20-40 kWh)

o Capacity and voltage of modules and of the complete battery
o Estimated cost of modules:
- at maximum current production rate (please indicate the current rate)
- at 30,000 kWh per year
- at 300,000 kWh per year
- at 3,000,000 kWh per year

o Cost of balance of battery system (BMS, case/tray, wiring, other hardware)
- at maximum current production rate (please indicate the current rate)
- at 30,000 kWh per year
- at 300,000 kWh per year
- at 3,000,000 kWh per year

E. Cost of your company´s NiMH technology for PHEV applications
(cell size 15-50Ah, capacity 5-20 kWh)

o Capacity and voltage of modules and the complete battery
o Estimated cost of modules:
- at maximum current production rate (please indicate the current rate)
- at 10,000 kWh per year
- at 100,000 kWh per year
- at 1,000,000 kWh per year

o Estimated cost of balance of battery system (BMS, case/tray, wiring, other hardware, battery assembly)
- at maximum current production rate (please indicate the current rate)
- at 10,000 kWh per year
- at 100,000 kWh per year
- at 1,000,000 kWh per year

F. Technology Improvements and Advancement Prospects

- In your company's view, which are the most important improvements of NiMH battery technology (materials, design, manufacturing) over the past five years? Which of these improvements are likely to be applicable to EV batteries and/or to PHEV batteries?
- Which are the most important NiMH technology improvements that your company predicts for the next five years?
- Which technology advances are most likely to increase NiMH battery calendar and/or cycle life? When does your company expect such life improvements to become part of commercially available technology?
- Which technology advances are most likely to reduce NiMH battery cost? When does your company expect such cost reductions to become part of commercially available technology?

10. Appendix C: Hydrogen Storage Questionnaire

Note to the respondent: This same questionnaire will be presented to different groups with different involvements in hydrogen storage. Not all questions are necessarily applicable to each of these groups, so please respond to the ones that you feel comfortable in answering. Respondents please include information requested below. Thank you.

Respondents name and/or organization

_____

Contact person if additional questions arise

_____

Contact person telephone number _____

There is a perception that consumer acceptance of hydrogen-fueled vehicles will be greatly influenced by both the normal driving range and refueling convenience. There are many other factors which will also be of considerable importance in the decisions to produce or purchase such vehicles including costs, safety concerns, and effects of the hydrogen storage system physical characteristics (e.g., weight and volume) on vehicle utility.

- Do you think vehicle range and refueling convenience are major factors for consumer acceptance?
- If so, what do you think, for the first generation of hydrogen-fueled vehicles (produced in at least thousands), the minimum acceptable normal driving range will be for consumers? The maximum acceptable refueling time?
- DOE has established 2010 and 2015 performance and cost targets for vehicle hydrogen storage systems to help movement towards mass-manufactured and consumer-acceptable, hydrogen-fueled vehicles. Some of the 2010 and 2015 key <u>system</u> targets are shown below:
    - <u>2015</u>
    - • Volume ~ 1.5 kWh/l 2.7
    - • Weight ~ 2.0 kWh/kg 3.0
    - • Cost ~ $4/kWh $2
    - • Refueling time ~ 3 min for 5 kg
    - • Discharge ~ 0.02 g/s/kW
    - • Durability ~ 1000 cycles

    - Do you think that overall the targets are
    - reasonable for 2010? for 2015?
    - too ambitious for 2010? for 2015?
    - too lax for 2010? for 2015?
- Are there specific targets which you think are not appropriate? If so,
    - which are too ambitious for 2010? for 2015?
    - which are too lax for 2010? for 2015?
- Do you think that some or all of the targets for 2010 will be met? If not, which ones are most likely <u>not</u> to be met?
- Do you think that hydrogen storage issues will be major or minor factors in determination of the time scale for the introduction of hydrogen-fueled vehicles?
- If you think that hydrogen storage issues will be major, which of the following do you think is more likely to occur?

- Hydrogen storage technology will continue to advance sufficiently to resolve major issues. If so, when?
- A reduced range requirement will be accepted by OEMs and consumers for early generations of hydrogen-fueled vehicles.
- The energy efficiency of hydrogen-fueled vehicles will reach sufficiently high levels to provide adequate range without significant advances in hydrogen storage technologies.
- A combination of the above.
- None of the above. Hydrogen storage will continue to be a major problem and delay the introduction of hydrogen-fueled vehicles.

A number of categories of storage technologies are being pursued by many different groups, including:

- High pressure gaseous storage tanks
- Chemical hydrides
- Metal hydrides
- Carbon/sorbents

and, referring the 2010 key DOE targets,

Which category of technology (or technologies) do you think are most likely to meet <u>each</u> of the various 2010 targets:
Volume?
Weight?
Cost?
Refueling time?
Discharge?
Durability?

Which category of technology do you think has the most promise for meeting <u>all</u> of the 2010 targets?
High pressure gaseous storage tanks?
Chemical hydrides?
Metal hydrides?
Carbon/sorbents?
Some combination of the above?
None of the above?

Please give brief comments on your overall impression of each of the technologies above for which you would like to express opinions. Please include your thoughts concerning the practicality and acceptability of gaseous storage pressures up to 700 bar (~ 10,000 psi).

Within each of the various storage technology categories, there are many investigations and projects involving many different materials and processes. Some specific technologies mentioned as examples of significant progress include (but are not limited to):

- ·**Advanced Metal Hydrides** such as Li Mg Amides, Alane, Li Borohydrides, Destabilized Binary Hydrides, and LiMgAlane, M-B-N-H.
- ·**Chemical H2 Storage** such as Phenanthraline/Organic Liquids, and Ammonia Borane/Scaffolds.
- ·**Carbon/Sorbents/New Materials** such as Metal/Carbon Hybrids, Metcars; Bridged Catalysts, IRMOF-8; and Metal-Organic Frameworks, IRMOF-177.

What do you think is the most promising (not necessarily from those mentioned above) specific technology?

- For gaseous storage tanks?
- For chemical hydrides?
- For metal hydrides?
- For carbon/sorbents?

What do you think the current state of the art is for the one specific technology you think is most promising overall?

For volume?
For weight?
For cost?
For refueling time?
For discharge?
For durability?

What hydrogen storage technology do you expect to be on the first generation of mass-produced (at least thousands) hydrogen-fueled vehicles? If you think that it will be high pressure gaseous storage, what pressure do you think will be used?

When do you think the first generation of hydrogen-fueled vehicles will be available?

What do you expect the range of these first-generation vehicles to be?

What do you expect the cost penalty, associated only with the hydrogen storage system, of the vehicle to be?

Are there other important issues associated with vehicle hydrogen storage that you think should be discussed? If so, please list them and include your comments.

11. Appendix D: Automotive Fuel Cell System Questionnaire

This Fuel Cell questionnaire is intended to assist the Independent Expert Panel to assess the technical status of fuel cell systems, especially with regard to technology development, performance, timing of commercialization, and likely costs. The questionnaire pertains to:

- Fuel cell technology your company is working on
- Technical goals for automotive fuel cell systems
- Technical issues impeding introduction of automotive fuel cell systems
- Commercialization challenges for automotive fuel cell systems

Not all questions are applicable to each company or organization to which this questionnaire will be presented. Please respond to the questions appropriate to your development and/or commercialization program. Any comments and suggestions not covered or omitted from the technical questionnaire are welcomed.

A. Fuel Cell Technology Your Company is Working On?

- Are you working as a vehicle system integrator or specific component supplier that others will integrate into an automotive system?
- Is the fuel cell application for primary propulsion power, auxiliary power, other?
- Fuel cell type and general characteristics, e.g. PEM, SOFC, gross/net power, expected efficiency etc.
- Will your automotive fuel cell system application be hybridized with energy storage, e.g. battery?
- Will the on-board automotive fuel be hydrogen or other?
- What are the expected first and subsequent automotive applications, e.g. cars, SUVs, trucks, buses?
- Do you anticipate non-automotive applications of your fuel cell technology?

B. Technical Goals for Automotive Fuel Cell Systems

The US Department of Energy (DOE) has determined fuel cell power train performance and cost targets based on direct comparison with conventional internal combustion engine/automatic transmission system vehicles.

- What do you think of the US DOE fuel cell power train goals?
- Considering the continued advances in ICE vehicles, is it possible for a fuel cell power train system to achieve parity in performance, durability and cost with a conventional internal combustion engine power system in the 2010 to 2020 time frame?

- Which of the following is most difficult in achieving parity with a conventional internal combustion engine power system? Also, consider what characteristics of the fuel cell system can exceed parity with conventional internal combustion engine power systems.
    - Performance (functional characteristics of power, efficiency, general operation, emissions, driving characteristics)
- Durability and life
- Initial vehicle cost and operating cost
- Please comment on any trade-offs to achieve goals.
- Is it necessary to utilize light weight chassis materials, and/or advanced aerodynamics to achieve parity?
- Is it necessary to hybridize a fuel cell system with energy storage to achieve parity? If your company is planning to hybridize the fuel cell, what are desired characteristics of the energy storage system?

C. Technical Issues of Automotive Fuel Cell Systems

What is the most important technical issue to be overcome before automotive fuel cell systems can be commercialized?

Please provide comments regarding:

- Energy efficiency at rated and expected average power
- Fuel consumption on standard driving cycles and expected customer experience
- Parameters effecting durability
- Balance of Plant requirements e.g. thermal management, humidification, air and fuel, control system
- Start up, shutdown and storage issues
- Operational ability in extreme hot and cold ambient conditions
- Cold start time
- The ability to change output power to match vehicle drive requirements
- Storage survivability in extreme hot and cold ambient conditions
- Necessary H2 storage and purity requirements
- Noise, harshness and vibration (NHV)

What are the technical advantages and disadvantages of Fuel Cell Vehicles compared to the following vehicle types? How are the technologies complementary or competitive in development and commercialization?

- Hybrid Electric Vehicle, e.g. Toyota Prius, Ford Escape
- Plug-In HEV e.g. a full hybrid type vehicle that can be plugged-in for limited EV range (20 to 40 km).
- Battery Powered Electric Vehicle e.g. EV1, RAV4 EV
- Hydrogen Fueled Internal Combustion Engine Vehicle

D. Commercialization of Automotive Fuel Cell Systems

Does your company have a commercialization plan for your automotive fuel cell technology?

Please describe.

The ARB fleet size definitions to achieve a level of maturity is described in terms of:

- Demonstration (100's of vehicles)
- Pre Commercialization (1000's of vehicles)
- Early Commercialization (10,000's of vehicles)
- Full Commercialization (100,000's of vehicles per year)

Are the above transition numbers reasonable considering the need for field experience compared to the resources expended at each step on service and support?

Given no infrastructure barriers, when will it be technically possible to reach early and full commercialization of fuel cell vehicles?

What is the expected retail vehicle cost compared to conventional internal combustion engine power system vehicles at time of market entry? Consider also, 10 years after market entry.

Is there adequate support to establish an OEM supplier base for a fuel cell industry?

Please provide comment on any obstacles.

12. Appendix E: Auto Manufacturers Questionnaire

A. Vehicle technologies – please include each type in answers to sections below:

- Zero Emissions Vehicles (ZEVs)
- Battery Electric Vehicle (BEV)
- Fuel Cell Electric Vehicle (FCEV)
- Advanced Technology Vehicles (ATVs)
- Neighborhood Electric Vehicle (NEV)
- Hybrid Electric Vehicle (HEV)
- Plug-in-Hybrid Electric Vehicle (PHEV)
- Hydrogen Internal Combustion Engine Vehicle (H2ICV)
- Fuel Cell Auxiliary Power Unit Vehicle (APUV)

What is the status of the Company's existing ZEVs/ATVs (demo/prototype/production) ?

- Name/Model Year(s)/Purpose Built or Conversion/Price – if Sold or Leased
- Specifications
- Major Differences – versus similar non-ZEVs/ATVs
    - Brief Description of Powertrain/Propulsion System
    - Brief Description of Energy Storage System
    - Brief Description of Other Major Differences
- Passenger, Luggage and/or Cargo Capacity
- Vehicle Weight (curb)
- Maximum Power (hp, kW, etc.)
- Fuel Storage Capacity (actual customer usable)
        - Energy Battery – based on kilowatt hours (kWh)
        - Hydrogen Fuel – based on kilograms (kg)
        - Fossil Fuels – liquid measurement
- Performance
- Emissions (specify test cycle)
- Fuel Economy
    - City/Highway (specify test cycle)
        - Energy Battery – based on kilowatt hours (kWh)
        - Hydrogen Fuel – based on kilograms (kg)
        - Fossil Fuels – liquid measurement
    - Comparison to Company's similar non-ZEVs/ATVs
- Acceleration (seconds, 0-60 mi/h or 0-100 km/h)
- Driving Range – from 0% to 100% of II-B-5 usable capacity
- Refueling Time – from 0% to 100% of II-B-5 usable capacity
- Crash Results (specify test, or if not tested – capability)
- Limitations (e.g., climatic, hill climb, start time, etc.) – versus Company standards
- Present Units in Operation
- North America
    - California
    - Other North America
- Europe
- Asia
- Other Global

What are the remaining unresolved issues of the Company's ZEVs/ATVs ? *

- Technical Issues
- Performance Related
- Reliability/Durability Related
- Other Technical Issues
- Commercial Issues
- Company Manufacturing Cost Related – versus similar non-ZEVs/ATVs
    - Unit Incremental Variable Cost (present automation/volume levels)
    - Potential Reduction of Cost (design/material revisions)
    - Potential Reduction of Cost (high automation/volume levels)
- Customer Cost of Ownership Related – versus similar non-ZEVs/ATVs
- Other Commercial Issues (e.g., infrastructure, codes and standards, etc.)

What are the prospects for advancement of ZEVs/ATVs within the Company ? *

- Company and Supplier Resources Committed (management priority, number of dedicated engineers/scientists, annual budget, dedicated facilities, number of patents, etc.)
- Present Status
- Future Plans
- Company Goals
- Technical Goals
- Commercial Goals
- Company Plans for Evaluation/Demonstration and Commercialization

When will ZEVs/ATVs become commercially viable ? *

When will total U.S. industry volume reach the following Levels (Phases) ?

- 100s (demonstration)
- 1,000s (pre-commercialization)
- 10,000s (early commercialization)
- 100,000s (mass commercialization)

What requirements/achievements are necessary to reach each Level (Phase) in V-A ?

- Technical Maturity Required
- Manufacturing Cost Required
- Other Requirements (e.g., infrastructure, subsidies, firm vehicle orders, etc.)

For ATVs only – what is the significance of each advanced technology toward enabling earlier ZEV (BEV and/or FCEV) commercialization ?

- Technical Synergies
- Affordability Synergies
- Other Synergies
- ATV volume necessary to provide benefit to ZEV commercialization
- Degree of significance to ZEV commercialization (high/medium/low/none)

13. Appendix F: Companies and Organizations Visited or Interviewed by the Panel

A123 Battery
AC Propulsion
Altair Nanotechnologies
Argonne National Laboratory
Ballard
BMW
Bosch
CalStart
DaimlerChrysler – Michigan
DaimlerChrysler – Stuttgart
DCX/GM/BMW
Department of Energy
EdF
Electrodyne
Electrovaya
EPRI
Ford (Twice)
GAIA Akkumulatorenwerke
General Motors – California
General Motors – Mainz
General Motors – Michigan
General Motors – New York
GS/Yuasa
Hitachi Vehicle Energy
Honda
Hydrogenics
Hyundai
Japanese NEDO
Matsushita
MES-DEA (ZEBRA Battery)
Mitsubishi Motors
Mitsubishi Motors/Litcell
NECLamillion
Nissan
Panasonic EV Energy (PEVE)
Quantum
SAFT
Sanyo
Toyota
UC Davis
UTC Fuel Cells
Volkswagen

14. Appendix G: From DOE Hydrogen Contractors Meeting

A. Summary of Hydrogen Storage Oral Presentations

1. "Chemical Hydrogen Storage in Ionic Liquid Media," Larry G. Sneddon (Penn), et al.
   " ... Work has now shown that ionic liquids provide advantageous media for ammonia borane dehydrogenation in which both the extent and rate of dehydrogenation are significantly increased."

2. "From Fundamental Understanding to Predicting New Nanomaterials for High Capacity Hydrogen Storage and Fuel Cell Technologies," T. Yildirum (Penn), et al.
   " ... focus on achieving fundamental understanding of the chemical and structured interactions governing the storage and release of hydrogen ..."

3. "Addressing Grand Challenges through Advanced Materials," M.S. Dresselhaus (MIT), et al.
   " ... The elements of the hydrogen initiative are reviewed with particular emphasis given to hydrogen storage ..."

4. "Atomistic Transport Mechanisms in Reversible Complex Metal Hydrides," Peter Sutter (BNL), et al.
   "The long-term goal of this project is to develop an atomistic understanding of the interaction of hydrogen with metal and alkali metal surfaces and nanostructures ..."

5. "Basic Research for the Hydrogen Fuel Initiative: Control of Hydrogen Release and Uptake in Condensed Phases," Nancy Hess (PNNL), et al.
   " ... knowledge that will provide the basis for the development of new materials ..."

6. "*In-Situ* Neutron Diffraction Studies Of Novel Hydrogen Storage Materials," William B. Yelon (Univ. Missouri-Rolla), et al.
   " ... to study the decomposition reactions of systems of the type AMH_4 where A is an alkali metal (Li,Na,K) and M is either Al or B ..."

7. "*In Situ* NMR Studies of Hydrogen Storage Systems," Mark S. Conradi (Washington Univ.), et al.
   " ... focuses on *in situ* NMR studies of solid-state hydrogen systems."

8. "High Throughput Screening of Nanostructured Hydrogen Storage Materials," Gang Chen (MIT), et al.
   " ... project combines high throughput combinatorial materials synthesis, high throughput screening along with fundamental studies to identify high capacity hydrogen storage materials ..."

9. "Complex Hydrides – A New Frontier for Future Energy Applications," Vitalij K. Pecharsky (Iowa State Univ.), et al.
   " ... to achieve a fundamental understanding of the relationships between the chemical composition, bonding, structure, microstructure, properties and performance of hydrogen-rich solids."

10. "Molecular Hydrogen Storage in Novel Binary Clathrate Hydrates at Near-Ambient Temperatures and Pressures," L.J. Rovetto (Colorado School of Mines), et al.
" ... a fundamental understanding of the structure, molecular-level dynamics, and H_2 formation/release rates and mechanisms in these novel crystalline compounds is the main objective ..."

11. "Atomistic Mechanisms of Metal-Assisted Hydrogen Storage in Nanostructured Carbon," Nidia C. Gallego (ORNL), et al.
" ... directed towards the development of a broad science foundation to identify and understand the atomistic mechanisms of metal-assisted storage in nanostructured carbons."

12. "A Synergistic Approach to the Development of New Classes of Hydrogen Storage Materials," A. Paul Alivisatos (UC Berkeley), et al.
" ... emphasis is on exploring the possibilities for nanoporous polymers, nonoporous coordination solids, destabilized high-density hydrides, nanostructured boron nitride, and magnesium and light alloy nanocrystals ..."

B. Summary of Poster Presentations

1. "Elucidation of Hydrogen Interaction Mechanisms with Metal-doped Carbon Nanostructures," Ragaiy Zidan (SRNL), et al.
" ... aimed at obtaining a better understanding of the nanoscale level of hydrogen sorption behavior of metal-doped carbon nanostructures."

2. "Characterization of Carbon Nanostructures in Pd containing Activated Carbon Fibers using Aberration-Corrected STEM," Klaus van Benthem (ORNL), et al.
" ... to obtain an in-depth characterization of atomic structures in Pd-doped activated carbon fibers (ACF) using sub-angstrom resolution electron nicroscopy, and to correlate these structures with their hydrogen storage properties."

3. "Theoretical Investigation of the Energies of Hydrogen Interaction with Graphene Layers: The Effect of Interlayer Spacing on Hydrogen Storage," Rachel S. Aga (ORNL), et al.
" ... to understand the interactions of hydrogen with graphite-like structures and the role of metal particles on the intercalation of hydrogen on grapheme surface."

4. "Neutron Scattering Aided Studies of the Design, Synthesis and Thermodynamics of Molecular Hydrogen Adsorption Materials," J.Z. Larese (ORNL), et al.
" ... focuses on the development of accurate potential energy surfaces to describe the interaction of molecular hydrogen with solid surfaces and within porous media to ultimately achieve predictive powers to tailor-make new materials."

5. "First Principles Studies of Phase Stability and Reaction Dynamics in Complex Metal Hydrides," Mei-yin Chou (Georgia Tech), et al.
"With the simulations, we will explore and screen the possibilities of forming new complex hydrides with high hydrogen contents from various lightweight metals."

6. "Crystal and Electronic Structures of $LiNH_2$ and Related Compounds," J.B. Yang (Univ. of Missouri-Rolla), et al.
" ... we report the revised crystal structure for $LiNH_2$ and show data for $LiNH_2$-$LiBH_4$

compounds, using neutron powder diffraction with high sensitivity."

7. "Understanding the Role (and Controlling Behavior) of Transition Metal Dopants in $NaAlH_4$ Systems," Tabbetha A. Dobbins (La. Tech), et al.
" ... will develop the fundamental materials science and engineering surrounding the behavior of transition metal catalysts added to complex metal hydrides using synchrotron x-ray studies ..."

8. "Integrated Nanoscale Metal Hydride-Catalyst Architectures for Hydrogen Storage," Yiping Zhao (Univ. of Georgia), et al.
" ... goal is to use a novel nanofabrication technique, glancing angle deposition (GLAD), to design and produce metal hydride nanorods and nanowires with different topography, structure, and composition, and probe how hydrogen interacts ..."

9. "The Molecular Design Basis for Hydrogen Storage in Clathrate Hydrides," Vijay A. John (Tulane), et al.
" ... develop new clathrate hydrates as inclusion compounds for hydrogen storage at moderate pressure (<100 bar) approaching 10 wt% hydrogen loading, and at ambient or near-ambient temperatures."

10. "First Principles Based Simulation of Hydrogen Interactions in Complex Hydrides," Qingfeng Ge (Southern Illinois), et al.
" ... to develop a multiscale approach to model desorption and adsorption of hydrogen in complex metal hydrides."

11. "Dehydrogenation of Boron-Nanoclusters," Aashani Tillekaratne (Univ. Illinois-Chicago).
" ... designed to test the hypothesis that at a certain length scale, the three-dimensional boron structural units found in certain boron-rich solids can be reversibly hydrogenated in the presence of a suitable catalyst to form boranes and/or carboranes with similar three-dimensional boron units."

12. NMR Studies of Metal-Hydrides: $MgScH_x$," Mark S. Conradi (Washington Univ.), et al.
" ... focuses on the *in situ* NMR studies of Solid-State Hydrogen Storage Systems."

15. Appendix H. Small-Cell Batteries for FPBEVs and PHEVs

Batteries consisting of thousands of Li Ion cells of the type normally used in laptop PCs and other consumer electronic products are currently used to power several prototypical electric and plug-in hybrid electric vehicles that are being sold in small numbers at high prices (see Vehicle Integration Chapter of this Report), primarily in California.

The main motivation for using multi-kWh FPBEV and PHEV batteries assembled from type 18650 Li Ion cells is the commercial availability of such cells from mass production in several Asian countries, at prices that are continuing to decline under the impact of growing competition. Li Ion batteries with cell sizes designed for FPBEV and PHEV applications, on the other hand, are available only as prototypes at very high prices.

The characteristics of currently used "small-cell" batteries and their constituent cells are summarized below:

Vehicle Manufacturer (California)	Batteries				Cells		
	Capacity[1] (kWh)	Weight (kg)	Voltage (Volt)	Number of Cells Total/Parallel/Series	Voltage (Volt)	Capacity (Ah)	Capacity (Wh)
AC Propulsion	35 [37.5]	284	355	5,088T/53P/96S	3.7	2.0	7.4
Tesla Motors	50	~410	~365	6,831T/69P/99S	3.6	n.a.	7.3[2]
Energy CS	9.0 [10.5]	~110	248	2,376T/33P/72S	3.25	1.35	4.4

[1] Capacity rated by vehicle manufacturer [in brackets: nominal capacity based on cell capacity and number]
[2] Estimated from battery capacity and total number of cells

Vehicle Manufacturer (California)	Batteries				Cells		
	Capacity[1] (kWh)	Weight (kg)	Voltage (Volt)	Number of Cells Total/Parallel/Series	Voltage (Volt)	Capacity (Ah)	Capacity (Wh)
AC Propulsion	35	284	355	5,088T/53P/96S	3.7	2.0	7.4
Tesla Motors	50	~410	~365	6,831T/69P/99S	3.6	n.a.	7.3[2]
Energy CS	9.0 [10.6]	~110	248	2,376T/33P/72S	3.25	1.35	4.4

[1] Capacity rated by vehicle manufacturer [in brackets: nominal capacity based on cell capacity and number]
[2] Estimated from battery capacity and total number of cells

As shown in the table, a large number of cells need to be connected electrically in parallel to achieve the needed battery capacities at practical voltages. The 35kWh and 50kWh small-cell batteries listed in the table have energy densities of around 120Wh/kg. If cells with capacities of about 2.6 Ah (yielding nearly 200Wh/kg) are becoming available as expected by the vehicle builders, battery energy density might increase to around 150Wh/kg, the USABC goal and well within FPBEV requirements (see Table 3-2).

Peak power data for these batteries were not made available. However, with a peak power-to-energy ratio of about 4 typical for small Li Ion cells, power should be more than sufficient, as attested to by the high performance claimed for the AC Propulsion and Tesla Motors vehicles. The 9 kWh battery used in the EnergyCS Prius conversion approaches 100Wh/kg, readily meeting the energy density requirement for a PHEV.

Small-cell batteries are enabling the construction and sale of FPBEVs and PHEVs at the present time, but several uncertainties and potential issues surround such batteries. One of these is rather high cost, despite assembly of the batteries from relatively low-cost cells. While

no battery cost information was made available to the Panel, a lower limit for small-cell battery cost can be estimated using the following cost factors:

- cost of single cells in mass production: $2-4
- Small Cells→ large-cell "sheets" of parallel-connected cells: factor 1.5-1.25
- Cell Sheets→ modules with distributed controls: factor 1.03 (see section 3.D, Table 3-12)
- Modules→ complete BEV battery: factor 1.2 (Table 3-12)

Applying the composite factor of 1.375 (average) x 1.03 x 1.2 to assumed cell costs of $3 results in estimates of approximately $25,000 for the AC Propulsion battery and about $35,000 for the Tesla Motors battery. For the smaller EnergyCS battery, and assuming a factor of 1.4 for module integration into batteries, the estimated battery cost is approximately $14,000. These estimates assume efficient (but not mass production) methods for the assembly of cell sheets, and large-scale assembly of modules and complete batteries. Present battery costs thus may be higher than the estimates above.

Large-scale manufacturing of small-cell batteries would likely reduce the cost ranges above by perhaps 15-20%, still not sufficient to bring costs of small-cell batteries for FPBEV or even PHEV applications down to the net present values of future fuel cost saving (see Table 3-15), or to the cost levels projected (see Table 3-13) for mass-produced Li Ion batteries with cell sizes designed for FPBEV or PHEV applications. Another major reduction of single cell costs to well less than $2 would be required to achieve this goal which is considered unlikely in the foreseeable future.

No information is as yet available on the calendar and cycle life of the small-cell batteries currently used in FPBEVs and PHEVs. It is reasonable to assume that calendar life will exceed the typical 3-year life of Li Ion cells in consumer products, possibly substantially because of the better control of cell temperature and state of charge (SoC) achieved in these batteries compared to the thermal and electric environment in laptop computers and other consumer products. Small-cell batteries should have the advantage of more effective temperature management also over batteries with cell sizes designed for FPBEV and PHEV applications which will benefit calendar life and safety.

The cycle life of small-cell batteries can be expected to depend sensitively not only on the representative cycle life of individual cells but on cell-to-cell uniformity. Differences in the capacities of cells connected electrically in parallel are less serious for Li Ion than for most other battery types because of the absence of side reactions (such as oxygen evolution at the positive electrode of NiMH batteries). However, existing differences in the capacity of parallel cells could grow with time and the number of cycles because even slightly lower-capacity cells will be fully charged somewhat sooner in each cycle and thus spend more time at high SoC which would tend to shorten life. This potential problem is being addressed by current assemblers of small-cell batteries through careful selection of cells and electronic controls of parallel blocks to maintain cell voltages within narrow ranges. It remains to be seen whether these measures, combined with high quality cell manufacturing, can assure continued cell uniformity and retention of battery capacity as small-cell batteries age.

The ultimate prospects of small-cell batteries appear rather uncertain because of their likely high costs even in volume production, and in view of the uncertainties in their calendar and cycle life capabilities. On the other hand, such batteries provide substantial packaging design flexibility in

the conversion of conventional vehicles, and they enable acquisition of experience in the construction and operation of early, fully capable FPBEVs and PHEVs. Positive experience could encourage interest and involvement of Li Ion battery manufacturers in design and development of FPBEV and/or PHEV batteries. Some that experience may be directly applicable in the evolution of Li Ion batteries for ZEVs and partial ZEVs, especially if that evolution proceeded through batteries with mass produced cells in sizes between consumer product cells and cells fully optimized for FPBEV and/or PHEV applications.

16. Appendix I. Net Present Value (NPV) of Fuel Cost Savings

The table below lists calculated NPVs of the fuel savings achieved by HEVs, PHEVs and BEVs relative to ICE vehicles of comparable performance and accommodations, with the assumptions given at the bottom of the table.

Vehicle Type	Annual Mileage		Gasoline Energy		Electric Energy		NPV of Energy Savings[3] $
	Gasoline miles/yr	Electric miles/yr	Cost $/gal	Efficiency[1] miles/gal	Cost $/kWh	Efficiency[2] miles/kWh	
HEV	10,000	0	2.50	30 (40)[4]	n.a.	n.a.	1,573
	10,000	0	3.00	27 (45)	n.a.	n.a.	3,356
	14,000	0	3.50	36 (50)	n.a.	n.a.	2,878
	14,000	0	4.00	33 (50)	n.a.	n.a.	4,356
PHEV-20	7,000	3,000	2.50	30 (40)	0.10	3.0	2,318
	6,000	4,000	3.00	27 (45)	0.06	3.5	4,909
	9,500	4,500	3.50	36 (50)	0.12	3.5	4,221
	8,500	5,500	4.00	33 (55)	0.08	4.0	7,407
PHEV-40	5,500	4,500	2.50	30 (40)	0.10	3.0	2,690
	4,500	5,500	3.00	27 (45)	0.06	3.5	5,491
	8,000	6,000	3.50	36 (50)	0.12	3.5	4,669
	7,000	7,000	4.00	33 (55)	0.08	4.0	8,029
FPBEV	0	10,000	2.50	30	0.10	3.0	4,055
	0	10,000	3.00	27	0.06	3.5	7,239
	0	14,000	3.50	36	0.12	3.5	7,056
	0	14,000	4.00	33	0.08	4.0	10,933

[1] efficiency (gasoline mileage) of baseline conventional ICE vehicle
[2] efficiencies (miles per kWh of AC electricity) used by PHEVs and EVs in EV (electric drive) mode
[3] NPV calculation basis: 10 year battery life, 3% inflation rate, 8% interest rate
[4] in parentheses: efficiencies (gasoline mileage) of HEVs and PHEVs in HEV (hybrid drive) mode

The first two lines for each vehicle type in the table can be viewed as near-term scenarios in terms of annual mileage, gasoline and electricity prices, and vehicle ICE and electric drive efficiencies; the other two lines can be considered longer term scenarios. For each set of scenarios, the upper line uses assumptions is more conservative and less favorable to ZEVs and near (including partial) ZEVs in terms of propulsion energy costs and vehicle efficiencies; the lower line is more favorable.

For each vehicle type, the NPV for the favorable longer-term scenario is nearly three times the value for the conservative near term scenario, indicating the large potential for growing fuel cost savings.

17. Appendix J: FPBEV Specifications and Performance

Table J-1: FPBEV Specifications[1]:

Vehicle	Platform	Motor[2] (kW)	Battery System (Rated[3] kWh – Type)	Curb Weight (pounds)
Chevrolet S10 EV[4]	S10	n.a.[11]/85	15 PbA[4]	4200
Chevrolet S10 EV[5]	S10	n.a.[11]/85	18.7 PbA[5]	4110
Chevrolet S10 EV[6]	S10	n.a.[11]/85	26.4 NiMH[6]	4037
Chrysler EPIC[7]	Dodge Caravan	75/100	27 PbA[7]	5018
Chrysler EPIC[8]	Dodge Caravan	75/100	29 NiMH[8]	4878
Ford Ranger EV[4a]	Ranger	32/67	25 PbA[4a]	4700
Ford Ranger EV[5]	Ranger	32/67	29 NiMH[5]	4100
Ford Postal Van EV[4a]	Ranger EV	32/67	25 PbA[4a]	5000
GM Gen I EV-1[4]	Dedicated	n.a.[11]/102	15 PbA[4]	2970
GM Gen I EV-1[5a]	Dedicated	n.a.[11]/102	15 PbA[5a]	3060
GM Gen II EV-1[5]	Dedicated	n.a.[11]/102	18.7 PbA[5]	3109
GM Gen II EV-1[6]	Dedicated	n.a.[11]/102	26.4 NiMH[6]	2946
Honda EV Plus[5]	Dedicated	49/49	29 NiMH[5]	3590
Nissan Altra[9]	Dedicated	40/62	30 Li Ion[9]	3940
Nissan Altra[10]	Dedicated	40/62	30 Li Ion[10]	3940
Toyota RAV4 EV[5]	RAV4	20/50	27 NiMH[5]	3440

1. Source: manufacturer data, Advanced Vehicle Testing Activity, Idaho National Laboratory, http://avt.inl.gov/fsev.shtml
2. Continuous power rating/peak power rating (e.g., 18 seconds)
3. Basis for measuring performance in USABC testing (e.g., depth of discharge - DOD) / established by developer or manufacturer based on best balance of power/capacity/life
4. Delphi 12 v.
4a. Delphi 8 v. (East Penn after 1999)
5. Panasonic
5a. Panasonic retrofit
6. GM Ovonic
7. Electrosource Horizon 12 N85 VRLA
8. SAFT
9. Sony July 1999
10. Shin-Kobe (Hitachi)
11. Continuous power constrained by wiring and battery pack limits

The performance of these vehicles was independently measured by Southern California Edison under a variety of real world driving conditions and is summarized below:

Table J-2: FPBEV Southern California Edison Pomona Loop Testing[1]:

Vehicle	**Payload**[2] (pounds)	**0-60 mph** (seconds)	**Driving Range**[3] (miles)	**Consumption**[3] (AC kWh/mile)
Chevrolet S10 EV PbA[4]	980	n/a	30-43	0.396-0.668
Chevrolet S10 EV PbA[5]	850	12.8	36-57	0.408-0.595
Chevrolet S10 EV NiMH[6]	920	14.4	60-84	0.667-0.906
Chrysler EPIC PbA[7]	860	n/a	46-61	0.520-0.720
Chrysler EPIC NiMH[8]	930	14.6	64-99	0.542-0.823
Ford Ranger EV PbA[4a]	960	n/a	52-72	0.400-0.500
Ford Ranger EV NiMH[5]	1220	17.4	63-81	0.391-0.503
Ford Postal Van EV PbA[4a]	960	n/a	52-72	0.400-0.500
General Motors EV-1 PbA[4]	460	8.0	60-91	0.233-0.304
General Motors EV-1 PbA[5]	447	8.0	73-114	0.223-0.331
General Motors EV-1 NiMH[6]	484[11]	8.0[11]	103-161[11]	0.233-0.304[11]
Honda EV Plus NiMH[5]	860	n/a	79-105	0.380-0.560
Nissan Altra Li Ion[9]	639	15.6	74-122	0.255-0.392
Nissan Altra Li Ion[10]	705	16.0	87-104	0.312-0.384
Toyota RAV4 EV NiMH[5]	766	16.3	69-93	0.329-0.434

1. Source: Advanced Vehicle Testing Activity, Idaho National Laboratory, http://avt.inl.gov/fsev.shtml
2. Actual tested maximum payload
3. range of results for eight test conditions (urban/freeway, minimum/maximum payload, with/without auxiliary loads -- ambient temperature varied from vehicle to vehicle and test to test, but did not include cold conditions)
4. Delphi 12 v.
4a. Delphi 8 v. (East Penn after 1999)
5. Panasonic
6. GM Ovonic
7. Electrosource Horizon 12 N85 VRLA
8. SAFT
9. Sony July 1999
10. Shin-Kobe (Hitachi)
11. Source: General Motors

EV America also independently tested many of these vehicles as summarized below:

Table J-3: FPBEV EV America Baseline Performance Testing[1]:

Vehicle	**Payload** (pounds)	**0-50 mph**[2] (seconds)	**Range**[3] (miles)	**Consumption** (AC kWh/mile)
1997 Chevrolet S10 EV PbA[4]	951	9.7	43.8	0.470
Chevrolet S10 EV PbA[5]	n/a	n/a	n/a	n/a
1999 Chevrolet S10 EV NiMH[6]	920	9.9	95.3	0.794
1997 Chrysler EPIC PbA[7]	882	12.3	52	0.499
1999 Chrysler EPIC NiMH[8]	945	12.3	79.1	0.784
1998 Ford Ranger EV PbA[4a]	669	11.6	65.1	0.484
1999 Ford Ranger EV NiMH[5]	1206	10.3	82.4	0.485
Ford Postal Van EV PbA[4a]	n/a	n/a	n/a	n/a
1997 General Motors EV-1 PbA[4]	440	6.3	78.2	0.248
General Motors EV-1 PbA[5]	n/a	n/a	n/a	n/a
1999 General Motors EV-1 NiMH[6]	440	6.3	140.3	0.373
Honda EV Plus NiMH[5]	n/a	n/a	n/a	n/a
Nissan Altra Li Ion[9]	n/a	n/a	n/a	n/a
Nissan Altra Li Ion[10]	n/a	n/a	n/a	n/a
1998 Toyota RAV4 EV NiMH[5]	759	12.8	94.0	0.432

1. Source: Advanced Vehicle Testing Activity, Idaho National Laboratory, http://avt.inl.gov/fsev.shtml
2. at 100% State of Charge (SOC)
3. Per SAE J1634 (two UDDS and two HFET)
4. Delphi 12 v.
4a. Delphi 8 v. (East Penn after 1999)
5. Panasonic
6. GM Ovonic
7. Electrosource Horizon 12 N85 VRLA
8. SAFT
9. Sony July 1999
10. Shin-Kobe (Hitachi)

18. Appendix K: NEV Specifications and Performance

Table K-1: NEV Specifications[1]

Vehicle	Body Type	Charger (type/voltage)	Battery System (voltage/Ah capacity[2])	Curb Weight (pounds)[3]
2002 Columbia Par Car	2-passenger open	offboard/120	48/146[4]	1205
2001 Frazer-Nash City Car	4-passenger enclosed	offboard/480 3-phase	48/136[5]	1961
2002 TH!NK Neighbor	2-passenger open	onboard/120	72/73[6]	1355
2005 GEM e-2	2-passenger enclosed	onboard/120 or 240	72/80[7]	1303

1. Source: Advanced Vehicle Testing Activity, Idaho National Laboratory, http://avt.inl.gov/nev.shtml
2. C/2
3. as delivered curb weight
4. Trojan T-105 Flooded PbA
5. Electrosource Absorptive Glass Mat PbA
6. East Penn 8G31 Gel PbA
7. GEM/Deka 8G31 Gel PbA (Deka is made by East Penn)

NEV America independently tested these vehicles as summarized below:

Table K-2: NEV America Baseline Performance Testing[1]

Vehicle	Payload[2] (pounds)	0-20 mph[3] (seconds)	Range[4] (miles)	Consumption[5] (AC kWh/mile)
2002 Columbia Par Car	707	22.9	52.9	0.133
2001 Frazer-Nash City Car	633	5.8	30.9	0.201[6]
2002 TH!NK Neighbor	544	6.3	33.1	0.163
2005 GEM e-2	547	4.9	44.3	0.184

1. Source: Advanced Vehicle Testing Activity, Idaho National Laboratory, http://avt.inl.gov/nev.shtml
2. as delivered payload
3. At 100% State of Charge (SOC) and 332 pounds payload; NEV America performance goal is 6.0 seconds
4. Operated at maximum speed until 18 mph could no longer be maintained
5. Drive cycle unknown, GEM states their vehicle achieves 0.200 to 0.240 AC kWh/mi in "neighborhood driving cycle"
6. Based on test result of 0.171 DC kWh/mile and assuming charging efficiency of 85% (AC kWh/mi was not tested)

Table K-3: NEV Specifications[1]

Vehicle	Body Type	Charger (type/voltage)	Battery System (voltage/Ah capacity[2])	Curb Weight (pounds)
ZX40	2-passenger enclosed	onboard/120 or 240	48/150[3]	2116
ZX40s	2-passenger enclosed	onboard/120 or 240	72/150[3]	2350
ZENN	2-passenger enclosed	onboard/120	72/TBD[4]	1280

1. Source: Miles Automotive Group, http://www.milesautomotive.com, ZENN Cars, http://www.zenncars.com/specifications/specs_index.html, Green Car Congress, http://www.greencarcongress.com/2006/05/feel_good_cars_.html
2. 10 hour rate

3. Tianjin Blue Sky Absorptive Glass Mat Sealed PbA
4. Deka Gel PbA (Deka is made by East Penn)

Table K-4: NEV Performance[1]

Vehicle	**Payload** (pounds)	**0-18.6 mph** (seconds)	**Range** (miles)	**Consumption** (AC kWh/mile)
ZX40	882[3]	11.9	40 – 50[2]	n/a
ZX40s	648[3]	3.0	60 – 70[2]	n/a
ZENN	425[4]	4.0	25-31	n/a

1. Source: Miles Automotive Group, http://www.milesautomotive.com, ZENN Cars, http://www.zenncars.com/specifications/specs_index.html, Green Car Congress, http://www.greencarcongress.com/2006/05/feel_good_cars_.html
2. 12.4 mph constant speed
3. Based on GVWR of 2998 lbs.
4. Based on GVWR of 1705 lbs.

19. Appendix L: HEV Specifications and Performance

Table L-1: HEV Specifications[1]

Vehicle	Platform	Engine (hp/kW)	Motor/Gen[2] (kW)[5]	Motor/Gen[3] (kW)[5]	Motor/Gen[4] (kW)[5]	Battery (type - voltage)
Chevrolet Silverado HEV[6]	Silverado	295/220	n.a./10	none	none	PbA 36
Chevrolet Tahoe HEV[6a]	Tahoe	n.a./n.a.	n.a./60	none	n.a./60	NiMH 288
2008 Ford Escape HEV[7]	Escape	133/99	70/n.a.	45/n.a	none	NiMH 330
Honda Accord HEV	Accord	253/189	12/21	none	none	NiMH 144
Honda Civic HEV	Civic	110/82	15/15	none	none	NiMH 158
Honda Insight	Dedicated	73/54	10/10	none	none	NiMH 144
Lexus GS450h	GS450	292/218	48[8]/147	n.a./n.a	none	NiMH 288
Lexus RX400h 4WD	RX400	208/155	32[8]/123	n.a./n.a	12[8]/50	NiMH 288
2007 Nissan Altima HEV	Altima	158/118	n.a./105	n.a./n.a	none	NiMH 245
Saturn Aura HEV	Aura	170/127	3/4	none	none	NiMH 36
Saturn VUE HEV	VUE	170/127	3/4	none	none	NiMH 36
Toyota Camry HEV	Camry	148/110	24[8]/105	n.a./n.a	none	NiMH 245
Toyota Highlander HEV 4WD	Highlander	208/155	32[8]/123	n.a./n.a	12[8]/50	NiMH 288
Toyota Prius	Dedicated	76/57	29[8]/50	n.a./n.a	none	NiMH 202

1. Source: manufacturer data, Automotive News, http://www.whybuyhybrid.com/current-hybrid-vehicles.htm
2. Traction motor/generator
3. Power split system sun gear motor/generator
4. Second traction motor/generator
5. Continuous power/peak power
6. Also GMC Sierra HEV
6a. Also GMC Yukon HEV
7. Also Mercury Mariner HEV and Mazda Tribute HEV
8. One hour rated output by Japanese Motor Output Measurement Test Procedure

HEVs have good performance and excellent fuel economy, and driving ranges that generally exceed conventional vehicles, as shown below:

Table L-2: HEV Performance[1]

Vehicle (all are HEVs)	**Payload** (pounds)	**Emissions** (California)	**0-60 mph** (seconds)	**Range** (miles)	**Economy**[2] (mi/gal)	**Consumption**[3] (kWh/mi)
2006 Chevrolet Silverado	1162	Bin 8	9	445	18/21	1.695/1.259
2008 Ford Escape 2WD	1000	ATPZEV	n/a	661	41/32[4]	0.744/0.826
2007 Honda Accord	n/a	ATPZEV	n/a	477	28/35	1.090/0.755
2007 Honda Civic	n/a	ATPZEV	n/a	554	49/51	0.623/0.518
2006 Honda Insight A/T	n/a	SULEV	n/a	534	57/56	0.535/0.472
2006 Honda Insight M/T	n/a	ULEV	n/a	601	60/66	0.509/0.401
2007 Lexus GS450h	n/a	SULEV	5.2	402	25/28	1.220/0.944
2007 Lexus RX400h 4WD	n/a	SULEV	7.6	449	31/27	0.984/0.979
2007 Nissan Altima HEV	n/a	ATPZEV	n/a	n/a	42/36	0.726/0.735
2007 Saturn VUE	n/a	Bin 5	10.2	418	27/32	1.130/0.826
2007 Toyota Camry	n/a	ATPZEV	8.9	604	40/38	0.763/0.696
2007 Toyota Highlander 4WD	n/a	SULEV	7.6	449	31/27	0.984/0.979
2007 Toyota Prius	n/a	ATPZEV	10.1	589	60/51	0.509/0.518

1. Sources: manufacturer data, and <www.fueleconomy.gov>
2. City label (FTP x 0.9)/highway label (HFET x 0.78)
3. FTP/HFET dynamometer vehicle fuel consumption "tank to wheels", gasoline LHV: 33.9 kWh/gallon
4. Old method labels shown for data consistency; 34/30 using new 2008 MY 5 cycle method

20. References

- F.R. Kalhammer et al., Performance and Availability of Batteries for Electric Vehicles: A Report of the Battery Technical Advisory Committee, California Air Resources Board, (1995)
- F.R. Kalhammer et al., Status and Prospects of Fuel Cells as Automobile Engines: A Report of the Fuel Cell Technical Advisory Panel, California Air Resources Board (1998)
- F.R. Kalhammer, Batteries for Electric and Hybrid Vehicles: Recent Development Progress, California Air Resources Board (1999)
- M. Anderman et al., Advanced Batteries for Electric Vehicles: An Assessment of Performance, Cost, and Availability (2000)
- M. Paster, "Hydrogen, Fuel Cells and Infrastructure Program," January 2005.
- M. Deiml et al., Proceedings of the Fifth International Advanced Battery and Ultracapacitor Conference, Session 3, Waikiki Beach, HI, June 14-17, 2005
- M. Duvall et al., Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options, Palo Alto, CA, 2001, EPRI Report No. 1000349
- T. Unkelhaeuser et a., Electrochemical Storage Systems Abuse Test Procedure Manual, Sandia National Laboratories, Albuquerque, NM, Report SAND 99-0479, July 1999

TITLE 13. CALIFORNIA AIR RESOURCES BOARD

NOTICE OF PUBLIC HEARING TO CONSIDER THE ADOPTION OF A PROPOSED REGULATION FOR IN-USE OFF-ROAD DIESEL VEHICLES

The Air Resources Board (ARB or Board) will conduct a public hearing at the time and place noted below to consider adopting a regulation to reduce emissions of diesel particulate matter (diesel PM) and oxides of nitrogen (NOx) from in-use off-road diesel vehicles that operate in California. This notice summarizes the proposed regulation. The staff report and technical support document present the regulation and information supporting the adoption of the regulation in greater detail.

DATE: May 24, 2007

TIME: 9:00 a.m.

PLACE: San Diego Marriot Del Mar
Grand Ballroom
11966 El Camino Real
San Diego, CA 92130

This item will be considered at a two-day meeting of the Board, which will commence at 9:00 a.m., May 24, 2007 and will adjourn at 6:00 p.m. The meeting will then continue at 8:00 a.m., May 25, 2007. This item may not be considered until May 25, 2007. Please consult the agenda for the meeting, which will be available at least 10 days before May 24, 2007, to determine the day on which this item will be considered.

For individuals with sensory disabilities, this document is available in Braille, large print, audiocassette or computer disk. Please contact ARB's Disability Coordinator at 916-323-4916 by voice or through the California Relay Services at 711, to place your request for disability services. If you are a person with limited English and would like to request interpreter services, please contact ARB's Bilingual Manager at 916-323-7053.

INFORMATIVE DIGEST OF PROPOSED ACTION AND POLICY STATEMENT OVERVIEW

Sections Affected:

Proposed adoption of new section 2449, title 13, California Code of Regulations (CCR).

Background:

Over 90 percent of Californians breathe unhealthful air at times. To improve air quality and human health, ARB establishes requirements to reduce emissions from new and in-use motor vehicles and engines, as well as other sources. To reduce emissions from off-road vehicles, ARB has adopted a series of regulations since 1992 requiring that

new 1996 and subsequent model year off-road compression-ignition (diesel) engines comply with increasingly stringent emission standards. The United States Environmental Protection Agency (U.S. EPA) has established similar regulations for new off-road engines in the same time frame. On December 9, 2004, the Board adopted a fourth phase of emission standards (Tier 4) that are nearly identical to those finalized by U.S. EPA on May 11, 2004, in its Nonroad Diesel Rule.[1] Engine manufacturers are now required to meet aftertreatment-based exhaust standards for particulate matter and NOx starting in 2011 that are at least 90 percent more stringent than current levels, putting off-road engines on a virtual emissions par with on-road heavy-duty diesel engines. However, significant opportunities exist to further reduce emissions from the nearly 180,000 in-use off-road vehicles that operate in the State.

Control of Toxic Air Contaminants

California's Air Toxics Program, established under California law by Assembly Bill 1807 (Stats. 1983, Ch. 1047) and set forth in Health and Safety Code (HSC) sections 39650 through 39675, mandates the identification and control of air toxics in California. The identification phase of the Air Toxics Program requires ARB, with the participation of other state agencies, such as the Office of Environmental Health Hazard Assessment, to evaluate the health impacts of, and exposure to, substances and to identify those substances that pose the greatest health threat as toxic air contaminants (TACs). The ARB's evaluation is made available to the public and is formally reviewed by the Scientific Review Panel (SRP) established under HSC section 39670. Following the ARB's evaluation and the SRP's review, the Board may formally identify a TAC at a public hearing. Following identification, HSC sections 39658, 39665, 39666, and 39667 require ARB, with the participation of the air pollution control and air quality management districts (districts), and in consultation with affected sources and interested parties, to prepare a report on the need and appropriate degree of regulation for that substance and to adopt airborne toxic control measures (ATCMs).

In 1998, the Board identified diesel PM as a TAC with no Board-specified threshold exposure level. A needs assessment for diesel PM was conducted between 1998 and 2000, which resulted in ARB staff developing and the Board approving a Risk Reduction Plan to Reduce Particulate Matter Emissions from Diesel-Fueled Engines and Vehicles (Diesel RRP) in 2000. The Diesel RRP presented information that identified the available options for reducing diesel PM and recommended regulations to achieve further reductions. The scope of the Diesel RRP was broad, addressing all categories of engines, both mobile and stationary, and included control measures for private and public fleets of off-road diesel vehicles, such as those covered by the proposed regulation. The ultimate goal of the Diesel RRP is to reduce California's diesel PM emissions and associated cancer risks from 2000 baseline levels by 85 percent by 2020.

[1] ARB's emission standards for new off-road compression ignition engines are codified at title 13, CCR, sections 2420-2427. U.S. EPA's final Nonroad Diesel Rule is set forth at 69 FR 38958 (June 29, 2004). The California term "off-road" and the federal term "nonroad" refer to the same sources and are used interchangeably.

Attainment of Ambient Air Quality Standards

The federal Clean Air Act (CAA) requires U.S. EPA to establish National Ambient Air Quality Standards (Standards) for pollutants considered harmful to public health, including fine particulate matter (PM2.5) and ozone. Set to protect public health, the Standards are adopted based on a review of health studies by experts and a public process. Ambient PM2.5 is associated with premature mortality, aggravation of respiratory and cardiovascular disease, asthma exacerbation, chronic and acute bronchitis and reductions in lung function. Ozone is a powerful oxidant. Exposure to ozone can result in reduced lung function, increased respiratory symptoms, increased airway hyper-reactivity, and increased airway inflammation. Exposure to ozone is also associated with premature death, hospitalization for cardiopulmonary causes, and emergency room visits for asthma.

Areas in the State that exceed the Standards are required by federal law to develop State Implementation Plans (SIPs) describing how they will attain the standards by certain deadlines. NOx emission reductions are needed because NOx leads to formation in the atmosphere of both ozone and PM2.5; diesel PM emission reductions are needed because diesel PM contributes to ambient concentrations of PM2.5. The South Coast and San Joaquin Valley air basins are both required to attain the PM2.5 standard by 2015. The U.S. EPA further requires that all necessary emission reductions be achieved one calendar year sooner – by 2014 – in recognition of the annual average form of the standard. By contrast, San Joaquin Valley and South Coast air basins are expected to have until 2023 to attain the federal ozone standard, by invoking the "bump-up" provision in the CAA.

The ozone and PM2.5 SIPs are due to the U.S. EPA by June 2007 and April 2008, respectively. Air quality modeling indicates that significant reductions of NOx are crucial to help meet both these standards. At this time, staff estimates that a 60 percent reduction in NOx emissions from 2006 levels (i.e., a total reduction of hundreds of tons per day) and a 12 percent reduction in direct PM2.5 emissions will be necessary for attainment of the PM2.5 standards in the South Coast Air Basin. Emission reduction targets have not yet been set for achieving the PM2.5 standard in the San Joaquin Valley Air Basin, but are expected to be significantly lower.

While all sources of NOx emissions are important, off-road diesel vehicles are one of four major categories that will determine whether California is able to meet the 2014 deadline for PM2.5 attainment in the South Coast Air Basin. The remaining emission source categories with the most impact on California's attainment prospects are in-use on-road heavy-duty diesel vehicles, line-haul locomotives, and marine vessels.

Authority

ARB has authority under California law to adopt the proposed regulation. HSC sections 43000, 43000.5, 43013(b) and 43018 provide broad authority for ARB to adopt emission standards and other regulations to reduce emissions from new and in-use vehicular and

other mobile sources. Under HSC sections 43013(b) and 43018, ARB is directly authorized to adopt emission standards for off-road vehicular sources, as expeditiously as possible, to meet state ambient air quality standards. ARB is further mandated by California law under HSC section 39667 to adopt ATCMs for new and in-use vehicular sources, including off-road diesel vehicles, for identified TACs, such as diesel PM.

Emission Reductions and Public Health Benefits Projected

The regulation is expected to significantly reduce emissions of diesel PM from in-use off-road diesel vehicles. Diesel PM emission reductions are needed to reduce premature mortality, cancer risk, and other adverse impacts from exposure to this TAC. The regulation would achieve the 2020 goal set forth in the 2000 Diesel RRP of reducing diesel PM by 85 percent from 2000 baseline levels. Staff projects that the regulation would reduce in-use off-road vehicle diesel PM emissions from the 2000 baseline by 37 percent in 2010 and 92 percent in 2020.

The regulation would also reduce diesel PM and NOx emissions that contribute to exceedances throughout the State of ambient air quality standards for both PM2.5 and ozone. In 2020, the rule is expected to reduce diesel PM emissions by 5.2 tons per day and NOx emissions by about 48 tons per day statewide, which represents a 74 percent reduction in diesel PM and a 32 percent reduction in NOx from emission levels anticipated in the absence of the rule.

The emission reductions from the regulation are expected to prevent approximately 4,000 premature deaths over the course of the regulation (1,100 to 6,800, 95% confidence interval).

Although some actions required by the rule would result in a fuel economy penalty, slightly increasing carbon dioxide (CO_2) greenhouse gas emissions, other actions required by the rule would reduce idling, increase the use of electric vehicles, and reduce emissions of black carbon (a likely contributor to global warming), and are expected to offset any fuel penalty effect. On the whole, staff expects the rule to have a negligible effect on global warming.

While the public health benefits of this rule are substantial, as noted above, the proposed rule is currently not sufficient to demonstrate full attainment of the federal PM2.5 standard by 2014. As a consequence, the Board may consider whether the proposal can be strengthened – either at the May 25-26 public hearing or at a subsequent meeting.

Comparable Federal Regulations

As noted above, U.S. EPA has promulgated federal emission standards for new nonroad engines. Presently, no federal standards have been promulgated addressing emission reductions from in-use diesel vehicle engines. Under CAA section 213, U.S. EPA is without authority to adopt in-use standards for nonroad engines. California

is the only governmental entity in the United States authorized by the CAA, in the first instance, to adopt emission requirements for in-use off-road engines.[2]

While CAA section 209(e)(1) conclusively preempts states, including California, from adopting requirements for new off-road engines less than 175 horsepower that are used in farm or construction equipment, the proposed regulation addresses in-use rather than new off-road engines. Under section 209(e)(2), California may adopt and enforce emission standards and other requirements for off-road engines and equipment not conclusively preempted by section 209(e)(1), so long as California applies for and receives authorization from the Administrator of U.S. EPA. To obtain authorization, the Board must make a finding that the California adopted standards will be, in the aggregate, at least as protective of public health and welfare as applicable federal standards.[3] The Administrator must grant a request for authorization from California unless he finds that ARB's protectiveness finding is arbitrary and capricious, that California does not need the standards to meet compelling and extraordinary conditions, or that the standards and accompanying enforcement procedures are not consistent with CAA section 209.

Staff Report and Further Information

The ARB staff has prepared two separate documents, an Initial Statement of Reasons (Staff Report) for the proposed regulation and a Technical Support Document that, together with the needs assessment (i.e., the Diesel RRP), serve as the report on the need and appropriate degree of regulation for in-use off-road diesel vehicles.

Description of the Proposed Regulatory Action

Applicability

The fleet requirements of this regulation would apply to any person, business, or government agency that owns vehicles with affected engines in California. Affected engines include diesel-fueled engines with maximum power of 25 horsepower (hp) or greater that are used to provide motive power in a workover rig or to provide motive power in any other motor vehicle that (1) cannot be registered and driven safely on-road, and (2) is not an implement of husbandry or recreational off-highway vehicle. The proposed regulation only addresses engines that drive self-propelled vehicles (i.e., does not apply to stationary equipment or portable equipment like generators).

Industries such as construction, mining, landscaping, airlines, retail, wholesale, equipment rental, ski, oil and gas drilling, recycling, utilities, telephone and cable, and many others would be subject to the regulation. Government agencies engaged in road maintenance, park maintenance, and other activities that operate covered vehicles would also be affected.

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[2] See *Engine Manufacturers Association v. U.S. EPA* (D.C. Cir. 1996) 88 F.3d 1075.

[3] CAA section 209(e)(2)(A). Other states may subsequently opt into the California program, but their regulations must be identical to California's requirements. CAA section 209(e)(2)(B).

The regulation contains different requirements for fleets of differing sizes. A fleet consists of one or more vehicles. Fleets are defined in the regulation as either small, medium, or large. Small fleets include: (1) fleets with total horsepower of less than or equal to 1,500 hp that are owned by a small business (as defined in Government Code section 11342.610) or by a governmental entity that is not a state or federal agency; and (2) all fleets of low population county local municipalities irrespective of total horsepower. Medium fleets are defined as those with total horsepower less than or equal to 5,000 hp that are not small fleets. Large fleets are defined as those with total horsepower greater than 5,000 hp. All state and federal agencies would be considered large fleets.

The proposed regulation also would impose requirements on sellers of new and in-use vehicles to disclose the regulation's potential applicability to buyers of the vehicles.

Fleet Requirements

In general, the rule would require owners to modernize their fleets by replacing engines with newer, cleaner ones (repowering), replacing vehicles with newer vehicles equipped with cleaner engines, retiring older vehicles, operating higher emitting vehicles less often (designating them as low-use vehicles) and applying exhaust retrofits that capture and destroy pollutants before they are emitted into the atmosphere.

The rule would establish fleet average emission rate targets for both diesel PM and NOx. By the applicable compliance date each year, the rule would require each fleet to demonstrate either that it meets the fleet average emission rate target for diesel PM or that it has applied the highest level verified diesel emission control system (VDECS) to 20 percent of the total horsepower of its fleet in the past year. The highest level VDECS is only required if a system has been verified by ARB to be effective and durable for the engine on which it will be installed, and if the system can be used safely. The rule would not penalize fleets if an appropriate VDECS is not available for a given engine or vehicle. The ARB's verification program, previously adopted by the Board,[4] is intended to ensure that an emission control system for in-use diesel engines achieves the advertised emission reductions and has been evaluated for durability. Also, to receive ARB verification, the device manufacturer is required to warrant the VDECS and warrant against any engine damage caused by the device.

For NOx, the rule would also require large and medium fleets to demonstrate that they meet the fleet average emission rate target for NOx or to turn over a certain percent of the fleet's total horsepower by the applicable compliance date each year. Small fleets are exempt from this provision. The mandatory turnover rate until 2015 is eight percent per year. Then, after 2015, it is 10 percent per year. If retrofits that reduce NOx emissions become available, they may be used in lieu of turnover.

[4] Title 13, CCR, sections 2700-2710.

The targets decline over time, requiring fleets to reduce their emissions further as time goes on. As stated, to meet the diesel PM or NOx fleet averages, fleets may retrofit their vehicles' exhaust systems with verified emission control devices to reduce PM and/or NOx emissions, repower existing vehicles with cleaner engines, retire higher-emitting vehicles and/or replace them with newer, cleaner vehicles, or designate high-emitting vehicles as low-use vehicles. Under the regulation, vehicles designated as low-use would not be included in calculating the fleet average and are exempt from the retrofit, turnover and fleet average requirements.

Fleets would have the option of satisfying either the fleet average requirements or the mandatory retrofit and/or turnover requirements each year. Satisfying either would be an acceptable way to demonstrate compliance with the regulation.

Finally, the regulation would require that operators of off-road diesel vehicles shut down their vehicles rather than operate them in idle mode for more than 5 minutes, unless such idling is necessary for the proper or safe operation of the vehicle.

Labeling, Recordkeeping, and Reporting Requirements

All fleet owners would be required to report their affected equipment and associated engine and retrofit data to ARB in 2009. Annually thereafter, fleets would need to report any changes made in the prior year. Fleet owners would also be required to label all affected equipment with a unique equipment identification number assigned by ARB. They would be required to keep records of all data reported, as well as any changes made since their last reporting, until 2030, or as long as the owner still owns the fleet.

Schedule

The reporting requirements would begin for all fleets subject to the regulation in 2009. The first fleet average targets would take effect in 2010 for the largest fleets and in 2013 for medium fleets. Small fleets would have until 2015 to comply with the PM retrofit or PM fleet average requirements.

Exemptions, Compliance Extensions and Special Circumstances

The regulation contains special, less strict provisions for all fleets in counties that currently are in attainment with the federal ambient air quality standards for ozone and particulate matter, as well as less strict provisions for public fleets in rural counties with low populations. The regulation would also exempt low-use vehicles (vehicles used less than 100 hours per year), emergency equipment, and vehicles used only to remove snow from public roads from all requirements but recordkeeping and reporting.

The following vehicles would be exempt from the mandatory turnover requirements:

- All vehicles in small fleets,
- Vehicles less than 10 years old,
- Specialty vehicles for which no used equipment or repowers are available,

- Vehicles retrofit with best available technology in the past 6 years, and
- Tier 4 and interim Tier 4 engines.

The following engines would be exempt from the retrofit requirements:

- Engines in vehicles less than 5 years old,
- Engines for which there is no retrofit available or for which a retrofit cannot be safely installed.
- New engines that come with a diesel particulate filter, and
- Engines already retrofit with the best available control at the time of installation.

The regulation would provide that fleet owners are subject to penalties for noncompliance consistent with the penalty provisions set forth in the Health and Safety Code. However, fleet owners would not be liable for noncompliance caused by manufacturer delays in the availability of retrofits, repowers, or new engines needed for compliance with the regulation.

At the hearing, the Board may consider other elements that may provide additional flexibility to affected fleets.

AVAILABILITY OF DOCUMENTS AND AGENCY CONTACT PERSONS

The Board staff has prepared a Staff Report for the proposed regulatory action, which includes a summary of the economic and environmental impacts of the proposal. The report is entitled, "Staff Report: Initial Statement of Reasons for the Proposed Rulemaking – Regulation for In-Use Off-road Diesel Vehicles."

Copies of the Staff Report and the full text of the proposed regulatory language may be obtained from the Public Information Office, Air Resources Board, 1001 I Street, Visitors and Environmental Services Center, 1st Floor, Sacramento, CA 95814, (916) 322-2990. They will be made available at least 45 days prior to the scheduled May 24, 2007 hearing.

Upon its completion, the Final Statement of Reasons (FSOR) will be available and copies may be requested from the agency contact persons in this notice, or may be accessed on the ARB's web site listed below.

Inquiries concerning the substance of the proposed regulations may be directed to the designated agency contact persons, Tony Brasil, Manager of the In-Use Control Measures Section, at (916) 323-2927, or by email at abrasil@arb.ca.gov, or Kim Heroy-Rogalski, Staff Air Pollution Specialist, at (916) 327-2200, or by email at kheroyro@arb.ca.gov.

Further, the agency representative and designated back-up contact persons to whom nonsubstantive inquiries concerning the proposed administrative action may be directed

are Alexa Malik, Manager, Board Administration & Regulatory Coordination Unit, (916) 322-4011, and Amy Whiting, Regulations Coordinator, (916) 322-6533. The Board has compiled a record for this rulemaking action, which includes all the information upon which the proposal is based. This material is available for inspection upon request to the contact persons.

This notice, the Staff Report and all subsequent regulatory documents, including the FSOR, when completed are also available on the ARB Internet site for this rulemaking at http://www.arb.ca.gov/regact/2007/ordiesl07/ordiesl07.htm

COSTS TO PUBLIC AGENCIES AND TO BUSINESSES AND PERSONS AFFECTED

Costs to Businesses and Private Individuals

The determinations of the Board's Executive Officer concerning the costs or savings necessarily incurred by public agencies and private persons and businesses in reasonable compliance with the proposed regulations are presented below.

The total cost of the regulation is expected to be between $3.0 and 3.4 billion in 2006 expenditure equivalent dollars (2006 dollars). This represents the total cost of the regulation if all money required to comply with the proposed regulation were spent today. This cost would be spread over the years 2009 to 2030, with the majority of costs occurring in the first 12 years. On an annual basis, the cost would vary between $229 million and $257 million per year, averaging $243 million per year. The total cost would include the expected cost of retrofit devices and engine repowers, as well as the cost of accelerating turnover to newer, cleaner vehicles. About half of this cost is expected to be incurred by the construction industry, nearly 15 percent by the rental industry, and about 10 percent by the mining industry. Government fleets would be expected to incur about five percent of the total cost. The remaining costs, approximately 20 percent, would be paid by other industries such as utilities, recycling, landfills, landscaping, and airlines.

Costs to individual fleet owners would vary depending on the size of each fleet, its initial vehicle composition and vehicle age, and its normal purchasing practices. Costs also would vary depending on the compliance strategy chosen by each fleet (retrofit, repower, retire, buy new, and/or buy used). For a typical fleet, total costs are expected to be $111 per hp (in 2006 dollars). Fleets could incur costs anywhere from $0 to $170 per hp, depending on their initial composition and vehicle age. For a typical medium-sized fleet with total fleet horsepower of 3,000 hp, the total cost of the regulation is expected to be about $333,000 (in 2006 dollars).

The Executive Officer has made an initial determination that the proposed regulatory action may have a significant statewide adverse economic impact directly affecting businesses, including the ability of California businesses to compete with businesses in other states, or on representative private persons. ARB staff has considered proposed alternatives that would lessen any adverse economic impact on business and invites

you to submit proposals. Submission may include the following approaches for consideration:

(i) The establishment of differing compliance or reporting requirements or timetables that take into account the resources available to businesses.
(ii) Consolidation or simplification of compliance and reporting requirements for businesses.
(iii) The use of performance standards rather than prescriptive standards.
(iv) Exemption or partial exemption from the regulatory requirements for businesses.

Alternatives that staff considered are described in more detail in the Staff Report.

In developing this regulatory proposal, ARB staff evaluated the potential economic impacts on representative private persons or businesses. Because the proposed regulation does not apply to vehicles used only for personal, residential, or non-commercial purposes, ARB is not aware of any cost impacts that a representative person would necessarily incur in his or her private capacity in reasonable compliance with the proposed action. Businesses such as construction firms typically pass some of the cost of compliance on to their customers. Accordingly, ARB anticipates that businesses would similarly pass on some of the costs incurred by this regulation. As a result, staff anticipates a representative individual may incur small additional costs (less than one percent) because of a possible rise in the cost of construction. (See *Effect on Housing Costs* below.)

Overall, most affected businesses will be able to absorb or pass on the costs of the proposed regulation with no significant adverse impacts on their profitability. This finding is based on ARB staff's analysis of the estimated change in "return on owner's equity" (ROE) for fleets within each industry type affected by the regulation. A 10 percent decline in ROE has traditionally been used by ARB to indicate a significant impact on profitability. For fleets that do not pass through any of the cost of compliance to their customers, the ROE analysis found that between about 60 and 80 percent of fleets would still be expected to be able to absorb the cost of the regulation without incurring more than a 10 percent change in ROE. Owners of small fleets are more likely to be able to absorb the cost of the regulation without exceeding 10 percent change in ROE because their exemption from the regulation's mandatory turnover provisions would result in significantly lower costs relative to medium and large fleets. The 20 to 40 percent of fleet owners for which the regulatory costs exceed a 10 percent change in ROE will have to pass through at least some of the costs to their customers in the form of higher prices for their services to maintain their profitability.

Most construction firms, rental companies, airlines, and landscaping services companies are expected to be able to pass on their costs to customers. Rental companies may actually see an increase in revenue as many affected fleets downsize, retire less-used vehicles, and consider rental as a more attractive alternative to owning vehicles.

In accordance with Government Code section 11346.3, the Executive Officer has determined that the proposed regulatory action may lead to the creation and elimination of some jobs within the State of California, the creation of new businesses and elimination of some existing businesses within the State of California, or the expansion of businesses currently doing business within the State of California. A detailed assessment of the economic impacts of the proposed regulatory action can be found in the Staff Report.

Because of the significant cost imposed by this regulation, it is possible that some businesses with affected fleets will be eliminated. It is also possible that some businesses will choose to consolidate (or merge), change owners, or relocate due to this regulation. However, this regulation would increase the use of VDECS in off-road diesel vehicles in the State. Staff estimates that over its course, the regulation will require the installation of over 126,000 VDECS. It is very likely that additional businesses will be created or existing businesses expanded to aid in the making, distribution, cleaning, and maintenance of these VDECS through the duration of the regulation.

The regulation would likely cause many jobs to be created due to the increase in demand for VDECS, newer engines, and newer vehicles, as well as for the need for fleets to plan for compliance. Staff expects new jobs to be created for the production, sales, installation, and maintenance of VDECS, the installation of repowers, and consulting to assist fleets in finding the most cost-effective path to compliance. It is expected that some jobs will also be consolidated (i.e., the employees of one company being absorbed by another) or modified (i.e., a muffler mechanic may be reassigned to VDECS maintenance and installation).

As structured, the proposed regulation would affect out-of-state businesses that operate vehicles in California just as it affects the California-based businesses that operate here. However, some large out-of-state businesses may find it less costly to comply because they can opt to move the cleaner portions of their fleets to California rather than pursuing retrofits or repowers. Fleets operated solely within California will not have this ability. The regulation may also have some adverse impacts on the ability of some California businesses that regularly use their California equipment to compete for projects outside the State. This is because to cover compliance costs, California businesses may need to bid higher than firms who are not subject to the rule. Similarly, the regulation may have some adverse impacts on manufacturing or mining businesses that operate in a very competitive national market and compete with firms outside California. However, staff expects that off-road vehicle use in manufacturing represents a smaller percentage of the company's total operating expense and that the increase in cost attributable to the regulation will only be a small portion of the operating expense. Thus, many owners of manufacturing fleets are expected to be able to absorb the costs without a significant impact on profitability.

The Executive Officer has also determined, pursuant to title 1, CCR, section 4, that the proposed regulatory action will affect small businesses. The total cost for a small business to comply with the in-use emission standards of the regulation (e.g., initial reporting and purchasing of retrofits, repowers and vehicles) is expected to be approximately $48/hp. Typical ongoing costs for small businesses, including retrofit maintenance (e.g., maintenance, fuel penalties, and electricity costs for active filters) and reporting costs will be approximately $2/hp per year from 2014 until 2026. A typical small business with 1,000 horsepower could expect the total cost of the regulation over its lifetime to be $48,000 (2006 dollars), with annual costs of $2,000 per year during that period.

In accordance with Government Code sections 11346.3(c) and 11346.5(a)(11), the Executive Officer has found that the reporting requirements of the regulation which apply to businesses are necessary for the health, safety, and welfare of the people of the State of California. The reporting requirements are necessary for the enforcement of the regulation, and enforcement of the regulation is necessary to ensure the emission reductions and public health benefits associated with the regulation occur.

Before taking final action on the proposed regulatory action, the Board must determine that no reasonable alternative considered by the board or that has otherwise been identified and brought to the attention of the board would be more effective in carrying out the purpose for which the action is proposed or would be as effective and less burdensome to affected private persons than the proposed action.

Fiscal Impact on State Government

The Executive Officer has determined that the proposed regulatory action will create costs or savings, as defined in Government Code sections 11346.5(a)(6) for a state agency or in federal funding to the state, as discussed in the "Fiscal Impact on State Government" section below. State agencies will incur costs if they own vehicles covered by the regulation.

Two separate fiscal effects may pertain at the state government level: costs to state agencies that own affected diesel vehicles for compliance and costs for ARB to implement and enforce the regulations. The proposed regulatory action will not affect federal funding to the state.

The total cost to state agencies for compliance is expected to be between $84 million and $90 million (2006 dollars). Annual costs are expected to be about $7 million per year (until 2030). Initial costs to state agencies will occur in fiscal year (FY) 2008-2009 for the initial reporting, with the initial costs for compliance actions such as installing retrofits or repowering engines occurring in FY2009-2010. The California Department of Transportation (CalTrans) is the State agency with the largest fleet and the State agency expected to incur the greatest cost impact. Compliance costs for CalTrans are expected to be $1.2 million on average annually from FY2009-2010 until FY2029-2030 and to total $11 million to $13 million over the course of the regulation (2006 dollars). It

is anticipated that affected agencies will be able to plan ahead for and budget adequately to cover the costs of compliance with the regulation.

The regulation will also impose additional staffing costs to ARB. ARB staff has identified a need for additional resources to aid in implementation, outreach, education, and enforcement of the regulation.

Fiscal Impact on Local Government

The Executive Officer has determined that the proposed regulatory action will result in nondiscretionary costs for local agencies or school districts (if they own affected vehicles), and may impose a mandate, as defined in Government Code section 11346.5(a)(5). However, the mandate is not reimbursable by the state pursuant to part 7 (commencing with section 17500), division 4, title 2 of the Government Code, because the costs would apply to all owners of affected vehicles, not just local agencies.

The regulation will impose costs on local agencies that own affected vehicles. The total cost to local agencies for compliance is expected to be between $95 million and $106 million (2006 dollars). Total annual costs for all affected agencies are expected to be about $8 million per year.

Local government fleets that are in low-population counties should expect lower annual costs of approximately $3.60/hp to $4.20/hp per year.

Local government agencies captive to attainment areas similarly should expect lower annual costs of $4/hp to $5/hp per year.

Total compliance costs for a typical local agency with 1000 hp would be $83,000 (2006 dollars), or $6,000 per year on average from FY2014-2015 through FY2029-2030.

The initial cost to local agencies would be in FY2008-2009 for reporting, with the first costs for compliance actions such as installing retrofits or repowering engines in FY2009-2010 for the largest local agency fleets, in FY2012-2013 for medium local agency fleets, and FY2014-2015 for small local agency fleets and those in low-population counties.

Effect on Housing Costs

The Executive Officer has determined that the proposed regulation would have an effect on housing costs. It has been estimated that the proposed regulation would potentially increase the costs of newly constructed housing approximately $1000 per unit. The ARB will make available to the public, upon request, the agency's evaluation of the effect of the proposed regulatory action on housing costs.

SUBMITTAL OF COMMENTS

The public may present comments relating to this matter orally or in writing at the hearing, and in writing or by e-mail before the hearing. To be considered by the Board, written submissions not physically submitted at the hearing must be received **no later than 12:00 noon, May 23, 2007**, and addressed to the following:

Postal mail: Clerk of the Board, Air Resources Board
1001 I Street, Sacramento, California 95814

Electronic submittal: http://www.arb.ca.gov/lispub/comm/bclist.php

Facsimile submittal: (916) 322-3928

The Board requests but does not require that 30 copies of any written statement be submitted and that all written statements be filed at least 10 days prior to the hearing so that ARB staff and Board Members have time to fully consider each comment. The board encourages members of the public to bring to the attention of staff in advance of the hearing any suggestions for modification of the proposed regulatory action.

STATUTORY AUTHORITY AND REFERENCES

This regulatory action is proposed under the authority granted to the ARB in Health and Safety Code sections 39002, 39515, 39516, 39600, 39601, 39602, 39650, 39656, 39658, 39659, 39665, 39667, 39674, 39675, 40000, 41511, 42400, 42400.1, 42400.2, 42402.2, 43000, 43000.5, 43013, 43016, and 43018. This action is proposed to implement, interpret, or make specific Health and Safety Code sections 39002, 39515, 39516, 39600, 39601, 39602, 39650, 39656, 39657, 39658, 39659, 39665, 39667, 39674, 39675, 40000, 41511, 42400, 42400.1, 42400.2, 42402.2, 43000, 43000.5, 43013, 43016, and 43018.

HEARING PROCEDURES

The public hearing will be conducted in accordance with the California Administrative Procedure Act, title 2, division 3, part 1, chapter 3.5 (commencing with section 11340) of the Government Code.

Following the public hearing, the Board may adopt the regulatory language as originally proposed, or with non substantial or grammatical modifications. The Board may also adopt the proposed regulatory language with other modifications if the text as modified is sufficiently related to the originally proposed text that the public was adequately placed on notice that the regulatory language as modified could result from the proposed regulatory action; in such event the full regulatory text, with the modifications clearly indicated, will be made available to the public, for written comment, at least 15 days before it is adopted.

The public may request a copy of the modified regulatory text from the ARB's Public Information Office, Air Resources Board, 1001 I Street, Visitors and Environmental Services Center, 1st Floor, Sacramento, CA 95814, (916) 322-2990.

CALIFORNIA AIR RESOURCES BOARD

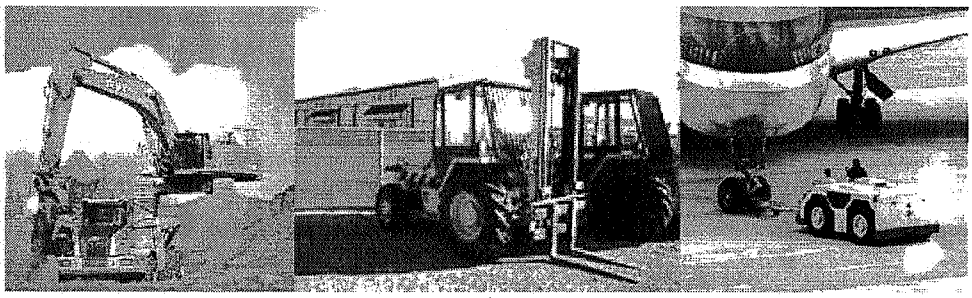
Catherine Witherspoon
Executive Officer

Date: March 27, 2007

California Environmental Protection Agency
AIR RESOURCES BOARD

STAFF REPORT: INITIAL STATEMENT OF REASONS FOR PROPOSED RULEMAKING

PROPOSED REGULATION FOR IN-USE OFF-ROAD DIESEL VEHICLES



Mobile Source Control Division
Heavy Duty Diesel In-Use Strategies Branch

April 2007

State of California
AIR RESOURCES BOARD

STAFF REPORT: INITIAL STATEMENT OF REASONS FOR PROPOSED RULEMAKING

Public Hearing to Consider

ADOPTION OF THE PROPOSED REGULATION FOR IN-USE OFF-ROAD DIESEL VEHICLES

To be considered by the Air Resources Board at a two-day meeting of the Board that will commence on May 24, 2007, and may continue to May 25, 2007, at

California Environmental Protection Agency
San Diego Marriot Del Mar
Grand Ballroom
11966 El Camino Real
San Diego, CA 92130

Mobile Source Control Division:
Robert Cross, Chief

Heavy-Duty Diesel In-Use Strategies Branch:
Erik White, Chief

In-Use Control Measures Section:
Tony Brasil, Manager

This report has been prepared by the staff of the Air Resources Board. Publication does not signify that the contents reflect the views and policies of the Air Resources Board, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

State of California
AIR RESOURCES BOARD

PROPOSED REGULATION FOR IN-USE OFF-ROAD DIESEL VEHICLES

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I. OVERVIEW AND STAFF RECOMMENDATION

Staff of the Air Resources Board (ARB or Board) is proposing a regulation that would reduce emissions of diesel particulate matter (PM) and oxides of nitrogen (NOx) from nearly 180,000 off-road diesel vehicles in the State. The regulation would achieve these emission reductions by requiring fleet owners to modernize their fleets and install exhaust retrofits. The regulation is projected to achieve significant emission reductions, but at a significant cost to affected fleets.

The scope of the regulation is far-reaching; vehicles of dozens of types used in over 8,000 fleets, in industries as diverse as construction, air travel, manufacturing, landscaping, and ski resorts, as well as by a considerable number of public agencies, would be affected. The regulation would affect the warehouse with one diesel forklift, the landscaper with a fleet of a dozen diesel mowers, the county that maintains rural roads, the landfill with a fleet of dozers, as well as the large construction firm or government fleet with hundreds of diesel loaders, graders, scrapers, and rollers.

The regulation, a copy of which is provided in Appendix A, would mean different things for different fleets, depending on their size and on the vintage of their vehicles. Fleets are defined in the regulation as small, medium, or large based on their total horsepower and whether they are a small business. The regulation has the strictest provisions for the largest fleets, which have the most significant emissions and which are most likely able to rapidly understand and absorb the costs of regulation compliance. The regulation has the least stringent provisions for the smallest fleets owned by small businesses or municipalities.

The regulation would establish fleet average emission rate targets for PM and NOx for all off-road vehicles operating in the state, regardless of whether they are California based or not. The targets decline over time, requiring fleets to reduce their emissions further as time goes on. Each year, the regulation requires each fleet to meet the fleet average emission rate targets for PM or apply the highest level verified diesel emission control system to 20 percent of its horsepower. Each year, the regulation also requires large and medium fleets to meet the fleet average emission rate targets for NOx or to turn over a certain percent of their horsepower (8 percent in early years, and 10 percent in later years). Turn over means repowering with a cleaner engine, retiring a vehicle, replacing a vehicle with a new or used piece, or designating a dirty vehicle as a low-use vehicle. If retrofits that reduce NOx emissions become available, they may be used in lieu of turnover as long as they achieve the same emission benefits.

Each year, fleets would have the option of satisfying either the fleet average requirements or the mandatory retrofit and/or turnover requirements. To meet the fleet averages, fleets may retrofit their vehicles' exhaust systems with verified diesel emission control devices, replace the engines in existing vehicles with cleaner engines (i.e., repower), retire high-emitting vehicles, and/or designate high-emitting vehicles as low-use vehicles. The regulation would also limit unnecessary idling to 5 minutes.

Small fleets would be subject only to the PM requirements beginning in 2015. Small fleets that do not meet the PM fleet average targets would need to install exhaust retrofits on 20 percent of their horsepower per year beginning in 2014. Small fleets with newer vehicles may choose to either voluntarily accelerate turnover of their fleets enough to meet the PM fleet average targets or to apply some exhaust retrofits.

Medium fleets would be subject to the PM and NOx requirements beginning in 2013. Medium fleets with the oldest vehicles would not be able to meet the fleet average targets and would need to accelerate turnover of engines to 8 percent of their horsepower per year and install exhaust retrofits on 20 percent of their horsepower per year beginning in 2012. Medium fleets with newer vehicles would not have to do the maximum turnover or maximum exhaust retrofit installations but may have to accelerate the purchase of some vehicles and install enough exhaust retrofits to meet the average targets.

Large fleets would be subject to the PM and NOx requirements beginning in 2010. Large fleets with the oldest vehicles would need to accelerate turnover of engines to 8 percent of their horsepower per year and install exhaust retrofits on 20 percent of their horsepower per year beginning in 2009. In 2015, the oldest large and medium fleets would need to further accelerate turnover to 10 percent of their horsepower per year. While the regulation provides time for retrofit vehicles to remain in the fleet, these oldest fleets may also need to turn over some of the oldest engines that are retrofit once the exhaust retrofits are older than 6 years. Large fleets with newer vehicles would need to accelerate turnover of their fleets enough to meet the NOx fleet average targets and to apply enough exhaust retrofits to meet the PM fleet average targets.

The regulation is expected to reduce 48 tons per day (tpd) NOx and 5.2 tpd of PM statewide in 2020. These reductions represent a 32 percent reduction in NOx and a 74 percent reduction in PM from the 2020 emissions that would otherwise occur in the absence of the regulation.

The regulation would also contribute to achieving the 2020 goal set forth in the 2000 Diesel Risk Reduction Plan of reducing diesel PM 85 percent from all diesel sources from 2000 baseline levels. The regulation is projected to reduce PM emissions 37 percent from the 2000 baseline by 2010, and 92 percent by 2020 from the sources subject to this regulation.

The emission reductions from the regulation would be expected to prevent approximately 4,000 premature deaths (1,100 to 6,800, 95% confidence interval) and tens of thousands of cases of asthma-related and other lower respiratory symptoms, and provide a benefit of $18 to $26 billion in avoided premature death and health costs.

The regulation is the next in a series of rules intended to reduce emissions from in-use diesel vehicles and equipment. However, the scope of the regulation dwarfs previous air toxic control measures that the Board has approved. By comparison, the cargo handling air toxic control measure (ATCM) affects about 3,700 pieces of cargo handling equipment; the solid waste collection vehicle rule affects about 12,000 solid waste

collection vehicles; and the portable engine ATCM covers about 33,000 portable engines (ARB, 2005a; ARB, 2006; ARB, 2004). Likewise, the benefits of the proposed regulation are dozens of times larger than those of previous measures. In total, the proposed regulation is expected to reduce 187,000 tons of NOx emissions and 33,000 tons of PM emissions between 2009 and 2030.

The regulation would provide greatly needed reductions of NOx emissions in the South Coast and San Joaquin Valley air basins. These areas must achieve significant NOx reductions from the off-road sector to achieve ambient ozone and fine particulate matter (PM2.5) standards by the federally-mandated deadlines. The deadline for the attainment of the PM2.5 standards in these regions is currently 2015, so emission reductions are urgently needed. Staff expects that despite a comprehensive effort to meet the PM2.5 standard, California may still come up short in achieving the needed emission reductions by the 2015 federal attainment deadline. Because the standard is an annual average, the U.S. EPA requires that all necessary emission reductions be achieved one calendar year sooner, or by 2014. While all sources of NOx emissions are important, off-road diesel vehicles are one of four major categories that will determine whether California is able to meet the 2014 deadline for PM2.5 attainment in the South Coast Air Basin. If the emissions reductions needed to achieve attainment of the federal standards cannot be demonstrated, the Board may need to consider additional measures or changes. However, staff believes the proposed regulation represents the economic limit of what industry could bear, and any further emissions reduction requirements would likely require financial incentives.

The regulation is controversial among the fleets it would impact in large part because it would impose significant costs on industry. The total cost of the regulation is expected to be between $3.0 and $3.4 billion in 2006 expenditure equivalent dollars (2006 dollars). This cost would be spread over the years 2009 to 2030, with the majority of costs occurring between 2010 and 2021. On average over the course of the regulation, the cost would vary between $229 million and $257 million per year, averaging $243 million per year (2006 dollars). About half the cost is expected to be incurred directly by the construction industry, nearly 15 percent by the business services sector, and about 10 percent by the mining industry. Government fleets are expected to incur about 5 percent of the total cost, with the remaining costs spread among various other affected industries.

Costs to individual fleets would vary depending on the size of each fleet, its initial vehicle composition and vehicle age, and its normal purchasing practices. Costs also would vary depending on the compliance strategy chosen by each fleet (retrofit, repower, buy new, and/or buy used). For a typical fleet, total costs over the life of the regulation are expected to be $104 to $117 per horsepower of affected vehicles (in 2006 dollars). Individual fleets may incur average costs anywhere from $0 to about $170 per horsepower (hp), depending on their initial composition and vehicle age. There may be cases where fleets would incur slightly higher costs. Annual costs for a typical fleet would range from $8 to $9 per horsepower per year (2006 dollars). For a typical medium sized fleet with total fleet horsepower of 3,000, the total cost of the regulation is

expected to be about $333,000 (in 2006 dollars), with average annual costs of $27,000 per year (in 2006 dollars) for 21 years.

Overall, most affected businesses could absorb the costs of the proposed regulation with no significant adverse impacts on their profitability. Manufacturing business are the least likely to be able to pass on their cost if the product they manufacture is sold nationally or globally, but the economic impact of the regulation is not expected to be a significant part of normal operating expenses. However, most construction fleets, rental companies, airlines, and landscaping service fleets who compete locally should be able to pass on some or all of the costs of compliance to their customers, thereby maintaining their profitability. Even if fleets were unable to pass on any of the cost of compliance to their customers, staff found that between about 60 and 80 percent of fleets would still be expected to be able to withstand the cost of the regulation without incurring more than a 10 percent change in their return on equity. Small fleets would be more likely to be able to absorb the cost of the regulation without exceeding 10 percent change in "return on owner's equity" (ROE) because they are not subject to the regulation's mandatory turnover provisions, and thereby would incur significantly less costs relative to medium and large fleets. The 20 to 40 percent of fleets for which the regulatory costs exceed a 10 percent change in ROE would have to pass through at least some of the costs to their customers to maintain their profitability.

The regulation is expected to raise the cost of construction in California by no more than 0.3 percent as fleets pass on the cost of compliance to their customers. Customers that could expect to pay higher construction costs include developers, home builders, and government agencies sponsoring road construction and other transportation projects. For the average new home buyer, the expected cost of the regulation could add about $5 per month to a 30-year mortgage.

The regulation would require fleets to change their operating and vehicle purchasing practices. For the first time, owners of off-road vehicles would need to label them and report them to the State. The regulation would require upgrades with newer engines or turnover of vehicles that fleets purchased years ago, and which they had assumed could be used indefinitely. The regulation would require use of retrofit devices that, while verified by the ARB, are unfamiliar to fleets.

The regulation contains flexibility provisions to allow each fleet to find its own most cost-effective way to comply. The regulation would allow fleets to comply by meeting a fleet average so each fleet can choose its own best, most cost-effective path toward compliance. The regulation contains special exemptions for low-use vehicles, specialty vehicles, emergency vehicles, and dedicated snow removal vehicles. The regulation contains provisions that would give fleets more time if they encounter delays in obtaining the engines, vehicles, or retrofits that they need to comply. Finally, the regulation gives the smallest fleets more time to comply, leaving them several years to apply for State incentive funding.

Staff has made an enormous effort to notify affected fleets and interested parties about the proposed regulation, and to solicit their input on the regulation. The latest seven

workshops held across the state since December 2006 were attended by over 1,500 people. These workshops capped a two-year long outreach and regulation development process that included 19 public workshops and workgroup meetings, dozens of site visits and private meetings with fleet owners, equipment dealers, and industry groups, and multiple mailings to over 300,000 contractors, landfills, owners of portable equipment, and numerous other potential owners of affected off-road vehicles.

Staff recommends that the Board adopt the regulation because its projected benefits - emissions reduced and adverse health impacts avoided - make it worth the anticipated cost and inconvenience to fleets and because emission reductions from the affected vehicles are urgently needed to meet State Implementation Plan commitments.

The following sections provide answers to the most salient questions about the regulation. Supporting material is provided in the Technical Support Document (ARB, 2007a).

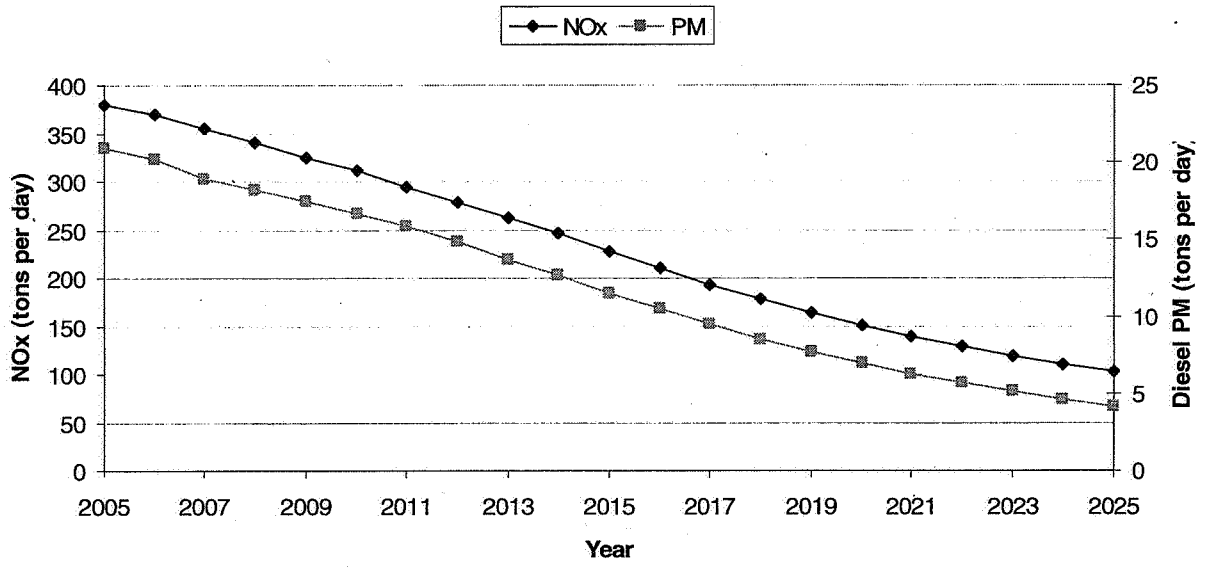
II. NEED FOR EMISSION REDUCTIONS

A. How significant are the emissions targeted by the regulation?

Off-road vehicles are a significant source of diesel particulate matter, as well as NOx emissions that lead to ozone and ambient PM. Statewide, they are responsible for nearly a quarter of the total PM emissions from mobile diesel sources and nearly a fifth of the total NOx emissions from mobile diesel sources. Although increasingly stringent new engine standards are reducing emissions from off-road diesel vehicles over time, because of their durability, most vehicles operate for several decades before being retired. Thus, in-use off-road diesel vehicles would continue to pose significant health risk for many years if this proposed regulation is not adopted. As discussed further below, without reductions from this large source category, the South Coast and San Joaquin Valley would be unable to attain the federal ambient air quality standards.

The regulation is projected to affect approximately 180,000 vehicles (year 2005 population), which currently emit about 386 tons per day of NOx emissions and 23 tons per day of PM emissions. Figure II-1 shows the statewide trend in diesel PM and NOx emissions that would be expected without the regulation. As can be seen, emissions would trend naturally down as the fleet gradually turned over to newer, cleaner engines. However, these reductions are not sufficient for many areas of the state to meet clean air standards. Because of this, the proposed regulation accelerates this anticipated reduction in emissions.

Figure II-1 – Statewide PM and NOx Emissions from In-Use Off-Road Diesel Vehicles without Regulation



In-use off-road diesel vehicles covered by the regulation are significant contributors to the State's total diesel mobile source emissions of PM and NOx. As Figure II-2 shows,

in 2005, off-road diesel vehicles were responsible for 24 percent of the total statewide diesel mobile source PM emissions, and 19 percent of the total statewide diesel mobile source NOx emissions.

As Figure II-3 shows, in 2020, without the regulation, the vehicles would still be responsible for 20 percent of total statewide diesel mobile source PM emissions and 19 percent of total statewide diesel mobile source NOx emissions.

Figure II-2 - In-Use Off-road Diesel Vehicle Contribution to Statewide PM and NOx Inventory- 2005[1]

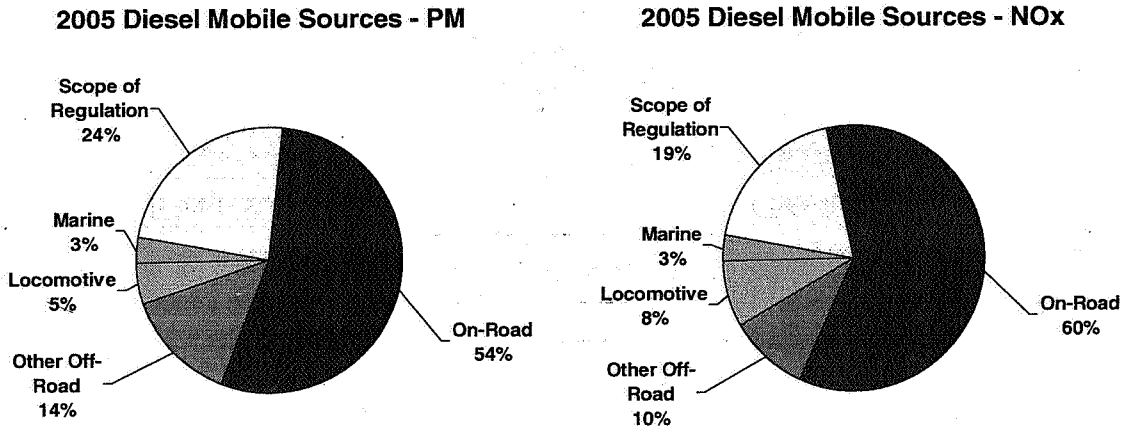
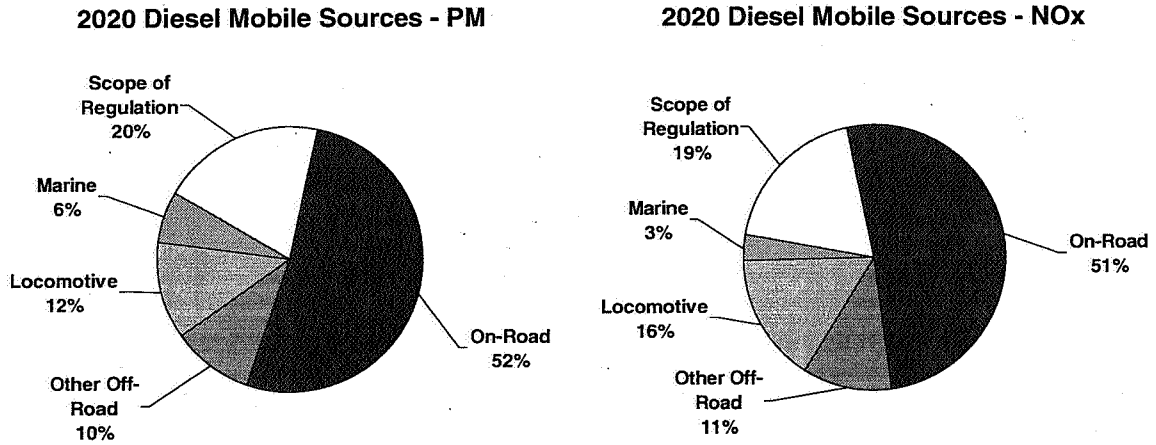


Figure II-3 - In-Use Off-road Diesel Vehicle Contribution to Statewide PM and NOx Inventory - 2020, Without Regulation



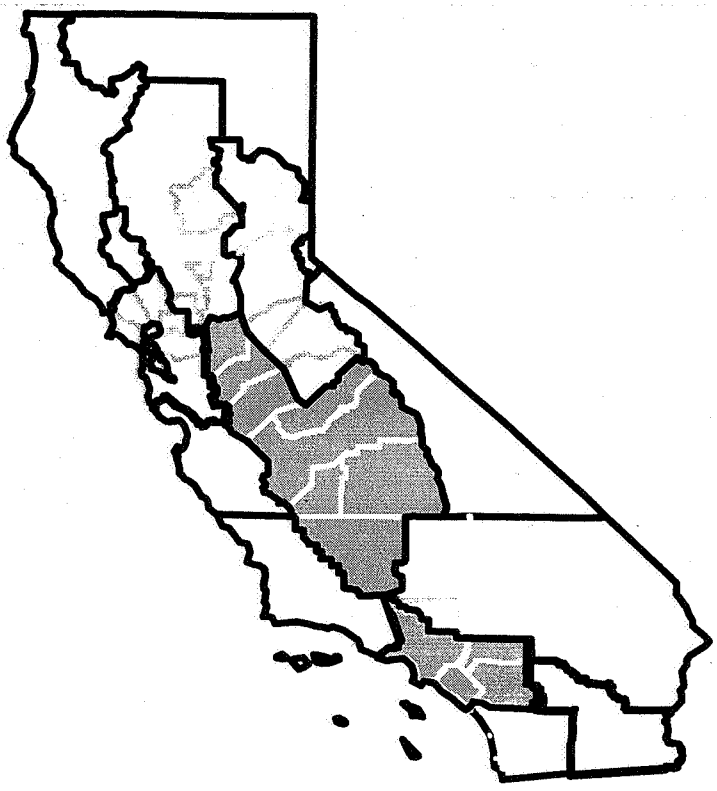
[1] Emissions from in-use off-road diesel vehicles covered by the proposed rule are labeled "Scope of Regulation." Other off-road sources are labeled "Other Off-road."

B. Why are diesel particulate matter emission reductions needed?

In 1998, following the ARB's identification of diesel PM as a toxic air contaminant (TAC), California embarked on an ambitious strategy to reduce emissions from diesel-fueled engines. The Diesel Risk Reduction Plan (DRRP), adopted by the Board in October 2000, outlined steps to reduce diesel emissions and associated potential cancer risks by 75 percent in 2010 and by 85 percent by 2020. Because of the potency and the large amount of emissions to California's air, diesel PM is the primary contributor to adverse health impacts, including an estimated 70 percent of all cancer risks, from TACs. The proposed regulation would achieve the emission reduction goals of the DRRP for off-road vehicles subject to the regulation.

PM emission reductions are also needed because diesel particulate matter contributes to ambient concentrations of fine particulate matter (PM2.5). Ambient PM2.5 is associated with premature mortality, aggravation of respiratory and cardiovascular disease, asthma exacerbation, chronic and acute bronchitis and reductions in lung function.

Figure II-4 - Areas of California that Exceed the Federal Annual PM2.5 Standard



Under the federal Clean Air Act (CAA), the U.S. Environmental Protection Agency (U.S. EPA) has established National Ambient Air Quality Standards (NAAQS) for pollutants considered harmful to public health, including PM2.5. Set to protect public health, the NAAQS are adopted based on a review of health studies by experts and a public

process. Areas in the State that exceed the NAAQS are required by federal law to develop State Implementation Plans (SIPs) describing how they would attain the standards by certain deadlines. Figure II-4 shows the areas of California that exceed the federal PM2.5 standard.

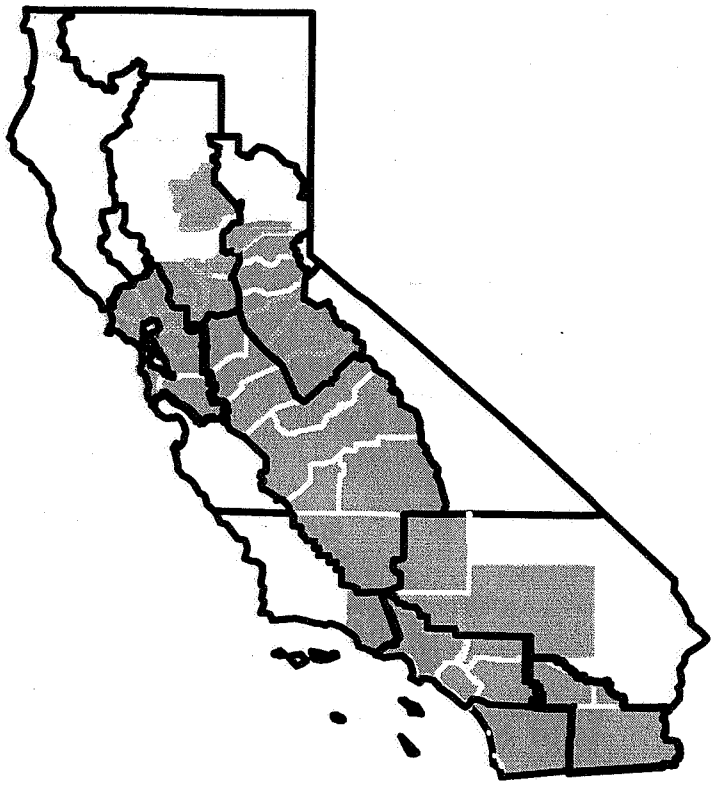
Neither the South Coast nor the San Joaquin Valley is in attainment for the PM2.5 NAAQS. Under the federal CAA, both are required to attain the PM2.5 standard by 2015, and the PM2.5 SIPs are due to U.S. EPA by April 2008. In addition to reductions in directly emitted diesel PM, these areas must achieve significant NOx reductions (NOx is a precursor to PM in the atmosphere) from the off-road sector to achieve the ambient PM2.5 standard by the federally-mandated deadlines. Staff expect that despite a comprehensive effort to achieve reductions from all possible sources to meet the PM2.5 standard, California may still come up short of achieving the needed emission reductions by the 2015 attainment deadline. Because the standard is an annual average, the U.S. EPA requires that all necessary emission reductions be achieved one calendar year sooner, or by 2014. While all sources of NOx emissions are important, off-road diesel vehicles are one of four major categories that will determine whether California is able to meet the 2014 deadline for PM2.5 attainment in the South Coast Air Basin. If the emissions reductions needed to achieve attainment of the federal standards cannot be demonstrated, the Board may need to consider additional measures or changes. However, staff believes the proposed regulation represents the economic limit of what industry could bear, and any further emissions reduction requirements would likely require financial incentives.

C. Why are oxides of nitrogen emission reductions needed?

NOx emission reductions are needed because NOx leads to formation in the atmosphere of ozone and PM2.5. Ozone is a powerful oxidant, and exposure to ozone can result in reduced lung function, increased respiratory symptoms, increased airway hyper-reactivity, and increased airway inflammation. Exposure to ozone is also associated with premature death, hospitalization for cardiopulmonary causes, and emergency room visits for asthma. Because of these health effects, U.S. EPA has established 8-hour NAAQS for ozone.

Figure II-5 shows the areas of California that exceed the federal 8-hour ozone standard. Most areas of the State, and in fact the places where most people live, exceed the federal 8-hour ozone standard. Requirements for attainment of the federal 8-hour ozone standard begin in some areas of the state as early as 2007. Currently, the South Coast's and San Joaquin Valley's deadlines for ozone attainment are 2021 and 2013, respectively.

Figure II-5 - Areas in California that Exceed the Federal 8-Hour Ozone Standard



The ozone SIP and PM2.5 SIPs are due to the U.S. EPA by June 2007 and April 2008, respectively and must necessarily include significant NOx reductions. The magnitude of emission reductions is large and represents an estimated 60 percent reduction in NOx emissions from 2006 levels (i.e., a total reduction of hundreds of tons per day) – and the time frame short to attain NAAQS in South Coast and San Joaquin Valley. The extremely large emission reductions needed in the South Coast and San Joaquin Valley drive the need for NOx reductions from this regulation.

D. What health impacts are occurring today due to the emissions from affected vehicles?

Table II-1 below summarizes the adverse health impacts occurring today from the current population of off-road diesel vehicles that would be covered by the proposed regulation. Staff estimates that approximately 1,100 premature deaths were associated with the baseline uncontrolled emissions from in-use off-road diesel vehicles in year 2005. The health impacts include direct effects from diesel particulate matter as well as effects from secondary pollutants such as nitrate particles.

Table II-1 - Health Impacts from Baseline Emissions of In-Use Off-road Diesel Vehicles Covered By Regulation (2005)[2]

Endpoint	Pollutant	# of Cases (Mean)	# of Cases 95% Confidence Intervals (Low - High)
Premature Mortality	NOx	450	120-770
	PM	690	190-1,200
	Total	1,100	310-1,900
Hospital admissions (Respiratory)	NOx	100	60-130
	PM	150	90-200
	Total	240	150-330
Hospital admissions (Cardiovascular)	NOx	180	110-270
	PM	270	170-420
	Total	440	280-690
Asthma & Lower Respiratory Symptoms	NOx.	13,000	5,000-20,000
	PM	19,000	7,400-31,000
	Total	32,000	12,000-51,000
Acute Bronchitis	NOx	1,100	0-2,300
	PM	1,600	0-3,500
	Total	2,600	0-5,700
Work Loss Days	NOx	77,000	65,000-89,000
	PM	120,000	100,000-140,000
	Total	190,000	170,000-220,000
Minor Restricted Activity Days	NOx	440,000	360,000-520,000
	PM	680,000	550,000-800,000
	Total	1,100,000	920,000-1,300,000

The health impacts from in-use off-road diesel vehicles are significant. To put the magnitude of impact in context, off-road diesel vehicles covered by the proposed regulation are equivalent to nearly one third of the number of deaths due to environmental tobacco smoke (secondhand smoke) and one fourth the number of deaths due to motor vehicle accidents. Secondhand smoke is estimated to cause to 4,021 premature deaths per year in California (ARB, 2006), while motor vehicle accidents killed 4,329 people in California in 2005 (NCSA, 2005).

E. What cancer risk would be expected from a typical large construction project and how would this regulation reduce this?

To evaluate the magnitude of risk to receptors from exposure to nearby construction sites, staff performed a risk assessment for a typical large two-year long construction project. This methodology is commonly used as a tool to estimate risk, from a generic

[2] Table includes indirect health impacts from NOx formation of secondary particulate as well as direct health impacts from PM. Table does not include indirect health impacts from NOx formation of ozone.

perspective, from a particular activity. The results from this assessment can then be overlaid on an actual population (i.e., those living near a potential construction site), to quantify risk from an actual project. Because staff's assessment was generic in nature, an actual number of affected individuals cannot be quantified, as any estimate would vary based on local population density (i.e., the more people near the site, the greater number of affected individuals.)

To get an upper end (conservative) estimate of possible risk, staff assumed all vehicles operating at the site were old and dirty (i.e., Tier 0 or uncontrolled). Staff estimated the risk to nearby receptors under various meteorological conditions. The analysis showed that cancer risks from such a project were not insignificant, but were much less than other large point sources that have been evaluated such as ports, rail yards, and distribution centers.

Even under the most unfavorable meteorological conditions modeled (i.e., those most conducive to elevated risk), the construction project would generate risks greater than 10 in a million for an area of only 26 acres surrounding the project. The actual numbers of affected individuals would depend on the population around a specific project. A cancer risk of 10 in a million is the most commonly used threshold above which facilities are required by the Air Toxics Hot Spots Information and Assessment Act to notify all exposed persons (ARB, 2005b). By comparison, the combined risk from the Ports of Long Beach and Los Angeles is estimated to subject an area of over 163,000 acres and over 2,000,000 people to a cancer risk of over 10 in a million, with 2,500 acres and 53,000 people subject to much higher risks of over 500 in a million (ARB, 2005c).

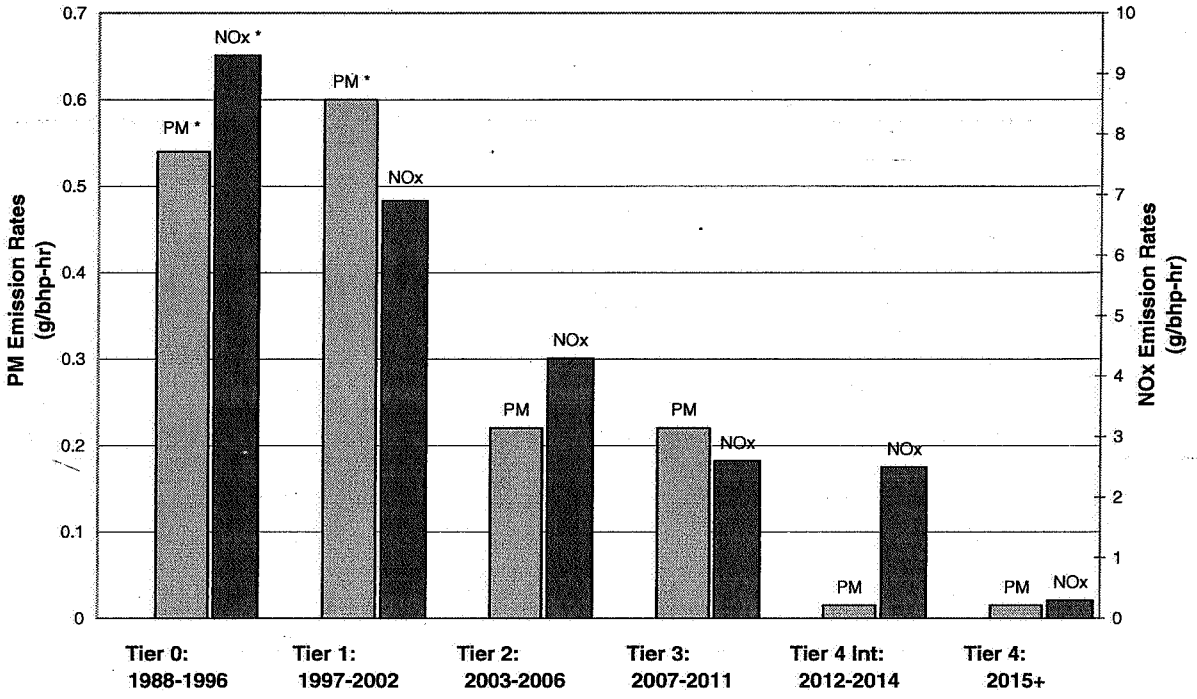
As the proposed regulation is implemented, the statewide construction fleet would become dramatically cleaner and staff's modeling indicates that the associated cancer risk from these types of construction projects would drop significantly.

F. What new engine emission standards apply to vehicles covered by the proposed regulation?

Since the mid 1990's, new engine standards adopted by U.S. EPA and ARB have required new off-road engines to become progressively cleaner. In developing the new engine standards, staff has worked closely with U.S. EPA to develop a harmonized federal and California program to more effectively control emissions from off-road vehicles. The emission standards are divided into four increasingly stringent levels (Tiers); the allowed emission level and effective dates vary with horsepower. Until the mid-1990s, off-road diesel engines were not subject to any emission standards (commonly known as Tier 0 or "uncontrolled"). In 1996 through 2000, the Tier 1 standards took effect. By 2006, all engine sizes were subject to Tier 2. Between 2006 and 2008, Tier 3 standards took effect for some horsepower groups. Tier 4 standards are divided into two stages: interim, which begins between 2008 and 2012 for most engines, and final, which is effective for all off-road engines by 2015. The final Tier 4 standards will require the use of advanced exhaust after-treatment technologies to control both PM and NOx, and will result in diesel engines that will be over 90 percent cleaner than Tier 0 engines. Figure II-6 illustrates how these standards change over time for one horsepower group, 100 to 174 horsepower engines. The numerical

standards vary by horsepower group, but the downward trend is the same for all horsepower groups.

Figure II-6 - ARB and U.S. EPA Diesel PM and NOx Emission Standards for New Off-road Engines 100 to 174 Horsepower



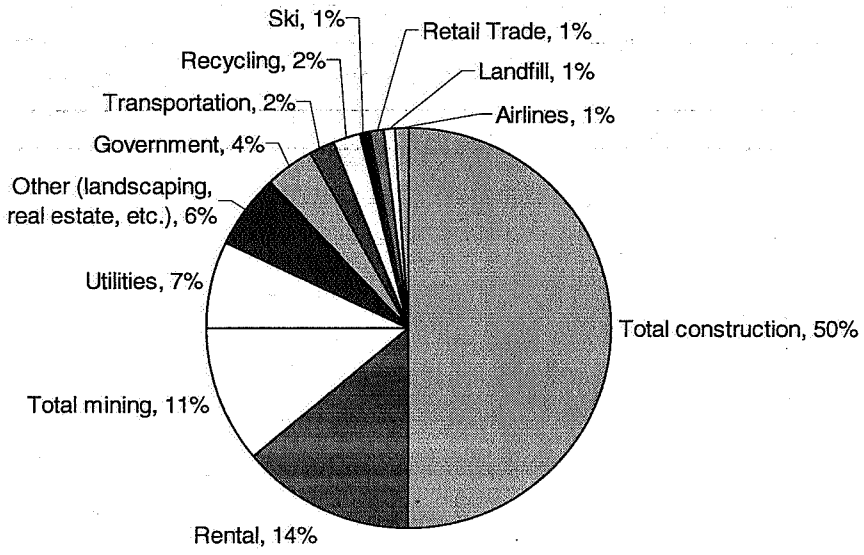
* - Estimated emission rate is shown because standards did not exist for this pollutant at that time.

III. AFFECTED INDUSTRIES AND VEHICLES

A. What industries and types of fleets would be affected by the proposed regulation?

The regulation would affect nearly all public and private fleets of off-road diesel vehicles operating in California. Industries such as construction, mining, landscaping, airlines, retail, wholesale, equipment rental, ski, oil and gas drilling, recycling, utilities, telephone and cable, and many others would be subject to the regulation. Government agencies engaged in road maintenance, park maintenance, and other activities would also be affected. Figure III-1 shows the distribution of fleet types, according to results from the 2005 ARB Off-road Equipment Survey.

Figure III-1 - Fleet Types Subject to the In-Use Off-road Diesel Vehicle Regulation (Percent of Vehicles Affected)



Construction vehicles make up roughly half of the vehicles affected by this regulation. A wide variety of construction vehicles, commonly ranging from 25 hp to 600 hp, are utilized during the various stages of different construction projects, which include tasks such as demolition, grubbing and clearing, dewatering, earthwork (excavation), grading, paving/surfacing, foundation work, building erection and other infrastructure developments. Vehicles used in construction range from production machines like large scrapers, which commonly have high utilization and are the primary source of income, to support or specialty vehicles like specialty paving equipment that are not highly utilized but are necessary to perform individual projects. Construction businesses range from owner operators and independent small contractor businesses with one vehicle to extremely large fleets with hundreds of vehicles and thousands of employees. There are also thousands of smaller subcontractors who most commonly perform somewhat

specialized work to support large projects led by larger contractors. In total, construction firms currently employ about 942,000 people in California and construction employment has been growing in recent years at about 0.5 percent per year (EDD, 2007). In 2006, building permits were issued for approximately 60 billion dollars in residential and nonresidential construction in California (DOF, 2007a).

Just fewer than 15 percent of the vehicles covered by the regulation are owned by rental companies. Rental companies tend to operate newer vehicles and provide individual consumers and contractors with the temporary use, on a fee basis, of a wide range of products and goods, including general construction, heavy vehicles, tools, and light equipment. In 2006, the rental industry generated revenues in California of an estimated $6.3 billion (American Rental Association, 2007).

Mining fleets make up a little over 10 percent of the vehicles covered by the regulation. The mining category represents about 1,000 active mines in California. The most common type of mining performed in California is open pit mining, which has activities similar to the earthwork and grading aspects of construction. Vehicles used in open pit mining typically include a broad a range of vehicles ranging from small horsepower vehicles up to the largest vehicles manufactured, with the largest vehicles typically having horsepower ranging from about 500 to several thousand horsepower. These high horsepower vehicles include trucks, loaders, and heavy shovels. Smaller vehicles, such as smaller loaders, graders and drill rigs, range from 150 hp to 500 hp and provide support and production functions. Mines often also have a limited number of small support vehicles with engines as small as 30 to 40 horsepower. Mining operations in California are varied, with operations ranging from fleets with a handful of vehicles at a single mine employing dozens of employees operating one shift a day to those operating hundreds of vehicles and employing hundreds of employees around the clock at numerous mines throughout the state.

The industrial sector includes thousands of manufacturing facilities and wholesale and retail distribution points throughout the state where forklifts, cranes and other tractors are used to facilitate manufacturing and to distribute raw materials and finished product. This sector includes a wide variety of business types, including ski resorts, recycling facilities, landfills, refineries, power plants, retail goods, wholesale good, utility services, golf courses, sewage treatment plants, landscape materials, factories and many other business types.

About one percent of affected vehicles are airport ground support equipment (GSE). Airport GSE vehicles perform a variety of functions, including but not limited to: aircraft maintenance, pushing or towing aircraft, transporting cargo to and from aircraft, loading cargo, and baggage handling. GSE vehicles include equipment types such as baggage tugs, belt loaders, and cargo loaders. Some airlines own and operate their own GSE, while others hire fixed base operators to service their aircraft. The largest airline fleets of GSE have several hundred vehicles spread across a number of airports.

B. How many and what types of vehicles are subject to the regulation?

Staff estimates that about 180,000 vehicles currently in use would be subject to the proposed regulation. Staff worked closely with stakeholders and gathered all publicly available information to update and refine estimates of off-road vehicle populations, their characteristics, and their expected lifetimes. The information gathered was incorporated into ARB's OFFROAD2007 model to estimate the number, types, and ages of vehicles affected by the regulation. Further detail on the sources of data used to develop staff's inventory estimates is included in the Technical Support Document.

The off-road diesel-powered mobile vehicles that would be subject to the requirements of this regulation are diverse. From off-road vehicles with engines as small as 25 hp to those with engines bigger than 2,500 hp, the regulation would affect any mobile (i.e., self-propelled) diesel-fueled vehicle that cannot be registered and licensed to drive on-road in California. The regulation would also cover workover rigs. Some examples of vehicle types affected include backhoes, dozers, loaders, trenchers, scrapers, forklifts, snow cats, baggage tugs, cargo loaders, belt loaders, and aircraft tractors. Table III-1 below shows the five most populous types of vehicles affected by the regulation.

Table III-1 - Top 5 Types of Vehicles Affected by In-Use Off-road Diesel Vehicle Regulation

Vehicle Category	2005 Population
Tractors/Loaders/Backhoes	30,665
Skid Steer Loaders	29,138
Rubber Tired Loaders	19,580
Excavators	19,354
Crawler Tractors	16,130

Figure III-2 shows the emission standard tier distribution of vehicles covered by the regulation. Over half of the vehicles are Tier 0 (i.e., uncertified engines), the newest of which were produced in 1999.

The majority of vehicles affected are relatively old. Figure III-3 shows the distribution of vehicles subject to the proposed regulation by age. The average age of affected vehicles in the State are about 10 years old, and nearly all vehicles are less than 40 years old, although some are much older.

Figure III-2 – Statewide Engine Tier Distribution of Vehicle Population Subject to Regulation (2005)

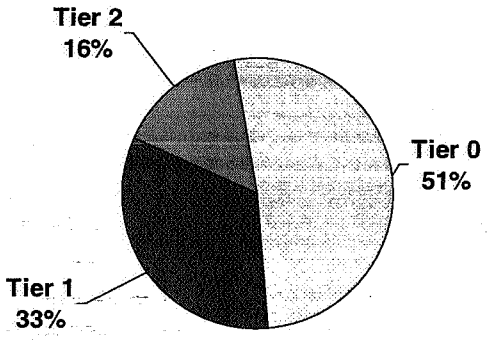
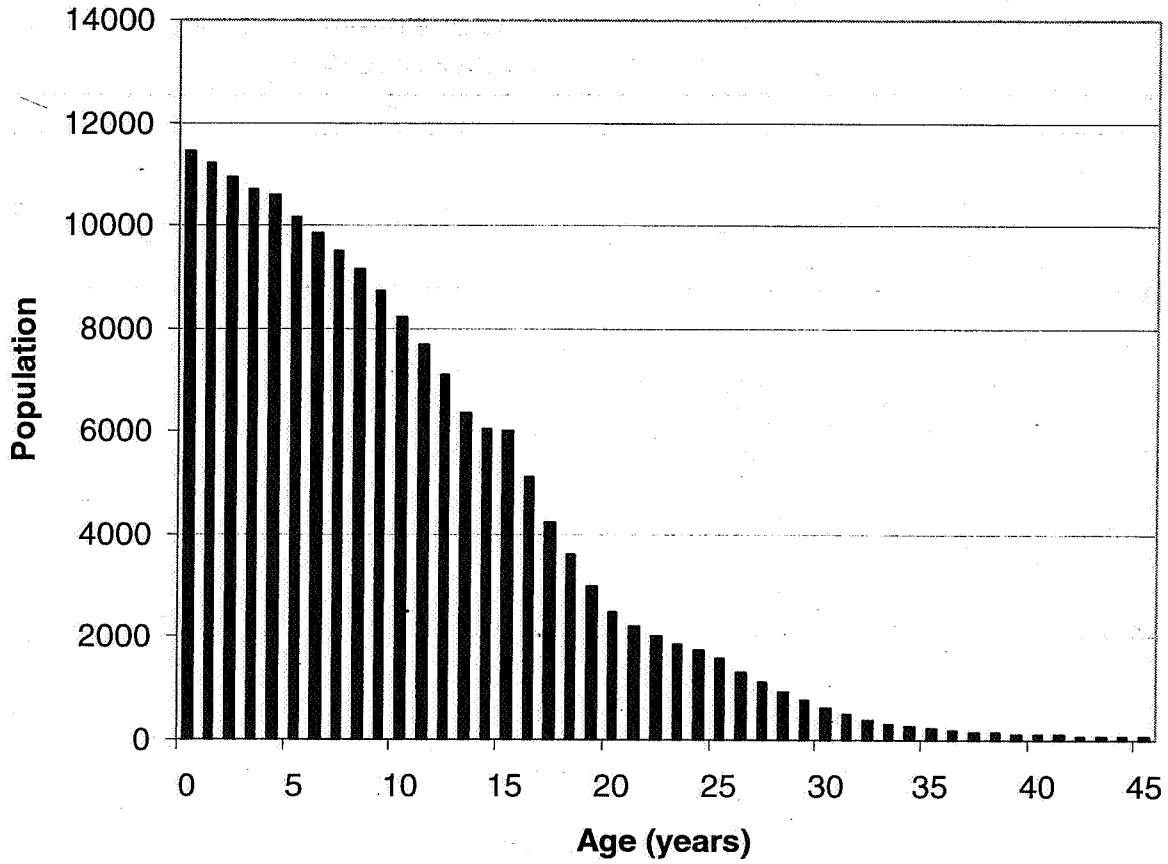


Figure III-3 - In-Use Off-road Diesel Vehicle Population by Age (2005)[3]



[3] Figure III-3 represents vehicles from 0 to 45 years old in 2005. There are an additional about 400 vehicles or 0.2% of the population that are between 46 and 76 years old not represented in the graph.

IV. DESCRIPTION OF REGULATION

A. What would the proposed regulation require?

The proposed regulation is included in Appendix A and contains different requirements for fleets of differing sizes, with the strictest provisions applying to the largest fleets. The regulation divides fleets into one of three categories, based on total horsepower of the affected vehicles and the type of owner. The fleet size definitions are summarized in Table IV-1 below.

Table IV-1 - Fleet Size Definitions

Fleet Size	Owner	Total Horsepower[4]
Small	Municipality	Less than or equal to 1,500 hp
	Small business (as defined in California Government Code 11342.610)	Less than or equal to 1,500 hp
	Municipality fleet in a low-population county	Any
Medium	Municipality	1,501 to 5,000 hp
	Business	Less than or equal to 5,000 hp and does not meet small fleet definition
Large	Municipality	Greater than 5,000 hp
	Business	Greater than 5,000 hp
	State and federal government fleets	Any

The regulation would establish the same fleet average emission rate targets for PM and NOx for medium and large fleets. The PM targets are delayed for five years for small fleets. Figure IV-1 depicts the large and medium fleet average targets for PM, compared to the overall fleet average emission rate expected for the California fleet in the absence of the regulation. Similarly, Figure IV-2 depicts the large and medium fleet NOx targets for the statewide fleet as a whole versus the overall fleet average emission rate expected in the absence of the regulation. Note that medium fleets would not be subject to the targets until 2013. The fleet average targets would drive fleets to clean up their fleets faster than natural turnover would. Figure IV-1 and Figure IV-2 are based on the horsepower distribution in the statewide fleet. Each individual fleet's emission targets would vary depending on the distribution of horsepower in their fleet.

[4] The sum of horsepower of all affected vehicles is used to determine the fleet size. Low-use vehicles (those that operate less than 100 hours per year) need not be included in the sum. All State and federal government fleets are considered large, regardless of total horsepower.

Figure IV-1 - Large and Medium PM Targets Versus Baseline PM Average for California Fleet as a Whole

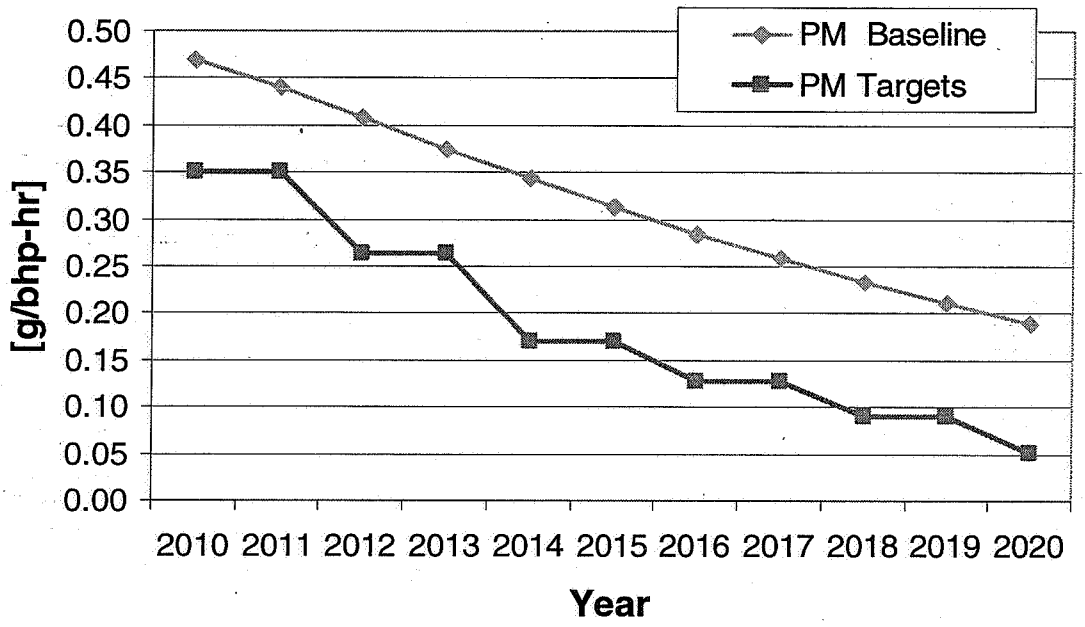
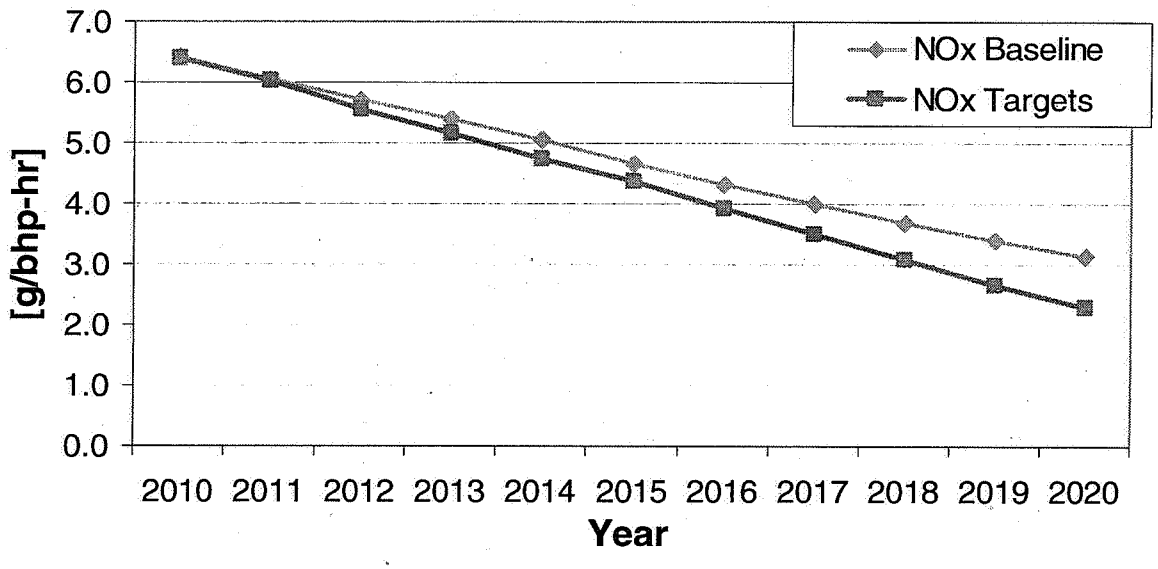


Figure IV-2 - Large and Medium NOx Targets Versus Baseline NOx Average for California Fleet as a Whole



Each year, fleets would have the option of satisfying either the fleet average requirements or the Best Available Control Technology (BACT) retrofit and/or turnover requirements. Satisfying either is an acceptable way to demonstrate compliance with the regulation.

Each year, all fleets would be required to demonstrate their fleet meets the fleet average emission rate targets for PM or to apply the highest level verified diesel emission control system (VDECS) to 20 percent of the horsepower in their fleets. The highest level VDECS would only be required if a system has been verified by ARB to be effective and durable for the engine on which it would be installed, and if the system can be used safely. The ARB's verification program, previously adopted by the Board, is intended to ensure that a device achieves the advertised emission reductions and has been evaluated for durability. Also, to receive ARB verification, the device manufacturer is required to warrant the VDECS and the engine against any damage caused by the device.

Each year, large and medium fleets would also be required to demonstrate that they meet the fleet average emission rate targets for NOx or have turned over a certain percent of the horsepower in their fleet (8 percent in early years, and 10 percent in later years). If retrofits that reduce NOx emissions become available and verified, they may be used in lieu of turnover.

The targets would decline over time, and would require fleets to reduce their emissions as time goes on. To meet the PM or NOx fleet averages, fleets may retrofit their vehicles' exhaust systems with verified emission control devices to reduce PM and/or NOx emissions, replace the engines in existing vehicles with cleaner engines (i.e., repower), retire high-emitting vehicles, and/or designate high-emitting vehicles as low-use vehicles. If retrofits that reduce NOx emissions become available, they may be used to lower NOx emissions in lieu of turnover as long as they achieve the same emission benefits.

Finally, the regulation would require that operators of off-road diesel vehicles shut down their vehicles rather than idle for more than 5 minutes, unless such idling is necessary for the proper or safe operation of the vehicle.

B. What are the reporting and recordkeeping requirements?

All fleets would be required to report their affected vehicles and associated engine and retrofit data to ARB beginning in 2009. Then, annually thereafter, fleets would need to report any changes made in the prior year. Fleets would also be required to label all affected vehicles with a unique equipment identification number (EIN) assigned by ARB. The EIN stays with the vehicle even if it is sold to a new owner, just like a license plate number for an on-road vehicle.

When vehicles are purchased or brought into the State, the owner would have 30 days from the date of purchase or entry to inform ARB of the purchase and apply to ARB for an EIN.

Fleets would be required to keep records of all data reported, as well as any changes made since their last reporting, until 2030, or as long as the owner still owns the fleet. Fleets would be required to provide the records to ARB within five business days upon request.

C. Would the regulation apply to out-of-state companies?

The regulation would apply to any affected vehicles being operated in California, whether they belong to government agencies, companies based inside California, or companies based outside the state. If they maintain fleets in California, out-of-state companies must meet the fleet requirements and abide by the idling limits just like any other fleet.

Out-of state companies that bring affected vehicles to California would have to report and label the vehicles. Vehicles brought into California must be reported to ARB within 30 days. If the vehicle does not have an EIN, ARB would assign one. The owner has 30 days upon receipt of the EIN to label the vehicle.

If a vehicle brought in from out-of-state is used less than 100 hours per year in California, it would qualify as low-use. However, if an owner wants to claim a vehicle that is used both inside and outside California as low-use, the owner would have to submit a log to ARB showing the date and hour meter reading upon entry to California and the date and hour meter reading upon exit.

Out-of-state companies that bring vehicles to California for the first time after March 1, 2009, must meet the fleet average requirements within three months of bringing vehicles to California. Such out-of-state fleets do not have the option of complying with the BACT mandatory retrofit and turnover requirements.

D. Would farmers, ranchers, and loggers be affected?

Vehicles used for over half their annual operating hours in agricultural operations are not covered by the regulation. Off-road diesel vehicles used in agricultural operations are expected to be covered by a future control measure. Agricultural operations include the growing or harvesting of crops (including forest operations), the raising of fowl or animals, as well as agricultural crop preparation services such as cotton gins, nut hullers and processors, dehydrators, and feed and grain mills.

E. Why is the regulation more stringent for larger fleets?

Staff proposed an earlier initial compliance deadline for the largest fleets because staff believes the largest fleets have the resources to understand and comply rapidly with the regulation. The larger fleets, with their economies of scale, greater revenue streams, and greater access to financing, are more likely to be able to absorb or pass through the cost of the regulation without major disruption. Finally, enforcing the regulation early in the implementation process for just the relatively few largest fleets would present less of a challenge than enforcing the regulation for the very numerous smallest fleets. In

these first years of implementation, ARB inspectors would have the opportunity to better learn the industry and observe common violations.

Conversely, staff proposed more time to the smallest fleets that are also small businesses, because many of them are one or two-person operations, for whom learning about and understanding the regulation may be a bigger challenge. In addition, smaller fleets would have fewer compliance options to choose from because of the limited number of vehicles they own. That is, larger fleets may be able to select their easiest, lowest cost vehicles to clean up in the early years, thereby giving themselves additional time to find solutions for their more expensive or difficult to control vehicles. Small fleets with only a few vehicles may not have this opportunity.

F. Would there be exemptions from the turnover requirements?

Small fleets (fleets with less than 1,500 total horsepower that are small businesses or municipalities, and municipalities in counties with low populations regardless of total horsepower) would not subject to the NOx fleet average requirements nor the turnover requirements. Similarly, fleets which operate exclusively in areas that are in attainment with the NAAQS for ozone and PM2.5 and do not contribute to downwind violations would also be excluded from the NOx requirements.

For the remaining fleets subject to the turnover requirements, the following vehicles would be exempt from turnover requirements:

- Vehicles less than 10 years old;
- Specialty vehicles if certain criteria are met;
- Engines equipped with the best available PM exhaust retrofit, installed within the past six years; and
- Engines meeting the Tier 4 or interim Tier 4 standards.

Finally, if NOx retrofits become available and verified, they may be used in lieu of the mandatory turnover so long as they achieve equivalent emission reductions.

G. Would there be exemptions from the PM exhaust retrofit requirements?

The following engines would be exempt from exhaust retrofit requirements:

- Engines in vehicles less than 5 years old;
- Engines for which there is no retrofit available or for which the retrofit cannot be safely installed;
- New engines that come with a diesel particulate filter (DPF);
- Engines already retrofit with the best available PM exhaust retrofit that achieves at least 50 percent PM reduction at the time of installation; and
- Engines retrofit with an experimental diesel emission control strategy approved by ARB's Executive Officer.

H. What if a VDECS is not safe for my particular vehicle or vehicle application?

If a fleet owner believes that a retrofit that is verified for a vehicle in his fleet would not be safe to operate, he would be able to apply to ARB with supporting documentation. ARB's Executive Officer may determine that the VDECS would not be appropriate for a certain vehicle or vehicle application because it impairs the safe operation of the vehicle. For example, in some cases VDECS may impair driver visibility, may not be able to be safely mounted without damaging the structural integrity of the vehicle, or may cause other safety concerns. In such a case, the VDECS in question would not be required, even though it might be verified for the particular engine in question.

I. Would there be special provisions for low-use vehicles?

Vehicles used less than 100 hours per year (either in the past year or on average over the past three years) need comply only with the labeling, reporting, and recordkeeping requirements. They do not need to be included when figuring compliance with the fleet average targets, nor do they need to be retrofit or turned over.

J. Would there be special provisions for vehicles used for emergency operations?

Vehicles used solely for emergency operations (for example, for fighting forest fires) would need to comply only with the labeling, reporting, and recordkeeping requirements. They would not need to be included when figuring compliance with the fleet average targets and would not need to be retrofit or turned over. For vehicles used part-time for emergency operations (such as for emergency road repairs or fighting forest fires), hours for emergency use would not need to be included when determining low-use status.

K. What if there are delays in the availability of retrofit systems, repowers, or new vehicles?

The regulation would not penalize fleets for delays in the availability of retrofits, repowers, or new vehicles. As long as the fleet owner orders the required retrofit, repower, or new vehicle at least six months prior to the required compliance date, the fleet owner would be able to count the new retrofit, repowered engine, or new vehicle just as if it had been delivered. The owner would need to place the new equipment or vehicles into operation immediately upon receipt.

The Executive Officer would also be able to grant additional time to fleets or groups of fleets if there were a delay in the availability of interim or final Tier 4 vehicles.

L. The proposed regulation is hard to understand, could it be simplified?

To simplify the regulation would require the removal of many of the elements that provide much of its flexibility, including the fleet average provisions. For a regulation to cover such a diverse and complex set of fleets and to provide the flexibility it needs to address the many situations and special cases that may arise and remain enforceable,

it must be somewhat complex. Situations that may arise, such as addressing fleets that add vehicles, face manufacturer delays, move vehicles in and out of state, apply experimental retrofits, or operate specialty vehicles, must be adequately addressed. Thus, the regulation is by necessity rather long and complex.

Much of the complexity of the regulation stems from its fleet average provisions. The regulation could be simplified, for example, by requiring that all vehicles be retrofit by a certain date, or by requiring phase-out of all engines of a certain tier by a certain date. However, doing so, would sacrifice much of the flexibility that the regulation provides and would result in higher compliance costs for no commensurate emission benefit. Further, for some fleets that specialize in operations with long-lived vehicles, the increased economic burden could be difficult to absorb without severe losses in profitability.

Staff plans to develop and provide fleets with a set of electronic tools for reporting and for determining compliance planning and tracking. Also, fleets who wish to avoid the complexity of the fleet average altogether may instead choose to comply exclusively with the mandatory annual turnover and retrofit provisions. Staff envisions that the electronic reporting system would automatically determine the fleet average and targets for each fleet such that fleets would be aware of whether or not they meet the fleet targets before taking more action than required. Staff also expects to commit significant resources for outreach and education about the regulation to assist fleets in meeting the requirements.

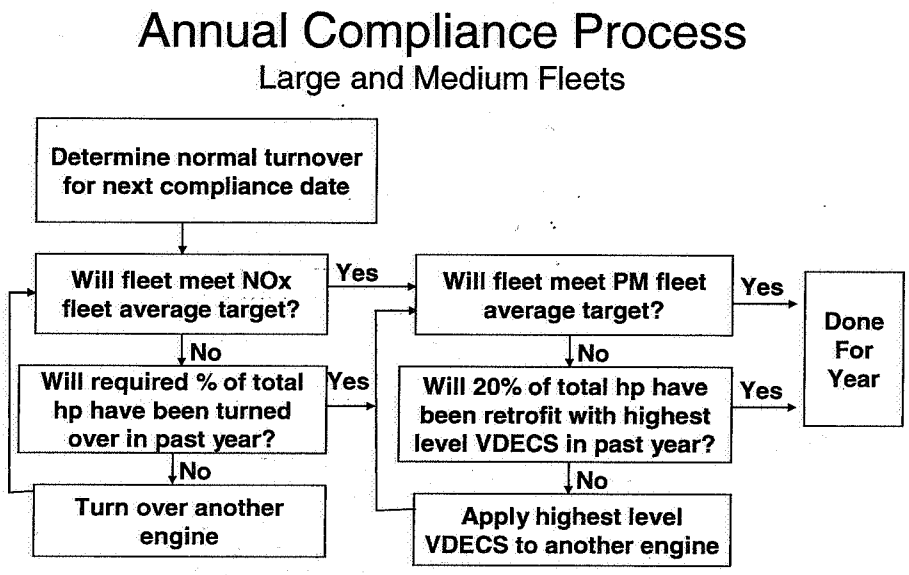
M. What would the regulation actually require fleets to do?

Because of the unique nature of each fleet, the regulation would mean different things for different fleets, depending on their size and on the vintage of their vehicles. For the fleets with the newest vehicles and high natural turnover rates as part of their normal business model, such as some rental fleets, the regulation would impose only labeling, reporting, and recordkeeping requirements.

Figure IV-3 below provides a graphical depiction of the compliance process. Note that large and medium fleets would be required to meet both the NOx and PM elements of the regulation, while small fleets would only have to comply with the PM components.

Small fleets with older vehicles would need to install exhaust retrofits on 20 percent of their horsepower per year beginning in 2014 because it would be unlikely they would be able to meet the PM fleet average. Small fleets with newer vehicles may choose to either voluntarily accelerate turnover of their fleets (for PM reasons only, as they do not need to meet any NOx requirements) enough to meet the PM fleet average targets or to apply some exhaust retrofits.

Figure IV-3 - Compliance Flowchart for Affected Fleets



Note: Turn over means repower with cleaner engine, replace vehicle with used vehicle or new vehicle, designate as low-use, or decrease fleet size. If NOx retrofits become available, they may be used in lieu of turnover.

Medium fleets with the oldest vehicles would need to accelerate turnover of engines to 8 percent of their horsepower per year and install exhaust retrofits on 20 percent of their horsepower per year beginning in 2012. Similarly, large fleets with the oldest vehicles would need to accelerate turnover of engines to 8 percent of their horsepower per year and install exhaust retrofits on 20 percent of their horsepower per year beginning in 2009. In 2015, the oldest large and medium fleets would need to further accelerate turnover to 10 percent of their horsepower per year. These actions would need to continue until the fleet averages are met. If the NOx fleet average is still not met, vehicles that are retrofit early in the implementation period may also need to be turned over once the exhaust retrofits are older than 6 years.

Large and medium fleets with newer vehicles would need to accelerate turnover of their fleets enough to meet the NOx fleet average targets and to apply enough exhaust retrofits to meet the PM fleet average targets. Most likely, such newer fleets would need to do less than 8 percent per year turnover and less than 20 percent per year exhaust retrofits, in the early years.

Also, if NOx exhaust retrofits, such as selective catalytic reduction, become verified and available for off-road diesel vehicles, the regulation would allow fleets to use these retrofits to meet the NOx fleet average targets or in lieu of the mandatory turnover. Staff believes that if such NOx exhaust retrofit technologies become available, they could lower the compliance costs below the estimates provided in this staff report.

N. Would there be special provisions for the areas of the state that meet the federal clean air standards?

Fleets that operate exclusively in counties that attain all the NAAQS and that do not contribute to downwind violations of the federal ozone standard would be exempt from the NOx fleet averages and the mandatory turnover requirements of the regulation. These counties are Alpine, Colusa, Del Norte, Glenn, Humboldt, Lake, Lassen, Mendocino, Modoc, Monterey, Plumas, San Benito, San Luis Obispo, Santa Cruz, Shasta, Sierra, Siskiyou, Trinity, Tehama, and Yuba. Fleets in these counties would still need to meet the PM fleet average or PM exhaust retrofit requirements.

O. Would there be special provisions for the areas of the state that are sparsely populated?

Municipalities in low-population counties (generally those with less than 125,000 people) would be classified as small fleets, would have more time to comply with the PM requirements, and would not be subject to the NOx requirements of the regulation.

P. When would the regulation take effect?

The regulation's idling requirements and restrictions on adding Tier 0 vehicles to fleets would begin in 2009. Initial reporting of fleet information to ARB would also begin in 2009 – with the largest fleets reporting first on May 1, and medium and small fleets having a few additional months to report. The first fleet average compliance dates would be March 1, 2010 for large fleets, March 1, 2013 for medium fleets, and March 1, 2015 for small fleets. The fleet averages would become more stringent over time, declining until 2020 for large and medium fleets, and until 2025 for small fleets.

Q. Would the regulation include special provisions for sensitive receptors?

Sensitive receptors, including such individuals as children, the elderly, and people whose health is already compromised, are particularly susceptible to pollution from diesel vehicles (ARB, 2005d). Staff considered including special requirements in the regulation for off-road vehicles used near sites where such sensitive receptors are likely to be present such as at schools and hospitals, but ultimately decided a fleet-based regulation that cleans up the entire fleet would be preferable for the following reasons:

- As previously discussed, the long term risk from any one construction project is expected to be low and is already subject to an environmental review process. For large public projects and for those that require any kind of public permitting or approval, the California Environmental Quality Act (CEQA) already requires a process by which risks from individual projects are evaluated and mitigated. This provides for project specific mitigation that takes into account local land use (such as how close is the nearest school, day care center, hospital, etc).
- The transient nature of off-road diesel vehicle use makes it more difficult to impose sensitive receptor provisions. Although several of ARB's existing air toxic control measures, such as that for emergency standby diesel generators, contain special requirements for sensitive receptors, the transient nature of off-road diesel vehicles (often used for just a short time and then moved to another

location) makes it much more difficult to incorporate special provisions for sensitive receptors into a statewide rule like that proposed.
- Sensitive receptor provisions would add complexity and make compliance and enforcement much more challenging.

The proposed regulation would require the gradual cleaning up of the statewide fleet of in-use off-road diesel vehicles. As the fleet is cleaned up, and especially as exhaust retrofits that capture toxic diesel PM emissions begin to be installed, the risk to sensitive receptors will decrease, along with the risk to all breathers in California. As discussed below, local agencies and others may wish to take action to further reduce the risk posed by large construction projects.

R. Could local agencies consider additional controls to further reduce the risk posed by large construction projects?

Yes, for large construction projects, local governments, communities, and developers may wish to consider additional requirements to limit the public's exposure to toxic emissions from diesel vehicles. Diesel PM is a carcinogen, and – as such – has no safe threshold below which there is no risk. Local agencies could choose to impose in-use operational controls, such as hours of use restrictions, or could possibly impose additional requirements through the CEQA process for projects that cause significant environmental impacts or through public project contract requirements.

For example, local governments, communities, or developers could adopt to limit construction-related diesel PM exposure to sensitive receptors could include those listed below. Such requirements could be applied to all projects within a certain distance of sensitive sites, or could be limited only to those of a certain duration or that disturb greater than a certain area of soil. The following requirements could be adopted on a project specific basis as mitigation measures as part of the CEQA or National Environmental Policy Act (NEPA) process or built into contract requirements for public projects:

- Limit construction vehicles used near such sensitive sites to vehicles cleaner than a certain tier (Tier 2 or cleaner, for example) and require that all such vehicles be retrofit with the highest level verified diesel emission control system.
- Limit construction to times when sensitive receptors are not present. For example, projects within 500 feet of a school could be limited to non-school hours.
- At a minimum, developers and public agencies that sponsor large construction projects should ensure that any contractors they hire have reported their vehicles to ARB and are in compliance with the proposed regulation.

Local governments could also consider the risk from off-road diesel vehicles when considering approval for construction near where sensitive receptors are likely to be present (i.e., schools, hospitals, housing). Conversely, land use planners may wish to consider the location of existing landfills, recycling centers, and other facilities that require the use of diesel vehicles when siting homes and schools and hospitals.

Several land use handbooks exist to help guide local land use decisions – for example, the *Air Quality and Land Use Handbook* (ARB, 2005d), and the *Guidance Document for Addressing Air Quality Issues in General Plans and Local Planning* (South Coast Air Quality Management District, 2004).

S. Would the regulation give credit to fleets that take early action to reduce their emissions?

The regulation would provide credit for early compliance action in a number of ways. First and foremost, such fleets would start out closer to meeting the fleet average targets and therefore would have less further action to take to reach the targets. Also, fleets that have phased out the dirtiest engines (Tier 0) would not be required to do any mandatory turnover of Tier 1 or newer vehicles until 2013.

Some fleets who took or are taking early action to reduce their emissions still would not meet the fleet average targets in the early years, either because they have longer-lived vehicles or because they started out with an older fleet. The following provisions would provide early action credit to such fleets, for such actions as:

- Early retrofits – Level 2 or 3 retrofits installed before March 1, 2009 may be counted double toward later requirements for mandatory annual retrofit requirements. This double credit for early retrofits would give fleets incentive to install retrofits early and would allow the market to ramp up production and installations of retrofit systems.
- Early repowers - Repowers to Tier 1 or better installed before March 1, 2009 may be counted toward later mandatory turnover requirements.
- Early turnover – Fleets that turned over their Tier 0 vehicles at a rate that was greater than 8 percent per year of their total horsepower between March 1, 2006 and March 1, 2009 may apply to ARB's Executive Officer for credit towards later mandatory turnover requirements.

V. REGULATORY AUTHORITY

A. Does ARB have the authority to adopt and enforce the regulation?

ARB has authority under California law to adopt the proposed regulation. California Health and Safety Code (HSC) sections 43000, 43000.5, 43013(b) and 43018 provide broad authority for ARB to adopt emission standards and other regulations to reduce emissions from new and in-use vehicular and other mobile sources. Under HSC sections 43013(b) and 43018, ARB is directly authorized to adopt emission standards for off-road vehicular sources, as expeditiously as possible, to meet state ambient air quality standards. ARB is further mandated by California law under HSC section 39667 to adopt Air Toxic Control Measures (ATCMs) for new and in-use vehicular sources, including off-road diesel vehicles, for identified TACs, such as diesel PM.

Under federal and California law, ARB is the primary agency in California responsible for making certain that all regions of the State attain and maintain NAAQS. To achieve this, California must adopt all feasible measures to obtain the necessary emission reductions, including measures from mobile sources. The federal CAA preempts states, including California, from adopting requirements for new off-road engines less than 175 horsepower used in farm or construction equipment. However, California may adopt emission standards for in-use off-road engines (federal CAA section 209(e)(2)). Because the proposed regulation addresses in-use rather than new off-road engines, it is permitted by the federal Clean Air Act. For example, turnover of a vehicle is not required until a vehicle is older than 10 years. California must obtain authorization from the Administrator of the U.S. EPA before the in-use emission standards of this proposed regulation become enforceable. Since the proposed regulation is not within the scope of any existing U.S. EPA authorizations, California must obtain a new authorization from U.S. EPA prior to the regulation becoming effective.

VI. EMISSION BENEFITS

A. What would be the emission benefits of the regulation?

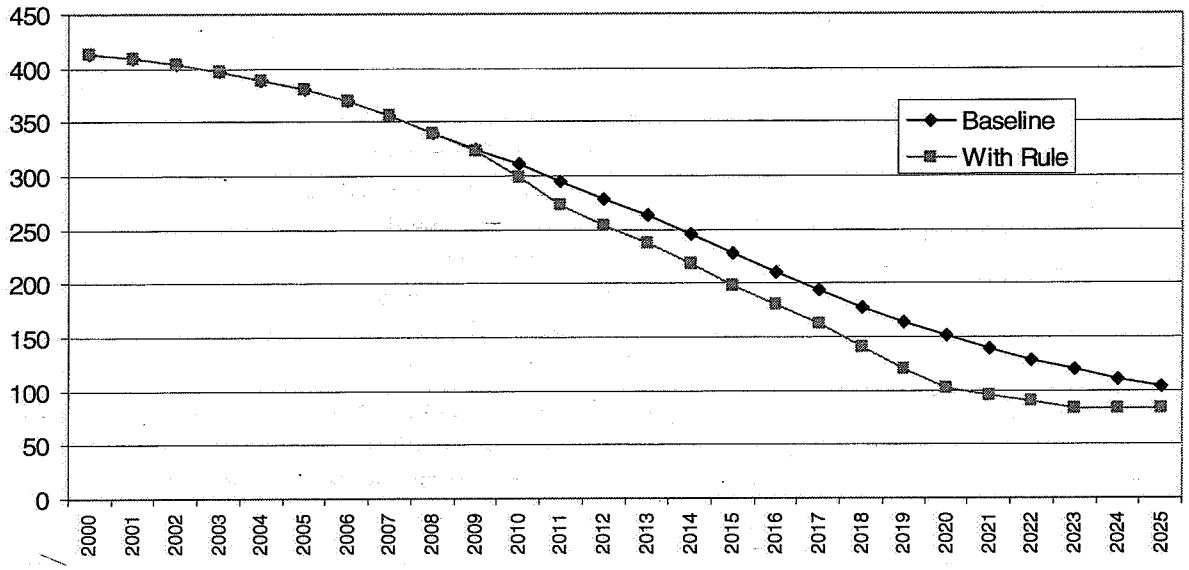
The regulation would be expected to significantly reduce emissions of NOx and PM. The regulation would achieve the 2020 goal of reducing PM 85 percent from 2000 baseline levels set forth in the 2000 Diesel Risk Reduction Plan. The regulation is projected to reduce PM emissions 37 percent from the 2000 baseline by 2010, and 92 percent by 2020. Although NOx and PM emissions are both projected to drop from now through 2020 even in the absence of the regulation, the proposed regulation would accelerate the anticipated emission reductions. For example, the PM emission inventory projected for 2020 with regulation in place would not be reached in the absence of the regulation until after 2025.

As shown in Table VI-1, the regulation would provide significant near- and long-term NOx emission benefits. As shown in Table 4, NOx is expected to be about 13 percent lower in 2015 as a result of the regulation, and by 2020, NOx emissions would be 32 percent lower than would occur in the absence of the regulation. Figure VI-1 below shows the NOx emissions expected with and without the regulation.

Table VI-1- Statewide NOx Emission Reductions from the In-Use Off-road Diesel Vehicle Regulation (tons per day)

Emission Reductions	2010	2015	2020	2025
NOx Without Regulation	311	228	151	103
NOx with Regulation	298	198	103	84
Benefits of Regulation	13	30	48	20
Percent Reduction	4%	13%	32%	19%

Figure VI-1 - Statewide NOx Emissions Inventory With and Without Regulation (tons per day)

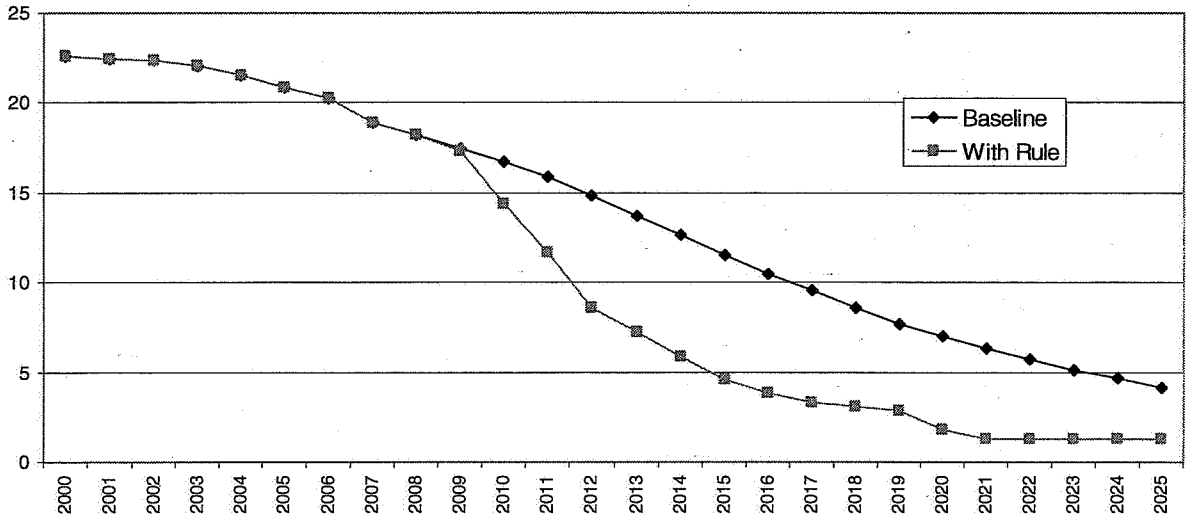


Similar to NOx, significant near-term and long-term PM benefits would be expected from the regulation. As shown in Table VI-2 and depicted graphically in Figure VI-2, PM emissions would be 60 percent lower in 2015, and 69 percent lower in 2020 than they would be in the absence of the regulation. The large reductions prior to 2013 are a result of fleets retiring some of their dirtiest engines and installing PM exhaust retrofits on nearly 20 percent of their hp per year. After 2013, most fleets would meet the PM fleet average targets and would be able to continue to meet subsequent PM averages with engine turnover and a small number of PM exhaust retrofits per year. PM emissions decline again in 2020 and 2021 when all remaining diesel engines that do not have PM exhaust retrofits would be required to have them.

Table VI-2 – Statewide PM Emission Reductions from the In-Use Off-road Diesel Vehicle Regulation (tons per day)

Emission Reductions	2010	2015	2020	2025
PM Without Regulation	16.7	11.5	7.0	4.2
PM With Regulation	14.4	4.6	1.8	1.3
PM Benefits of Regulation	2.3	6.9	5.2	2.9
Percent Reduction	14%	60%	74%	69%

Figure VI-2 - Statewide PM Emissions Inventory With and Without Regulation (tons per day)



The proposed regulation is one of the new measures included in the draft SIP currently being developed by ARB staff. Both the South Coast and San Joaquin Valley must achieve significant NOx reductions to meet the ambient PM2.5 standard by the federally mandated 2015 deadline. U.S. EPA guidelines require that the necessary emission reductions be achieved by 2014 for PM2.5. Significant NOx reductions are also needed by these two regions to meet their ozone attainment deadlines which are currently 2021 for the South Coast and 2013 for the San Joaquin Valley. In light of the magnitude of the NOx reductions needed, these two regions are expected to take the full time allowable, with ozone attainment deadlines as late as 2024 (ARB 2007b). The necessary emission reductions would then have to be achieved by 2023 for ozone attainment.

As shown in Table VI-3, the proposed regulation would reduce annual average NOx emissions from off-road diesel vehicles in the South Coast by about 10 tons per day in 2014 and 13 tons per day in 2023. In 2014, the projected annual average NOx emissions would be about 11 percent lower than would occur in the absence of the regulation, and in 2023, they would be 30 percent below the 2023 baseline emissions. Annual average directly emitted PM2.5 emissions would be decreased by more than 50 percent (or 2.7 tons per day) in 2014 and by over 90 percent (or 1.5 tons per day) in 2023.

Table VI-3 - Projected Emissions Reductions for South Coast

Calendar Year	Annual Average Emissions (tons per day)					
	PM2.5		NOx		ROG	
	Baseline	Reductions	Baseline	Reductions	Baseline	Reductions
2010	6.6	0.9	117	4.8	14.9	1.0
2014	5.0	2.7	93	10.3	12.0	2.5
2020	2.8	2.1	55	17.6	8.5	2.7
2023	2.0	1.5	44	13.1	7.4	1.8

As shown in Table VI-4, the proposed regulation would reduce annual average NOx emissions from off-road diesel vehicles in the San Joaquin Valley by about 3.6 tons per day in 2014 and 5.1 tons per day in 2023. In 2014, the projected annual average NOx emissions would be about 11 percent lower than would occur in the absence of the regulation, and in 2023, they would be 30 percent below the 2023 baseline emissions.

Table VI-4 - Projected Emissions Reductions for San Joaquin Valley

Calendar Year	Annual Average Emissions (tons per day)					
	PM2.5		NOx		ROG	
	Baseline	Reductions	Baseline	Reductions	Baseline	Reductions
2010	2.0	0.3	41	1.7	4.7	0.3
2014	1.5	0.8	33	3.6	3.8	0.8
2020	0.9	0.6	22	6.9	2.9	0.9
2023	0.7	0.5	17	5.1	2.5	0.6

B. What effect would the regulation have on the health of Californians?

The emission reductions obtained from this regulation would result in lower ambient PM levels and reductions of exposure to diesel PM. Staff estimates that approximately 4,000 premature deaths (1,100 – 6,800, 95 percent confidence interval (95% CI)) statewide would be avoided by the year 2030 from the implementation of the proposed regulation. Estimates of other health effects avoided statewide include:

- 840 hospital admissions due to respiratory causes (540 to 1,200, 95% CI)
- 1,600 hospital admissions due to cardiovascular causes (980 to 2,400, 95% CI)
- 110,000 cases of asthma-related and other lower respiratory symptoms (43,000 to 180,000, 95% CI)
- 9,200 cases of acute bronchitis (0 to 20,000, 95% CI)
- 680,000 work loss days (580,000 to 790,000, 95% CI)
- 3,900,000 minor restricted activity days (3,200,000 to 4,600,000, 95% CI)

Benefits from the proposed regulation are substantial. Staff estimates the benefits to be $26 billion using a 3% discount rate or $18 billion using a 7% discount rate. (CARB follows U.S. EPA practice in reporting results using both 3% and 7% discount rates.) Nearly all of the monetized benefits result from avoiding premature death. The estimated benefits from avoided morbidity are less than $400 million with a 3% discount

rate and less than $300 million with a 7% discount rate. Most of the benefits, approximately 85 percent, are associated with reduced diesel PM, and the remaining 15 percent with reduced NOx.

C. What effect would the regulation have on global warming and greenhouse gas emissions?

Although some actions required by the regulation would slightly increase carbon dioxide (CO_2) greenhouse gas emissions because they have a fuel economy penalty impact on fleets, on the whole, staff expects the regulation to result in a negligible effect on global warming. The regulation would push fleets to move from uncontrolled engines to cleaner engines with NOx controls and to apply exhaust retrofits. These cleaner engines and retrofit devices can have a fuel economy penalty as high as two to four percent. When more fuel is burned, more CO_2 is produced, and CO_2 is a greenhouse gas.

The following actions required by the regulation, however, would reduce greenhouse gas emissions and are expected to offset the fuel penalty effects:

- The regulation reduces black carbon emissions, which contribute to global warming.
- The regulation also limits unnecessary idling, which would reduce CO_2 emissions.
- The regulation gives credit for use of electric vehicles, including double credit incentives for the replacement of diesel engines with electric vehicles in early years. While not expected to be widely used in construction, electric vehicles are expected to be used by the airline industry and may have applications in mining as well. On a lifecycle basis, electric vehicles have lower associated CO_2 emissions than diesel vehicles (Delucchi, 2005).

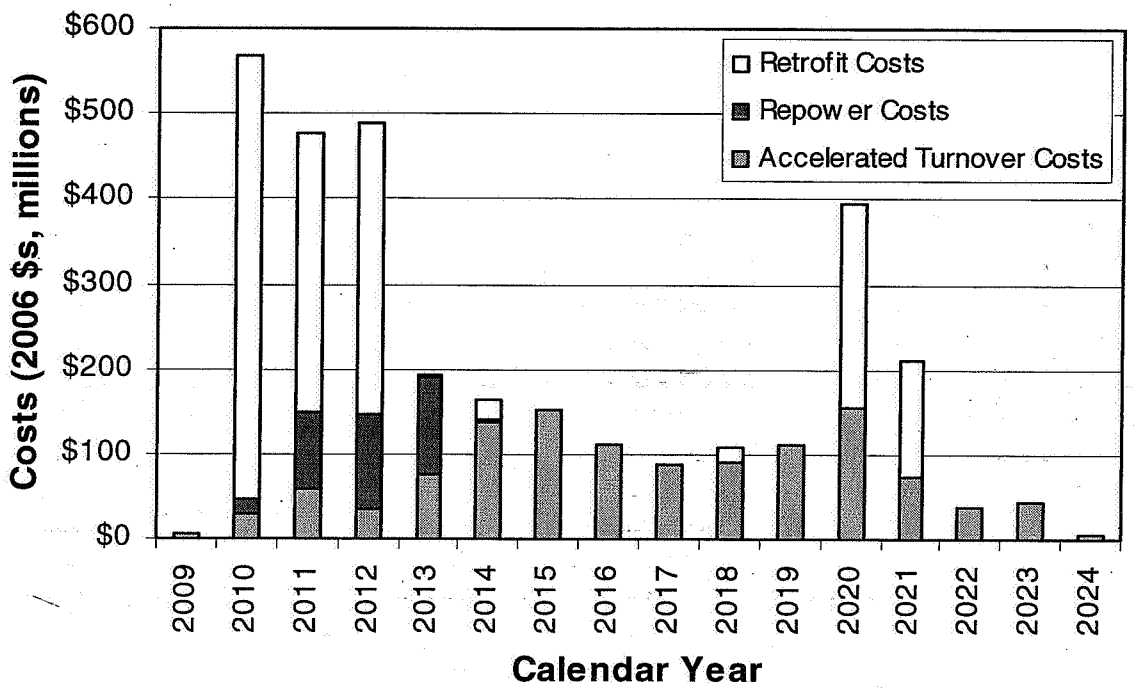
VII. COSTS AND ECONOMIC IMPACTS

A. How much would the regulation cost?

The total statewide cost of the regulation is expected to be significant. The total cumulative cost of the regulation between 2009 and 2030 would be between $3.0 and 3.4 billion (2006 dollars), with the majority of costs these costs occurring between 2010 and 2021. Annually, this would represent $229 million to $257 million per year, averaging $243 million per year (2006 dollars). The total cost includes the expected cost of exhaust retrofit devices and repowers, as well as the cost of accelerating turnover to newer vehicles. No cost savings are included from lower vehicle maintenance costs as a result of operating newer engines or vehicles. Expenditures for new vehicles that would be incurred in the absence of the regulation due to natural turnover (i.e., money that fleets are already spending on new vehicles) over this same period are estimated to be about $16.1 billion ($8.6 billion in 2006 dollars) and would not be attributed to the regulation nor included in these estimates.

Figure VII-1 shows the costs projected for each year, and the portion of cost due to accelerated turnover, engine repowers, and exhaust retrofits (including retrofit maintenance, fuel penalty, etc.) The majority of the regulation's cost - just over half – would be due to costs for exhaust retrofits.

Figure VII-1- Statewide Annual Costs (in millions) from In-Use Off-road Diesel Vehicle Regulation (2006 dollars)[5]



To put the regulatory cost in context, on an annual basis, the cost to the construction industry is less than 0.3 percent per year of the total annual statewide value of construction in California, which in 2006 was about $60 billion (DOF, 2007a), and represents the annual statewide increase in construction costs anticipated as a result of the regulation.

B. How much would the regulation cost fleets?

Costs to fleets would vary depending on the size of each fleet, its initial composition and vehicle age, and its normal purchasing practices. Costs also would vary depending on the compliance strategy chosen by each fleet (retrofit, repower, buy new, and/or buy used). Additionally, there would be ongoing costs for annual reporting and annual maintenance costs for retrofits.

Table VII-1 presents the expected range of costs on a per horsepower basis for small, medium and large fleets based on the average vehicle age at the beginning of the regulation. As Table VII-1 shows, fleets that start out older would face higher per horsepower costs. The youngest, cleanest fleets may only incur additional costs for reporting and recordkeeping. Some fleets may pay up to approximately $170 per hp, depending on their initial composition, vehicle age, and compliance strategy. Some fleets may incur slightly higher costs. Small fleets face the lower average costs than

[5] The costs in this figure do not include reporting costs, which are expected to be about $8 million in 2009 and $2 million per year in subsequent years.

medium and large fleets. Table VII-2 below presents costs for a typical small, medium and large fleet.

Table VII-1 – Expected Total Regulation Cost for Fleets with Various Initial Average Ages (2006 dollars)

Average Fleet Age (years)	Small Fleets ($/hp)	Medium Fleets ($/hp)	Large Fleets ($/hp)
Less than 8	0-50	0-50	0-50
8 to 12	0-110	40-110	40-115
12 to 16	0-110	75-120	75-130
16 to 20	0-150	75-150	110-150
20 and up	0-150	110-150	110-180

Table VII-2 – Expected Annual Cost Due to Regulation for a Typical Medium, and Large Fleet

Fleet Category	Total Fleet Horsepower	Typical $/hp/yr Cost (2006 $s)	Typical Annual Cost ($/yr, 2006 $s)
Small	1,000	$6.0	$6,000
Medium	3,000	$8.9	$27,000
Large	10,000	$8.9	$89,000

C. What would be the impact on small businesses?

The total cost for a small business (i.e., a small fleet) to comply with the regulation would be approximately $73/hp. Of this, $21/hp represents the typical ongoing costs for retrofit maintenance, fuel economy losses, and ongoing reporting costs. A typical small business with 1,000 horsepower could expect the total cost of the regulation over its lifetime to be $73,000 (2006 dollars), with average annual costs of $6,000 per year (2006 dollars) over the years 2009 to 2030.

D. What would be the impact on government agencies?

Two separate economic impacts may apply at the state government level: costs of compliance for state agencies that own affected diesel vehicles and costs for ARB to implement and enforce the regulations. The proposed regulation would not affect federal funding to the state. The total cost to state agencies for compliance would be expected to be between $48 million and $54 million (2006 dollars). Average annual state agency costs for compliance would be about $4 million per year between 2009 and 2030. For a typical state agency fleet, the expected total cost would be about $110/hp. The cost for ARB to implement and enforce the regulation would be expected to be $3 million per year on average for the years 2009 to 2030. Overall, the total costs to State agencies would be approximately $84 to $90 million.

The regulation would also impose costs on local agencies that own affected vehicles. The total cost to local agencies for compliance is expected to be about $100 million (2006 dollars). Total annual costs for all affected agencies are expected to be about $8 million per year. The estimated total cost for local government fleets on a dollar per horsepower basis, is shown in Table VII-3.

Table VII-3 – Expected Total Regulation Cost for Local Government Fleets by Type (2006 Dollars)

Fleet Type	Low Cost (2006 $/hp)	High Cost (2006 $/hp)
Low Population County Local Municipality Fleets	$62	$70
Captive Attainment Area Local Municipality Fleets	$82	$92
All Other Local Government Fleets	$109	$122

E. How significant would the regulation's costs be to fleets, and how would fleets handle the costs?

Staff expects many affected businesses would pass through the regulation's costs to their customers. This could be achieved, for example, through higher bids for construction projects throughout the state, resulting in higher revenue (but not necessarily higher profits) for affected fleets. As previously discussed, the increase in construction costs would be less than 0.3 percent.

Staff believes that most fleets would be able to absorb the costs of the proposed regulation should they not be able to pass costs on to their customers, without significantly harming their profitability. This finding is based on staff's analysis of the estimated change in "return on owner's equity" (ROE) for fleets within each industry type affected by the regulation. A 10 percent decline in ROE has traditionally been used by ARB to indicate a significant impact on profitability. For fleets that do not pass through any of the cost of compliance to their customers, the ROE analysis found that between about 60 and 80 percent of fleets would still be expected to be able to absorb the cost of the regulation without incurring more than a 10 percent change in ROE. Small fleets are more likely to be able to absorb the cost of the regulation without exceeding a 10 percent change in ROE because they are not subject to the regulation's mandatory turnover provisions, resulting in significantly less costs relative to medium and large fleets. For the 20 to 40 percent of fleets for which the regulatory costs exceed a 10 percent change in ROE, these fleets will have to pass through at least some of the costs to their customers in the form of higher prices for their services to maintain their profitability.

Any necessary increases in revenue will be higher for firms where vehicles provide the primary source of income and will be lower where vehicles are used primarily as for

support services. Also, some fleets may find it more difficult to raise revenues if they are competing against competitors who start with cleaner fleets. Such fleets will need to consider other means of managing costs, such as renting or leasing vehicles rather than owning them.

Most construction firms that compete for projects with other construction firms, rental companies, airlines, and landscape services companies are expected to be able to pass on their costs to customers. Rental companies may actually see an increase in revenue as many affected fleets downsize, retire less-used vehicles, and consider rental as a more attractive alternative to owning vehicles.

Municipalities and government fleets would need to absorb the costs as part of their operating budgets and therefore would need to increase operating budgets to cover the cost of the regulation. In addition, some mining and most industrial and manufacturing businesses are not expected to be able to pass on most of the costs incurred by this regulation because they operate in very competitive national markets. However, staff expects that off-road vehicle use in this sector represents a smaller percentage of the company's total operating expense and that the increase in cost attributable to the regulation is only a small portion of the operating expense. Thus, many are expected to be able to absorb the costs without a significant impact on profitability.

Costs for small fleets are generally lower in total than for medium or large fleets, but costs as a percent of revenue are often higher. However, because their initial compliance dates do not begin until 2015, many small fleets would have the opportunity to pursue the use of incentive funds, such as those available through the Carl Moyer program to install needed retrofits or repowers early. Also, because small fleets' compliance begins later, their fleets may have naturally turned over and come closer to the targets by 2015. This could offset some or all of the regulation's impact for small fleets.

In addition to the ROE analysis for typical fleets discussed above, staff performed a case study on the economic impacts of the regulation for seven actual California construction fleets who voluntarily shared financial and fleet data with ARB. Staff evaluated the regulatory costs relative to the fleets' financial data to determine the expected economic impact of the regulation on the fleets. It is important to note that the vehicle profiles of these fleets are not representative of the California fleet as a whole, and as such, the regulatory costs to each fleet are unique and different than the statewide average. It is also important to note that staff does not believe these fleets are statistically representative of the economic impacts of the regulation on the California fleet as a whole. Financial and fleet differences between companies (overhead costs, wage scales, type of work, insurance costs, profitability, etc) are great. However, the results show how a handful of actual fleets in the state would be impacted by the proposed regulation.

Staff's analysis of these seven fleets showed that one of the fleets evaluated would be able to absorb the cost of the regulation no noticeable impact on their profitability (i.e., compliance costs would reduce the profitability less than 10 percent) and so does not

necessarily need to raise revenues to comply with the regulation. The remaining six fleets would either have to bear significantly lower profits or pass on some of the costs to their customers to increase revenue. In total, for the seven fleets analyzed, the revenue increase needed ranged from none up to 4 percent, with most fleets right in the middle.

The greatest economic impact, as expected, was on the largest fleet with the oldest, most expensive, longest-lived vehicles. This fleet was an earth-moving fleet with all Tier 0 vehicles. For this fleet, staff estimated that the annual cost of the regulation would significantly exceed the company's annual profits. To remain viable, such a heavily impacted fleet would need to pass on most, if not all, of the costs of the regulation to its customers. Staff's analysis showed that the regulation would require an increase in revenues for this fleet of about 2.4 percent to bring the impact of the regulation to less than 10 percent ROE.

F. How would the regulation affect customers?

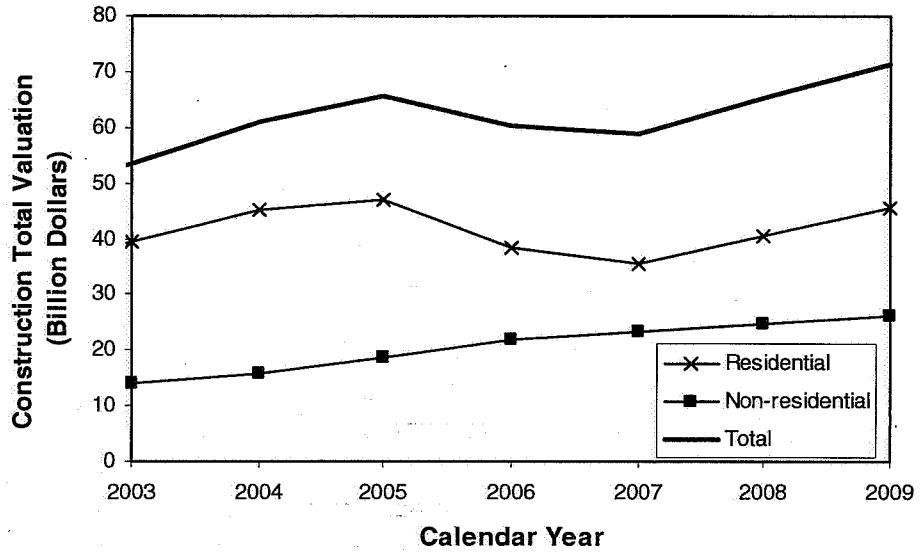
The regulation is expected to increase the cost of construction, mined materials, and other services performed by off-road vehicles in the state. Customers that could expect to pay higher construction costs include developers, home builders, and government agencies sponsoring road construction and other transportation projects. For construction, this increase would be expected to be less than 0.3 percent.

To put this in perspective, the regulation would impact all types of construction, including new housing. Based on the number of housing permits issued each year, and allocating half of the regulatory costs to construction (which is proportional to their representation of horsepower in the statewide fleet), staff estimates that the regulation could increase the cost of a new home by less than $1,000 (which represents about a 0.3 percent increase in price for a median priced home in California). In considering the impact of this on a potential new homebuyer, for a new home purchased with a 30-year mortgage, this cost would represent about a $5 per month increase in the mortgage payment.

G. How would the regulation affect the construction industry?

While the cost of the regulation would be significant to the construction industry, staff does not believe it would impact the ability of the industry to meet the current demand for building projects. As can be seen in Figure 16, construction valuation had been steadily increasing from 2002 until 2006, when a downturn in the residential housing industry reduced this valuation (DOF, 2007a). However, despite the downturn in residential construction, non-residential construction has grown by more than 5 percent per year since 2002 and is projected to increase in the next several years. Between 2007 and 2009, construction valuation is expected to increase over 10 billion dollars, which greatly exceeds the expected cumulative cost of this regulation.

Figure VII-2 - California Construction Valuation



H. How would the regulation impact the value of existing vehicles?

The regulation would tend to decrease the value of older, dirtier vehicles and increase the value of newer, cleaner vehicles. Beginning March 1, 2009, fleets in California would not be permitted to add Tier 0 vehicles to their fleets. After the first fleet average compliance dates, fleets would be restricted from adding vehicles that exceed the fleet targets for engines in the same horsepower group (i.e., they cannot add vehicles that make their fleet dirtier).

However, even with this restriction, the demand in the United States and around the world for used Tier 0 and Tier 1 vehicles would not evaporate. Staff expects that there would be significant continued demand for construction vehicles worldwide such that these older vehicles would retain much of its residual value, less increased transportation costs to destinations outside California.

However, staff cannot predict with certainty the decrease in value of Tier 0 vehicles as a result of the regulation, but for modeling purposes, staff assumed a decrease in value of $10 per horsepower for each Tier 0 piece replaced. This is an approximation of the shipping costs for transporting a Tier 0 vehicle for sale out of state.

I. What would be the statewide economic impact of the regulation?

Staff would not expect a noticeable change in employment, business creation, elimination, or expansion, and business competitiveness in California due to the regulation. As discussed above, staff's analysis of the estimated change in "return on owner's equity" for fleets within each industry type affected by the regulation indicated the proposed regulation would not alter significantly the profitability of most businesses. In addition to an assessment of the regulation's impact on individual fleets, staff in consultation with University of California, Berkeley researchers also conducted an assessment of the economic impacts of the proposed regulation on the California

economy. Staff used a computable general equilibrium model of the California economy called E-DRAM to model the many complex interactions of the California economy. The results of the analysis confirmed that in the context of the State's economy, the economic impact of the proposed regulation is minor and is not expected to impose a noticeable impact.

According to the E-DRAM analysis, in 2010, the year of highest annual costs due to the regulation, the costs of the proposed regulation would reduce California economic output by roughly $700 million (0.02 percent) and California employment by approximately 1,000 jobs (0.01 percent). Personal income would also decline by roughly $2.3 billion (0.2 percent) in 2010. Changes in the overall economy on the order of 0.02 percent are not expected to be noticeable.

The E-DRAM analysis did not include the economic benefit expected due to decreased health costs due to the health benefits of the proposed regulation. These benefits are expected to be between $18 billion and $26 billion from 2009 to 2030 and would offset the impacts described above.

J. What would be the impact of the regulation on employment?

Because the regulation imposes a cost on the overall economy, as noted above, staff expects it to reduce overall employment in California by a small amount. In the highest cost year, employment would be expected to decrease by about 1,000 jobs. This decrease would be spread throughout the economy and not just felt by the industries directly impacted by the regulation, such as construction. However, the California economy is adding new jobs at a rate of about 230,000 per year (DOF, 2007b). The proposed regulation would not eliminate the creation of new jobs in California, but it may slow the rate at which jobs are created.

In particular, the California construction industry is expected to add about 8,000 jobs per year from 2006 to 2014 (EDD, 2007). This increase is driven by the anticipated future need for construction projects in the state (and the labor to perform that work), which would not be impacted by the regulation. It is possible that because of the large cost imposed by this regulation, some businesses with affected fleets would be eliminated. It is also possible that some businesses would choose to consolidate (or merge), change owners, or relocate due to this regulation. However, staff expects that any dislocated employees of these companies would be able to find employment in an industry with an expanding workforce.

Because the regulation would increase the use of VDECS in off-road diesel vehicles in the State, the regulation would result in the creation of some new jobs. Staff estimates that over its course, the regulation would require the installation of over 125,000 VDECS. It is very likely that additional businesses would be created or existing businesses expanded to aid in the making, distribution, cleaning, and maintenance of these VDECS, resulting in an increase in job demand.

Also, because there would be an increase in demand for cleaner engines and vehicles, a similar increase in businesses and jobs selling, manufacturing, and installing these

vehicles and engines is expected. As it encourages some fleets to choose to rent vehicles rather than own them, the regulation may also provide new business to some rental companies, thereby also creating new jobs.

K. How cost effective would the regulation be and how does this compare to previous measures adopted by ARB?

The cost-effectiveness in terms of dollar per pound ($/lb) of emission reduction achieved is expected to be $37 to $43/lb PM and $2.1 to $2.5/lb NOx. This cost-effectiveness is within the range of cost-effectiveness of previous measures adopted by ARB. The cost-effectiveness of the PM emission reductions, on a per death avoided basis, is about 6 times lower than the U.S. EPA's benchmark for value of avoided death (which equates to about $248/lb). Therefore, the regulation is a cost-effective mechanism to reduce premature deaths that would otherwise be caused by diesel PM emissions without this regulation.

Table VII-4 below compares the estimated cost-effectiveness of the regulation to the estimated cost-effectiveness of other recently adopted in-use diesel measures. For comparison purposes, all cost-effectiveness estimates shown in Table VII-4 attribute part of the total regulation cost to PM reductions and part to NOx or hydrocarbon (HC) plus NOx reductions. Rules are ranked from lowest $/lb PM cost to highest. As Table VII-4 shows, the cost-effectiveness of the regulation would be within the range of measures previously adopted by ARB.

Table VII-4 – Cost-effectiveness Compared to Previously Adopted ARB Regulations

Rule	NOx ($/lb)	PM ($/lb)	Source of Estimate
Stationary Compression Ignition Engine ATCM	0.9*	$7.7	(ARB, 2003a)
Portable Engine ATCM	<$2	$8-$10	(ARB, 2004)
Cargo Handling ATCM	$1	$21	(ARB, 2005a)
Solid Waste Collection Vehicle ATCM	$1.8*	$32	(ARB, 2003b)
In-Use Off-Road Diesel Vehicle Regulation	***$2.1-2.5***	***$37-43***	***See Technical Support Document***
Public Fleets Rule	$10.9*	$160	(ARB, 2005e)

* Combined HC+NOx

L. Are there incentive funds available to help fleets comply with the regulation?

The opportunities for fleets to utilize incentive funds to comply with the regulation would be limited, and most fleets would still need to plan on paying for the majority of compliance costs with their own funds. California has the largest clean air incentive program in the nation, the Carl Moyer Program, with over $140 million available each year primarily through the local air districts. In addition, ARB is in the process of awarding a one-time $25 million grant program to public agencies for the purchase of low-polluting construction vehicles, which would help public agencies begin to clean their fleets in advance of the proposed regulation.

Even so, this level of funding is far from sufficient to pay for all the reductions. The Carl Moyer Program will only pay for emission reductions that go beyond the requirements of the regulation and occur at least three years early. Because the compliance dates for large fleets would begin in 2010, the majority of large fleets would not be able to access Carl Moyer Program funds once the regulation is adopted. Because the compliance dates for medium fleets would begin in 2013, medium fleets would likely have two or three years to apply for incentive funds and still be able to claim a three year project life. After that, most medium fleets would also not be able to access Carl Moyer Program funds. However, many small fleets would be able to access Carl Moyer Program funds in advance of their first 2015 compliance date and would always be eligible for projects that achieve NOx reductions. Also, captive fleets in attainment areas, which would only be subject to the PM portion of the regulation, would be eligible for projects that achieve NOx reductions.

ARB recognizes that compliance with the proposed regulation may be financially challenging for owners of regulated vehicles. Fleets may need to borrow money to purchase retrofits, repowers, or to upgrade their vehicles. In addition to the Carl Moyer Program, to minimize the cost-impact of compliance, staff is consulting with other state agencies such as the Pollution Control Financing Authority in the State Treasurer's Office and private lenders to look for ways to leverage existing public programs and funding in the private sector, through potential programs such as government loan guarantees, interest rate buy down programs, etc. It is hoped that these efforts could make compliance with the regulation more affordable and access to capital more widely available. However, ARB does not currently have the funds to help create such programs, and thus their availability remains speculative at this time.

VIII. Technology Available to Meet Regulatory Requirements

A. What are verified diesel emission control systems and how do we know they really work?

The regulation would only require and give credit for diesel emission control systems that have been verified by ARB. ARB adopted a procedure to verify retrofit diesel emission control systems in 2003. Verification is an approval from ARB, which tells end users that the verified device achieves the advertised emission reductions and is durable. To be verified, retrofit devices must demonstrate the efficacy and durability of their products and provide a warranty. The warranty guarantees the retrofit's efficacy for 4 to 5 years and 2,600 to 4,200 operating hours, depending on engine size, and warrants that the retrofit will not cause engine damage.

ARB's verification procedure is a multi-level verification system consisting of three PM reduction levels and optional NOx reduction levels (see Table VIII-1). Reductions in NOx are not required for verification, but ARB's procedure recognizes and verifies NOx reductions that are greater than or equal to 15 percent in five percent increments. This system has broadened both the spectrum of control technologies available to participate in California's diesel emission control effort and the number and types of vehicles and engines that can be controlled. This multi-level approach to verification is consistent with the goal of achieving the maximum reductions in diesel PM emissions that are economically and technologically feasible. At this time, nearly all the verified emissions control strategies are retrofit exhaust aftertreatment devices.

Table VIII-1 - Levels of ARB Verification for Diesel Emission Control Systems

Category	PM Reduction
Level 1	≥ 25%
Level 2	≥ 50%
Level 3	≥ 85%, or 0.01 g/bhp-hr
Category	**NOx Reduction**
Optional	≥ 15%; in 5% increments

B. What exhaust retrofits would the regulation require?

The fleet average provisions of the regulation give credit for PM retrofits that achieve at least a 50 percent reduction in PM (i.e., Level 2 or 3) and for any verified NOx retrofit. Credit would not be given for Level 1 devices. The mandatory retrofit provisions of the regulation would require the use of the highest level verified device, which in most cases would be a diesel particulate filter (DPF). A DPF typically consists of a ceramic wall-flow monolith or a silicon carbide substrate that captures PM before it can be released to the atmosphere. The accumulated soot is then burned off (regenerated) either through an active or passive process. In passively regenerated DPFs, the substrate is coated with a catalyst that burns off the collected PM during "regeneration." In actively regenerated DPFs, an external source of heat such as an electrical heater or

fuel burner is used to oxidize the collected PM. It is likely that many of the diesel particulate filters used would need to be actively regenerated, either through plug-in or through an on-board fuel burner, because the exhaust temperatures in some off-road applications are not sufficient to support passive regeneration.

C. What devices have been verified for off-road applications?

Table VIII-2 shows the Level 2 and Level 3 diesel emission control systems have been verified for use in off-road diesel vehicles by ARB. There are currently level 3 PM retrofits for off-road vehicles verified by three manufacturers, and staff believes more would be likely to be verified (both in passive and active configurations) after a regulation is adopted and the market conditions for their use are better defined.

Table VIII-2 - Level 2 and 3 VDECS for Off-road Diesel Vehicles[6]

Product Name	Technology Type	PM Reduction	NOx Reduction	Applicability
Cleaire Horizon	DPF	85%	N/A	Conditionally verified for most Tier 1 off-road engines
Huss Umwelttechnik FS_MK	DPF	85%	N/A	Most off-road diesel engines through 2007 model year
Engine Control System Combifilter	DPF	85%	N/A	1996-2004 off-road engines
Engine Control System AZ Purimuffler/Purifier	Diesel oxidation catalyst (DOC) + Alt Fuel	50%	20%	1996-2002 off-road; Requires the use of PuriNOx fuel

D. Have these devices been demonstrated in off-road applications?

Around the world over the past several decades, various government agencies have begun to require the retrofit of in-use diesel engines, especially to reduce diesel PM. In the past 20 years, over 130,000 DPFs have been retrofitted on heavy-duty vehicles worldwide (MECA, 2006).

The Europeans have taken the lead in requiring DPF retrofits of construction vehicles. European interest in diesel retrofits was spurred in the early 1990s when large-scale tunnel projects in Switzerland, Austria, and Germany using heavy diesel equipment were planned. The Europeans formed the VERT project to find technologies that could allow heavy diesel equipment to be used in confined spaces, and have subsequently began to require diesel retrofits widely on construction projects. Approximately 35,000 DPFs have been installed on all varieties of construction vehicles used on large construction projects in Switzerland and in confined spaces in Germany.

[6] Current verifications as of April 6, 2007

The European experience is slowly being duplicated in the U.S. through a variety of projects and rules. To date, the largest construction retrofit projects have been on the East Coast. In Boston, on the Central Artery/tunnel Project and in New Haven, on the Interstate 95 New Haven Harbor Crossing Corridor, 200 to 300 pieces of construction vehicles have been retrofitted with diesel oxidation catalysts (DOCs). DOCs will be retrofitted on approximately 290 pieces of construction equipment in Chicago on the Dan Ryan Expressway. For the reconstruction of the World Trade center, low-sulfur diesel fuel was used, and eight pieces of construction equipment were retrofit with DOCs or DPFs. For the Croton project, a North Bronx, New York, drinking water construction project that began in 2005 and is continuing, over 25 pieces of construction equipment including loaders, excavators, dozers, drill rigs, and off-road trucks were retrofit with DPFs. The filters were from four different retrofit manufacturers and included actively and passively regenerated models. In 2006, twelve construction vehicles including a compactor, excavator, and off-road vehicles were retrofit with diesel particulate filters during construction of a new runway at the Los Angeles International Airport.

Laws, regulations, and rules are being promulgated that require retrofitting construction equipment. German and Swiss legislation has stimulated thousands of retrofits to date. In the U.S. various jurisdictions including New York City, Connecticut, Massachusetts, and New York State are requiring some level of retrofits on construction equipment.

The ARB recognizes the need for more verified diesel emission control devices for off-road applications. Therefore, staff has been collaborating with the Mobile Source Air Pollution Reduction Review Committee (MSRC) of the South Coast Air Quality Management District (SCAQMD) to develop and implement the "Showcase Program". The Showcase Program, which has been funded in the so far with $1,000,000 from MSRC, will pay for the cost and installation of retrofit devices in the South Coast Air Quality Management District. It is designed to encourage owners of off-road diesel construction equipment to work with diesel emission control system manufacturers to retrofit their engines with diesel emission control devices. The goal of the program is to demonstrate new emission control systems that will earn ARB-verified status, while achieving significant near-term emission reductions of both PM and NOx. Participation in the Showcase Program is open to private construction companies, public agencies, local governments, and other owners of off-road diesel construction equipment in the SCAQMD.

E. Are engine repowers really possible?

Repowering a vehicle, i.e., replacing an existing engine with a newer and cleaner engine, is often possible, but is not always feasible. Some vehicle manufacturers already have standard engine kits designed to replace older engines in existing machines. The State's Carl Moyer program has funded 4,500 engine repowers in various vehicle types, including over 300 off-road vehicles such as scrapers, wheel loaders, compactors, tractors, excavators, and rough terrain forklifts (ARB, 2007b).

For most off-road vehicles, repowering from a pre-controlled Tier 0 engine to a Tier 1 certified engine is relatively straightforward because the engine block has the same dimensions and major changes are only required to exhaust lines. Repowering to a Tier 2 engine is generally more complicated and costly, and may not be feasible for some vehicles. It often requires components in the engine compartment to be changed out or added, and some parts such as brackets and supports may need to be fabricated. Repower to Tier 3 is often more complex and costly but has already been accomplished in a number of applications. It is unlikely that repowering to Tier 4 engines will be feasible because of size and exhaust after treatment constraints.

Repowers would only be used if this option costs less than buying a replacement vehicle.

F. Are NOx exhaust retrofits feasible?

Staff estimates that between 20 and 25 percent of off-road vehicles could be suitable for the use of combined PM and high efficiency NOx exhaust retrofit systems, such as those using selective catalytic reduction. In the off-road emissions inventory, over half the total horsepower in the State is represented by engines with less than 120 horsepower. These engines are not likely to be appropriate for use of NOx exhaust retrofit systems because of engine compartment size limitations, and the costs for such systems relative to engine and vehicle replacement options.

The remaining engines greater than 120 hp in the fleet are potential candidates for high efficiency NOx systems. However, exhaust temperatures (or duty cycle limitations) will likely dictate the actual suitability of certain vehicles to use selective catalytic reduction or other technologies. In general, high efficiency NOx control systems will need to operate in temperature regimes similar to those required for passive DPF systems. Staff estimates that only about 30 percent of off-road vehicles greater than 120 hp would have exhaust temperature characteristics suitable for passive DPF systems.

G. Would enough used vehicles be available to help satisfy the regulation requirements?

Staff anticipates that fleets would comply with the regulation by a variety of methods. Increases in demand to meet the NOx requirements would likely be satisfied through a combination of engine repowers, purchase of new vehicles, purchase of used vehicles, and/or installation of NOx retrofits.

The turnover requirements imposed by the regulation would require a maximum of 8 percent of the statewide fleet's horsepower to turn over per year until 2015. The baseline natural rate of turnover of the statewide fleet is about 5 percent per year. Thus, the regulation would at most require 3 percent more turnover per year than normal. After 2015, although individual fleets would have to turn over as much as 10 percent of their horsepower per year, most fleets would meet the fleet averages and few would need to do the maximum turnover. The regulation affects about 180,000 vehicles, so an increase in demand for Tier 2 or better vehicles and engines in California would represent about 5,400 vehicles per year.

Staff compared the number of used off-road vehicles recently for sale on two used equipment websites on a single day. On these two sites, there were over 80,000 vehicles for sale and over 30,000 of them were 2003 model year or newer (likely Tier 2 or better) (Ritchie Brothers, 2007; Machinery Trader, 2007). By the time the first requirements for accelerated turnover take effect in 2010, there is likely to be an even greater number of Tier 2 or better used vehicles available. Based on this evaluation, it appears likely that there would be a sufficient number of used vehicles available to meet the increased demand due to the regulation.

H. Would enough new vehicles be available to satisfy the regulation requirements?

Staff believes enough new vehicles would be available to satisfy the regulation requirements. As stated above, the regulation would increase demand for vehicles by at most about 5,400 vehicles per year. This demand in the context of the national and international market for off-road diesel vehicles is small. In 2005, there were over 329,000 new off-road construction vehicles sold in the United States. If all fleets were to comply with the regulation by buying new vehicles, the increase in demand for new vehicles in California would represent less than 3 percent of national sales.

Further, the regulation contains provisions so that fleets are not penalized if manufacturer delays prevent them from acquiring the equipment or vehicles they need to comply. Also, the proposed regulation contains special provisions that would exempt from the mandatory turnover requirements specialty equipment for which repowers and used vehicle replacements are not available.

IX. PUBLIC OUTREACH

A. What outreach did staff do to inform the public about the regulation and solicit input on its development?

Staff has been notifying affected industry and other interested parties regarding the proposed regulation and soliciting input regarding its development for two and half years. Table IX-1 below summarizes the outreach efforts, and the discussion below provides further details. Staff has made dozens of changes to the regulation at the request of stakeholders, including incorporating fleet average requirements, additional flexibility, and other elements to improve the clarity and effectiveness of the regulation. Staff also made extensive updates to the emission inventory as a result of information and feedback from stakeholders at a special workgroup meeting focused on emissions inventory issues.

Table IX-1 - Summary of Outreach Efforts for the Proposed Regulation

Outreach Effort	Number	Number and Description
Public Workshops	13	Workshops were held in 6 cities across the state between November 16, 2004 and March 1, 2007. Five of the workshops were broadcast via the internet so stakeholders could participate remotely. Over 1,000 people attended at least one of the workshops.
Public Workgroup Meetings	6	Meetings were held simultaneously in Sacramento and El Monte. Stakeholders could also participate via phone.
Mailings	Over 376,200 mailings sent in total	July 2005 mailing to 79,000 licensed contractors in classifications likely to own affected vehicles; February 2007 post card to all 290,000 licensed contractors; Additional mailings to over 4,000 landfills, recycling facilities, and mining facilities; 500 small airports; and 2,700 owners of registered portable equipment.
Calls and Emails	Over 85 contacts	Calls and follow-up emails with further information to dealers, affected companies, associations, and other organizations
Meetings and presentations	Over 45	Staff met with and gave presentations to over 45 interested stakeholders and organizations

The first public workshops concerning development of the regulation were held in November 2004. Since then, staff hosted 13 workshops and 6 public workgroup meetings. Workshops were held up and down the state – in Sacramento, Riverside, Los Angeles, El Monte, Fresno, and San Diego – and many of the workshops were broadcast via the internet so interested parties could participate remotely via computer. The most recent series of four workshops held in March 2007, were attended by over

1,000 people. Staff has also spoken to groups regarding the regulation in Lakeport, Calaveras County, Napa, Bakersfield, Walnut, Pleasanton, Redding, San Diego, Sierra County, Santa Rosa, West Covina, West Sacramento, Sacramento, Siskiyou County, Truckee, and Glenn County.

To facilitate communication with stakeholders, staff created an electronic listserve for the in-use off-road diesel vehicle regulation, and sent regular notices to it concerning regulation development. The email listserve for the regulation grew to nearly 3,000 members. Notices were sent to other email lists, including those for portable equipment owners, for the portable equipment air toxic control measure, for the cargo handling equipment and public fleets air toxic control measures, among others, also in an attempt to reach any and all who would be interested.

Staff also did a series of mass mailings regarding the regulation. Early in the process, staff sent information and surveys to 79,000 potential owners of vehicles affected by the regulation, as well as to over 4,000 mines and solid waste and recycling facilities. Most recently, in February 2007, staff sent a mailing to the nearly 300,000 licensed contractors in the State and one to the over 4,000 registered owners of portable equipment in the state.

Staff also called and sent emails and letters to as many industry associations as could be identified who might have members affected by the regulation. These included contractors associations, chambers of commerce, and organizations that represent engine manufacturers, equipment manufacturers, and drilling contractors. Staff also contacted owners of portable equipment, and public agency fleet managers, and as well as less obvious groups that represent unions, graveyards, amusement parks and fairs, among others.

Staff called dozens of off-road equipment dealers and gave them flyers to mail to their customers. Staff also worked with the trade group that represents independent sellers and dealers of diesel fuel to have them distribute flyers concerning the regulation to buyers of diesel fuel.

X. IMPLEMENTATION AND ENFORCEMENT

A. How would the regulation be implemented?

For the regulation to be fair to fleets that would spend considerable funds and effort to comply, fleets must be assured that their competitors would also be complying. For this to happen, there must be an effective outreach campaign and the regulation must be vigorously enforced. Staff recognizes that creating a level playing field for all affected fleets is important, and is committed to obtaining the resources necessary to do so.

If the proposed regulation is adopted, staff, in cooperation with affected industries, would develop and conduct an extensive outreach campaign to be sure affected parties are aware of their responsibilities under the regulation. This campaign would build on the outreach staff has already done throughout development of the proposed regulation. First, staff would continue to work with industry groups to inform their members about the regulation. Second, as we have for our existing fleet rules for transit buses and public fleets, staff plans to hold training workshops across the state and invite manufacturers of verified diesel emission control systems to share information about their products with affected fleets. Third, staff would provide training and educational materials at the workshops and on our website to help fleets understand the choices they would face with respect to finding the most cost-effective path to compliance. Staff will also operate a toll-free number set up to answer questions about the regulation (866-6DIESEL). Finally, staff would send electronic and hard-copy mailings to affected parties prior to the initial reporting dates in 2009 to inform fleet owners about their responsibility to report their vehicles.

Staff also plans to develop and provide electronic tools for compliance planning that would allow fleets to determine what retrofits are available for their vehicles, and to experiment with various possible compliance paths. In addition, staff plans to develop and provide electronic reporting forms that would allow fleets to report their vehicles on-line and demonstrate how they have met the fleet average or BACT requirements. For fleets that prefer, staff would also be prepared to receive reports in non-electronic format.

B. How would the regulation be enforced?

Staff has the responsibility for enforcing the regulation. ARB inspectors may use a variety of opportunities to find and inspect off-road vehicles such as audits of facilities such as landfills, mines, and recycling facilities. They may also inspect construction sites or off-road vehicles they encounter being transported by truck, as well as complaints from the public.

The two keys to enforcement of the in-use off-road diesel vehicle regulation would be the annual reporting and the equipment identification number (EIN). The reporting would allow staff to determine if fleets have met the fleet average targets or complied with the BACT requirements. Fleets would be required to report information about each vehicle, its engine data, its model year, as well as the actions taken to comply with the

regulation such as any repowering or retrofitting done. For vehicles claimed as low-use, owners must report the hour-meter readings.

In addition, each vehicle would have its EIN displayed prominently on the side of the vehicle. When ARB inspectors are in the field, they would be able to link the vehicle EIN to whatever action was claimed for that vehicle. They would be able to tell if the vehicle does not have the proper engine installed, or is not outfitted with the retrofits claimed. Even though in most cases inspectors would never be able to view an owner's entire fleet, inspectors would be able to verify the accuracy of the reported information for whatever vehicles they encounter.

If ARB inspectors find vehicles that are subject to the regulation that are not labeled with an EIN, then that would be an immediate indication of noncompliance.

Enforcement of the idling portion of the regulation would be conducted similarly to enforcement of ARB's commercial vehicle and school bus idling rules, which rely on complaints from the public to trigger inspections by ARB field inspectors and further enforcement action.

C. What additional resources are needed for implementation and enforcement?

Because of the need to ensure a high level of compliance with the regulation, ARB would request additional staff to aid in outreach, education, and enforcement of the regulation. Staff would conduct outreach and education for fleet owners, develop and implement the reporting tools the regulation would rely upon, manage the reporting data, conduct inspections, and to research and prosecute enforcement cases.

XI. ALTERNATIVES CONSIDERED

A. What alternatives to the regulation were considered, and why were they rejected in favor of the proposed regulation?

Throughout the regulation development process, staff considered many possible regulation structures and regulatory elements. Staff incorporated many recommendations from stakeholders such as allowing fleet averaging, giving double credit for electric vehicles in some years, raising the annual hour threshold for low-use vehicles, including more horsepower groups in the calculation of the fleet average, and providing credit for early actions.

However, staff did not accept all suggestions from stakeholders because in developing the regulation, staff was striving to achieve the following goals:

- Achieve the maximum, fastest possible, reduction in diesel PM emissions;
- At the same time, maximize NOx reductions achieved by 2015 to aid in attainment of the PM2.5 standards in South Coast and San Joaquin Valley;
- Minimize the cost for fleets and, in particular, minimize the need for fleets to control equipment twice (for example, by having to turn it over twice during the course of the regulation);
- Achieve cost-effective emission reductions on a dollar per ton basis; and
- Staff sought to achieve these goals while keeping in mind the technology available today and likely to become available over the next decade.

The alternatives considered and reasons they were rejected in favor of the chosen NOx and PM fleet average approach are summarized in Table XI-1 below.

Table XI-1 - Alternative Regulation Structures Considered

Approach	Why Rejected
No action - allow natural turnover of the statewide fleet to gradually lower emissions over time.	Would not achieve the emission reductions as quickly as needed to meet the state's air quality commitments or public health goals.
Traditional Best Available Control Technology (BACT) PM retrofit rule – Like the solid waste collection vehicle rule, require fleets to phase-in a certain percent of PM retrofits per year until all vehicles are retrofit.	Would not offer fleets flexibility to choose the most cost-effective combination of retrofits, repowers, and accelerated turnover. Would not be guaranteed to achieve critically needed NOx reductions.
PM-only fleet average rule – Require fleets to meet a declining PM fleet average	Would achieve significantly less NOx reductions than a combined NOx and PM fleet average.
Mandatory phase-out of the dirtiest engines - Phase out Tier 0s by a certain date, Tier 1s by a later date, etc. and require exhaust retrofits	Could encourage acquisition or holding of Tier 0 and 1s before mandatory turnover starts, which could cause a loss of emissions benefits before the rule takes effect and which might achieve very little benefit in the early years of implementation. Lacks the flexibility of a fleet average to allow credit for strategies other than turnovers such as PM or NOx retrofits.
Mandatory NOx retrofit and PM retrofit – A traditional BACT rule with BACT defined as highest level NOx and PM retrofit.	Would achieve less NOx reductions in long-term because vehicles that are retrofit cannot be immediately turned over. There is also uncertainty regarding availability and feasibility of NOx retrofits. Higher cost than PM and NOx fleet average approach. Would eliminate fleet's ability to choose a cost-effective path to compliance.

Overall, the NOx and PM fleet average approach, coupled with the minimum annual turnover/retrofitting alternative (i.e., the BACT requirements) was chosen as the best structure. It provides maximum flexibility for fleets to find their own, most cost-effective combination of retrofits, engine repowers, retirements, and accelerated turnover that would bring them to compliance. It allows fleets to make decisions concerning which vehicles they plan to keep for a long time versus those that are not worth repowering or retrofitting because they would be turned over soon. It also rewards fleets that start out cleaner (i.e., newer fleets or fleets that have already installed some exhaust retrofits) because they would have to do less to reach the fleet average targets. Finally, the option of complying with the BACT requirements (i.e., retrofit a certain percent and turn over a certain percent of fleet per year) allows fleets that start out very dirty or that

happen to own very long-lived vehicles and who cannot realistically meet the fleet average targets, especially in the early years of implementation, to have an affordable path to compliance. Staff also considered requiring higher turnover rates and more stringent NOx averages, but the higher costs would likely be more than the industry could bear.

During the course of the workshop process, construction industry representatives proposed alternative, much looser, fleet averages than those included in the proposed regulation. Staff evaluated these industry-proposed fleet averages but did not recommend them because, over the life of the regulation, they would achieve less than 20 percent of the PM reductions and less than 45 percent of the NOx reductions expected from ARB's proposal.

XII. REFERENCES

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XIII. List of Acronyms

$/HP --- Dollars per Horsepower

$/Lb --- Dollars per Pound

ARB --- Air Resources Board

ATCM --- Air Toxic Control Measure

BACT --- Best Available Control Technology

CAA --- Clean Air Act

CEQA --- California Environmental Quality Act

CO_2 --- Carbon Dioxide

DOCs --- Diesel Oxidation Catalysts

DOF --- Department of Finance

DPF --- Diesel Particulate Filter

DRRP --- Diesel Risk Reduction Plan

E-DRAM --- Environmental-Dynamic Revenue Analysis Model

EIN --- Equipment Identification Number

GSE --- Ground Support Equipment

HC --- Hydrocarbon

HP --- Horsepower

HSC --- Health and Safety Code

MSRC --- Mobile Source Air Pollution Reduction Review Committee

NAAQS --- National Ambient Air Quality Standards

NCSA --- National Center for Statistics and Analysis

NEPA --- National Environmental Policy Act

NO_X --- Oxides of Nitrogen

PM --- Particulate Matter

PM2.5 --- Particles up to 2.5 microns in diameter

ROE --- Return on Owner's Equity

SCAQMD --- South Coast Air Quality Management District

SIPs --- State Implementation Plans

TAC --- Toxic Air Contaminant

TPD --- Tons per Day

U.S. EPA --- United States Environmental Protection Agency

VDECS --- Verified Diesel Emission Control System

VERT --- Verminderung der Emissionen von Real-Dieselmotoren in Tunnelbau,
Curtailing Emissions from Diesel Engines in Tunnel Construction

Appendix A

Proposed Regulatory Language

PROPOSED REGULATION FOR IN-USE OFF-ROAD DIESEL VEHICLES

Adopt new section 2449, in title 13, article 4.8, chapter 9, California Code of Regulations (CCR) to read as follows:

(Note: The entire text of article 4.8, section 2499 is new language.):

Article 4.8 In-Use Off-Road Diesel-Fueled Fleets

Section 2449 Emission Standards for In-Use Off-Road Diesel-Fueled Fleets

(a) **Purpose**

The purpose of this regulation is to reduce diesel particulate matter (PM) and criteria pollutant emissions from in-use off-road diesel-fueled vehicles.

(b) **Applicability**

Except as provided in the paragraph below, the regulation applies to any person, business, or government agency who owns or operates within California any diesel-fueled off-road compression ignition vehicle engine with maximum power of 25 horsepower (hp) or greater that is used to provide motive power in a workover rig or to provide motive power in any other motor vehicle that (1) cannot be registered and driven safely on-road or was not designed to be driven on-road, and (2) is not an implement of husbandry or recreational off-highway vehicle. Vehicles that were designed to be driven on-road, have on-road engines, and still meet the original manufacturer's on-road engine emission certification standard are considered on-road and are specifically excluded from this regulation, even if they have been modified so that they cannot be registered and driven safely on-road. Off-road vehicles that were designed for off-road use and have off-road engines are considered off-road and are subject to this regulation, even if they have been modified so that they can be driven safely on-road.

This regulation also applies to any person who sells a vehicle with such an engine within California.

Persons who provide financing in the form of "finance leases," as defined in California Uniform Commercial Code Section 10103(a)(7), for in-use off-road diesel-fueled vehicles, do not "own" such vehicles for the purposes of this regulation.

Vehicles with engines subject to this regulation are used in construction, mining, rental, government, landscaping, recycling, landfilling, manufacturing, warehousing, ski industry, composting, airport ground support equipment, industrial, and other operations. The regulation does not cover locomotives, commercial marine vessels, marine engines, recreational vehicles, or combat and tactical support equipment. The

regulation also does not cover stationary or portable equipment, or equipment or vehicles used in agricultural operations, or equipment at ports or intermodal railyards. Off-road diesel vehicles owned and operated by an individual for personal, non-commercial, and non-governmental purposes are exempt from the provisions of this regulation.

(c) **Definitions**

(1) **Agricultural operations** means (1) the growing or harvesting of crops (including forest operations) or the raising of fowl or animals for the primary purpose of making a profit, providing a livelihood, or conducting agricultural research or instruction by an educational institution, or (2) agricultural crop preparation services such as packinghouses, cotton gins, nut hullers and processors, dehydrators, and feed and grain mills. Agricultural crop preparation services include only the first processing after harvest, not subsequent processing, canning, or other similar activities. For forest operations, agricultural crop preparation services include milling, peeling, producing particleboard and medium density fiberboard, and producing woody landscape materials.

(A) **Part-time agricultural use** – For purposes of this regulation, a vehicle that is used by its owner for both agricultural and nonagricultural operations is considered to be a vehicle engaged in agricultural operations, only if over half of its annual operating hours are for agricultural operations

(B) **Part-time agricultural use of rental vehicles** - A vehicle that is rented or leased by its owner for use in agricultural and nonagricultural operations by others, unless it is exclusively used for agricultural operations.

(2) **Airport ground support equipment** (GSE) is mobile diesel-fueled off-road compression ignition vehicles used to service and support aircraft operations. GSE vehicles perform a variety of functions, including but not limited to: aircraft maintenance, pushing or towing aircraft, transporting cargo to and from aircraft, loading cargo, and baggage handling. GSE vehicles include equipment types such as baggage tugs, belt loaders, and cargo loaders.

(3) **Alternative fuel** means natural gas, propane, ethanol, methanol, gasoline (when used in hybrid electric vehicles only), hydrogen, electricity, fuel cells, or advanced technologies that do not rely on diesel fuel. "Alternative fuel" also means any of these fuels used in combination with each other or in combination with other non-diesel fuels.

(4) **Best Available Control Technology** (BACT) means the exhaust retrofit and accelerated turnover requirements in section 2449(d)(2).

(5) **Captive Attainment Area Fleet** means a fleet, regardless of size, in which all of its vehicles operate exclusively only in the following counties: Alpine, Colusa, Del Norte, Glenn, Humboldt, Lake, Lassen, Mendocino, Modoc, Monterey,

Plumas, San Benito, San Luis Obispo, Santa Cruz, Shasta, Sierra, Siskiyou, Trinity, Tehama, and Yuba. Fleets that operate one or more vehicles outside the counties listed above may not be defined as captive attainment area fleets.

(6) **Carryover retrofit credit**, as calculated under section 2449(d)(2)(B)2., means a way of tracking retrofits accomplished in excess of those required by the BACT retrofit requirements. Fleets may take credit for such excess retrofits in earlier years in order to do less retrofitting in later years.

(7) **Carryover turnover credit**, as calculated under section 2449(d)(2)(A)2., means a way of tracking turnover accomplished in excess of the BACT turnover requirements. Fleets may take credit for such excess turnover in earlier years to do less turnover in later years.

(8) **Combat and Tactical Support Equipment** means equipment that meets military specifications, is owned by the U.S. Department of Defense and/or the U.S. military services or its allies, and is used in combat, combat support, combat service support, tactical or relief operations or training for such operations.

(9) **Common ownership or control** means being owned or managed day to day by the same person, corporation, partnership, or association. Vehicles managed by the same directors, officers, or managers, or by corporations controlled by the same majority stakeholders are considered to be under common ownership or control even if their title is held by different business entities.

(10) **Dedicated Snow Removal Vehicle** means a vehicle that is operated exclusively to remove snow from public roads, private roads, or other paths from which snow must be cleared to allow on-road vehicle access. Dedicated snow removal vehicles must have permanently affixed snow removal equipment such as a snow blower or auger and may include, but are not limited to, motor graders, loaders, and snow blowers.

(11) **Diesel particulate matter (diesel PM)** means the particles found in the exhaust of diesel-fueled compression ignition engines. Diesel PM may agglomerate and adsorb other species to form structures of complex physical and chemical properties. The Air Resources Board (ARB) has identified diesel PM as a toxic air contaminant.

(12) **Diesel PM Index** means an indicator of a fleet's overall diesel PM emission rate. The diesel PM Index for a specific fleet is determined by summing the product of the maximum power of each engine times the diesel PM Emission Factor, and dividing by the fleet's total maximum power.

(13) **Diesel PM Target Rate** means the fleet average that a specific fleet must meet in a compliance year in order to show compliance with the fleet average requirements. The Diesel PM Target Rate varies depending on a fleet's horsepower distribution. The Diesel PM Target Rate for a specific fleet for each compliance year is determined by summing (adding) the product of the maximum power of each engine times the Diesel PM target, and dividing the resulting sum by the fleet's total maximum power.

(14) **Emergency operation** means helping alleviate an immediate threat to public health or safety. Examples of emergency operation include repairing or preventing damage to roads, buildings, terrain, and infrastructure as a result of an earthquake, flood, storm, fire, terrorism, or other infrequent act of nature. Routine maintenance or construction to prevent public health risks does not constitute emergency operation.

(15) **Emission Factor** means diesel PM or oxides of nitrogen (NOx) emission rate in grams per brake-horsepower hour (g/bhp-hr) as shown in Attachment A, unless the engine is a Post-2007 Flexibility Engine (see definition).

(A) Engines certified to Family Emission Limits and flexibility engines certified before January 1, 2007 should still use the emission factors in Attachment A.

(B) If the model year is unknown, the emission factor is the emission factor shown in Attachment A for 1900-1969 model years.

(C) For engines that have been retrofit with VDECS, the PM Emission Factor is reduced 50 percent for a Level 2 VDECS, and 85 percent for a Level 3 VDECS; the NOx Emission Factor is reduced by the percentage NOx emission reductions that are verified, if any. The PM Emission Factor is not reduced for a Level 1 VDECS.

(16) **Equipment Identification Number** means a unique identification number assigned by ARB to each vehicle in an owner's fleet subject to this regulation. All reporting and recordkeeping will link vehicle data with this number.

(17) **Executive Officer** means the Executive Officer of the ARB or his or her authorized representative.

(18) **Family Emission Limit (FEL)** means an emission level that is declared by the manufacturer to serve in lieu of an emission standard for certification purposes and for the averaging, banking, and trading program, as defined in title 13, California Code of Regulations, section 2423.

(19) **Fleet** means all off-road vehicles and engines owned by a person, business, or government agency that are operated within California and are subject to the regulation. A fleet includes one or more vehicles. A fleet does not include vehicles that have never operated in California.

(A) **Rental Fleets** - Vehicles that are owned by a rental company and that are leased by the same lessee for a period of one year or more may be excluded from the rental company fleet and included in the fleet of the lessee only if such arrangement is delineated in the written lease agreement. Vehicles that are rented or leased for a period of less than one year must be included in the fleet of the rental company. Off-road vehicles and engines owned by a lessor and leased to a lessee under a "lease" as defined in California Uniform Commercial Code Section 10103(a)(10), of a duration of at least one year, dated prior to the effective date of these regulations, are considered part of the fleet of the lessee rather than the lessor.

(20) **Fleet Size Category-** Fleets are classified by size as described below. A fleet must meet large fleet requirements if the total vehicles under common ownership or control would be defined as a large fleet. A fleet must meet medium fleet requirements if the total vehicles under common ownership or control would be defined as a medium fleet. Individual federal or state agencies may report their vehicles separately, but all vehicles owned by agencies of the United States or the State of California agencies must meet the large fleet requirements. Low-use vehicles, dedicated snow-removal vehicles, and vehicles used solely for emergency operations need not be included in the total maximum power used to classify fleets by size.

(A) **Large Fleet** – A fleet with a total maximum power (as defined below) greater than 5,000 horsepower (hp). A fleet must meet large fleet requirements if the total vehicles under common ownership or control would be defined as a large fleet. All fleets owned by the United States, the State of California, or agencies thereof (i.e., an agency in the judicial, legislative, or executive branch of the federal or state government) will be considered as a unit whole and must meet the large fleet requirements set forth in section 2449(d)(1), *infra*.

(B) **Medium Fleet** – A fleet that is not a small nor large fleet.

(C) **Small Fleet** – A fleet with total maximum power of less than or equal to 1,500 hp that is owned by a small business or less than or equal to 1,500 hp that is owned by a local municipality, or a local municipality fleet in a low population county irrespective of total maximum power.

(21) **Forest operations** means cutting or removal or both of timber, other solid wood products, including Christmas trees, and biomass from forestlands for commercial purposes, together with all the work incidental thereto, including but not limited to, construction and maintenance of roads, fuel breaks, firebreaks, stream crossings, landings, skid trails, beds for falling trees, fire hazard abatement, and site preparation that involves disturbance of soil or burning of vegetation following forest removal activities. Forest operations include the cutting or removal of trees, tops, limbs and or brush which is processed into lumber and other wood products, and or for landscaping materials, or biomass for electrical power generation. Forest operations do not include conversion of forestlands to other land uses such as residential or commercial developments.

(22) **Highest Level Verified Diesel Emission Control System (VDECS)** means the highest level VDECS verified by ARB under its *Verification Procedure, Warranty and In-Use Compliance Requirements for In-Use Strategies to Control Emission from Diesel Engines* (*Verification Procedure*), title 13, California Code of Regulations (CCR), sections 2700-2710, for a specific engine as of 10 months prior to the compliance date, which (1) can be used without impairing the safe operation of the vehicle as demonstrated per section 2449(e)(8), and (2) the diesel emission-control strategy manufacturer and authorized diesel emission-control strategy dealer agree can be used on a specific engine and vehicle combination without jeopardizing the original engine warranty in effect at the time of application.

Plus designations do not matter; that is, a Level 3 Plus is the same diesel PM level as Level 3; and Level 2 Plus is the same diesel PM level as Level 2.

The highest level VDECS is determined solely based on verified diesel PM reductions, not based on verified NOx reductions. All Level 3 diesel PM devices are higher than all Level 2 diesel PM devices. Level 1 devices are never considered highest level VDECS for the purpose of this regulation.

(23) **Implement of husbandry** is as defined in California Vehicle Code (VC) Division 16.

(24) **Local Municipality** means a city, county, city and county, special district, or other public agency, or two or more public entities acting jointly, or the duly constituted body of an Indian reservation or rancheria. Agencies of the United States of America or the State of California, and departments, divisions, public corporations, or public agencies of this State or of the United States are not considered local municipalities.

(25) **Low-Population County Local Municipality Fleet** means a fleet owned by a local municipality (as defined above) that is located in a county as defined in title 13, CCR, section 2022(b)(2) and identified in section 2022(c)(2), Table 2, or, using the criteria set forth in title 13, CCR, section 2022.1(c)(4), a local municipality not located in a low-population county that has requested and has received Executive Officer approval to be treated like a municipality in a low-population county. Fleets owned by such local municipalities shall be treated as small fleets even if their total maximum power exceeds 1,500 horsepower.

(26) **Low-use vehicle** means a vehicle that operated in California less than 100 hours during the preceding 12-month period running from March 1 to end of February. For example, when reporting in 2009, the hours of use between March 1, 2008 and February 28, 2009 would be used to determine low-use status. To be considered a low-use vehicle, the fleet owner must submit engine operation data from a functioning non-resettable hour meter.

(A) **Vehicles used outside California -** Vehicles that operate both inside and outside of California can meet the low-use vehicle definition if they are used less than 100 hours per year in California.
(B) **Three-year rolling average** - A vehicle operated only in California for the previous three years and owned by the same owner during that period will be considered low-use if it operated on average less than 100 hours per year during that previous three-year period.
(C) **Emergency operation hours** - Hours used for emergency operations are not counted when determining low-use status.

(27) **Maximum power** (Max Hp) means the engine's net horsepower or net flywheel power certified to Society of Automotive Engineers (SAE) Method J1349. If the engine's net horsepower or net flywheel power certified to SAE Method J1349 is not available, another net horsepower or net flywheel power from the manufacturer's sales and service literature may be used.

(28) **Motor vehicle** has the same meaning as defined in VC Section 415.

(29) **New fleet** means a fleet that is acquired or that enters California after March 1, 2009. Such fleets may include new businesses or out-of-state businesses that bring vehicles into California for the first time after March 1, 2009.

(30) **NOx index** means an indicator of a fleet's overall NOx emission rate. The NOx Index for a specific fleet is determined by summing the product of the maximum power of each engine times the NOx Emission Factor, and dividing by the fleet's total maximum power.

(31) **NOx target rate** means the NOx fleet average that a specific fleet must meet in a compliance year in order to show compliance with the fleet average requirements. The NOx Target Rate varies depending on a fleet's horsepower distribution. The NOx Target Rate for a specific fleet for each compliance year is determined by summing (adding) the product of the maximum power (Max Hp) of each engine times the NOx target, and dividing the resulting sum by the fleet's total maximum power.

(32) **Off-highway vehicle** is defined in VC Division 16.5.

(33) **Oxides of nitrogen (NOx)** means compounds of nitric oxide, nitrogen dioxide, and other oxides of nitrogen. Nitrogen oxides are typically created during combustion processes and are major contributors to smog formation and acid deposition.

(34) **Post-2007 Flexibility Engine** means an engine certified on or after January 1, 2007 to the implementation flexibility standards in title 13, CCR, section 2423(d). Such flexibility engines are generally labeled as follows by the engine manufacturer:

"THIS ENGINE COMPLIES WITH CALIFORNIA EMISSION REQUIREMENTS UNDER 13 CCR 2423(d)..." or
"THIS ENGINE CONFORMS TO CALIFORNIA OFF-ROAD COMPRESSION-IGNITION ENGINE REGULATIONS UNDER 13 CCR 2423(d)."

Post-2007 flexibility engines should use the emission standard to which the engine is certified. For example, a Tier 4 engine flexed back to Tier 2 emission levels should use the Tier 2 PM standard as the emission factor (converted from grams per kilowatt hour (g/kW-hr) to g/bhp-hr by multiplying by 0.746).

(35) **Queuing** means the intermittent starting and stopping of a vehicle while the driver, in the normal course of doing business, is waiting to perform work or a service, and when shutting the vehicle engine off would impede the progress of the queue and is not practicable. Queuing does not include the time a driver may wait motionless in line in anticipation of the start of a workday or opening of a location where work or a service will be performed.

(36) **Registered and driven safely on-road** means a vehicle meets the requirements to be registered for on-road operation in VC Division 3, Chap. 1, Article 1, Sec. 4000 et seq. (i.e., required to be registered or could be registered), and the requirements to be driven safely on-road in "Equipment of Vehicles" requirements in VC Division 12, Chap. 1, Sections 24000 et seq. and "Size, Weight, and Load" requirements in VC Division 15, Sections 35000 et seq. Having a California Special Construction Equipment plate as defined in California Vehicle Code Section 565 and 570 does not constitute registration.

(37) **Repower** means to replace the engine in a vehicle with another engine meeting a subsequent engine emissions standard (e.g., replacing a Tier 0 engine with a Tier 2 or later engine).

(38) **Responsible Official** means one of the following:

(A) For a corporation: A president, secretary, treasurer, or vice president of the corporation in charge of a principal business function, or any other person who performs similar policy or decision-making functions for the corporation,

(B) For a partnership or sole proprietorship: a general partner or the proprietor, respectively

(C) For a municipality, state, federal, or other public agency: either a principal executive officer or ranking elected official. For the purposes of this part, a principal executive officer of a federal agency includes the chief executive officer having responsibility for the overall operations of a principal geographic unit of the agency (e.g., a Regional Administrator of the U.S. EPA).

(39) **Retire** means to take an engine out of service and not operate it again in the State of California. To retire an engine, the vehicle with the engine may be moved outside of California, sold, or scrapped.

(40) **Small business** is as defined in Government Code section 11342.610.

(41) **Snow removal operations** means removing snow from public roads, private roads, or driveways.

(42) **Specialty vehicle** means a vehicle for which no used vehicle with a cleaner engine that can serve an equivalent function and perform equivalent work is available.

(43) **Tier 0 Engine** means an engine not subject to the requirements in title 13, CCR, section 2423; Title 40, Code of Federal Regulations (CFR), Part 89; or Title 40, CFR, Part 1039.

(44) **Tier 1 Engine** means an engine subject to the Tier 1 new engine emission standards in title 13, CCR, Section 2423(b)(1)(A) and/or Title 40, CFR, Part 89.112(a). This also includes engines certified under the averaging, banking, and trading program with respect to the Tier 1 Family Emission Limits (FEL) listed in Title 13, CCR, 2423(b)(2)(A) and/or Title 40, CFR, Part 89.112(d).

(45) **Tier 2 Engine** means an engine subject to the Tier 2 new engine emission standards in title 13, CCR, Section 2423(b)(1)(A) and/or Title 40, CFR, Part 89.112(a). This also includes engines certified under the averaging, banking, and trading program with respect to the Tier 2 FEL listed in Title 13, CCR, 2423(b)(2)(A) and/or Title 40, CFR, Part 89.112(d).

(46) **Tier 3 Engine** means an engine subject to the Tier 3 new engine emission standards in title 13, CCR, Section 2423(b)(1)(A) and/or Title 40, CFR, Part 89.112(a). This also includes engines certified under the averaging, banking, and trading program with respect to the Tier 3 FEL listed in Title 13, CCR, 2423(b)(2)(A) and/or Title 40, CFR, Part 89.112(d).

(47) **Tier 4 Final Engine** means an engine subject to the final after-treatment-based Tier 4 emission standards in title 13, CCR, Section 2423(b)(1)(B) and/or Title 40, CFR, Part 1039.101. This also includes engines certified under the averaging, banking, and trading program with respect to the Tier 4 FEL listed in Title 13, CCR, 2423(b)(2)(B) and/or Title 40, CFR, Part 1039.101.

(48) **Tier 4 Interim Engine** means an engine subject to the interim Tier 4 emission standards (also known as transitional) in title 13, CCR, Section 2423(b)(1)(B) and/or Title 40, CFR, Part 1039.101. This also includes engines certified under the averaging, banking, and trading program with respect to the Tier 4 FEL listed in Title 13, CCR, 2423(b)(2)(B) and/or Title 40, CFR, Part 1039.101.

(49) **Total maximum power** means the sum of maximum power for all of a fleet's engines that are subject to this regulation. Low-use vehicles, dedicated snow-removal vehicles, and vehicles used solely for emergency operations need not be included in the sum.

(50) **Verified Diesel Emission Control System (VDECS)** means an emissions control strategy, designed primarily for the reduction of diesel PM emissions,

which has been verified pursuant to the *Verification Procedures*. VDECS can be verified to achieve Level 1 diesel PM reductions (25 percent), Level 2 diesel PM reductions (50 percent), or Level 3 diesel PM reductions (85 percent). VDECS may also be verified to achieve NOx reductions. See also definition of Highest Level VDECS.

(51) **VDECS Failure** means the condition of not achieving the emissions reductions to which the VDECS is verified. Such condition could be due to inappropriate installation, damage, or deterioration during use. If a Level 3 VDECS is emitting visible smoke, it should be assumed to have failed.

(52) **Workover rig** means a mobile self-propelled rig used to perform one or more remedial operations, such as deepening, plugging back, pulling and resetting liners, on a producing oil or gas well to try to restore or increase the well's production.

(d) **Performance Requirements –**
Each fleet must meet the fleet average requirements below by March 1 of each year or demonstrate that it met the best available control technology (BACT) requirements as described in section 2449(d)(2). There are differing requirements for large, medium, and small fleets. If various portions of a fleet are under the control of different responsible officials because they are part of different subsidiaries, divisions, or other organizational structures of a company or agency, the fleet portions may comply with the performance requirements separately and be reported separately. However, the total maximum power of the vehicles under common ownership or control determines the fleet size. Fleets owned by low-population county local municipalities are subject to the small fleet requirements, even if their total maximum power exceeds 1,500 horsepower. Captive attainment area fleets are not subject to the NOx fleet average requirements. Section 2449(d)(4) describes requirements for fleets that change size.

(1) **Fleet Average Requirements**

(A) Fleet Average Requirements for Large and Medium Fleets

1. **NOx Fleet Average** - For each compliance date, a large or medium fleet that is not a captive attainment area fleet must demonstrate that its NOx Index was less than or equal to the calculated NOx Target Rate.

The equation for calculating NOx Target Rate is below:

NOx Target Rate = [SUM of (*Max Hp* for each engine in fleet multiplied by *Target* for each engine in fleet) for all engines in fleet] divided by [SUM of (Max *Hp*) for all engines in fleet]

where Target is the NOx target in g/bhp-hr from Table 1. To find the Target for each engine, read the value for the appropriate row based

on the compliance year and the appropriate column based on the engine's maximum power from Table 1.

The equation for calculating NOx Index is below:

NOx Index = [SUM of (*Max Hp* for each engine in fleet multiplied by NOx *Emission Factor* for each engine in fleet) for all engines in fleet] divided by [SUM of (Max *Hp*) for all engines in fleet]

Table 1 shows the targets used to calculate the NOx Target Rate for each compliance date for large and medium fleets. The Emission Factors are defined in Attachment A.

Table 1 – Large and Medium Fleet NOx Targets For Use in Calculating NOx Target Rates [g/bhp-hr]

	NOx Targets for each Max Hp Group							
Compliance Date: March 1 of Year	**25-49 hp**	**50-74 hp**	**75-99 hp**	**100-174 hp**	**175-299 hp**	**300-599 hp**	**600-750 hp**	**>750 hp**
2010 (large fleets only)	5.8	6.5	7.1	6.4	6.2	5.9	6.1	7.2
2011 (large fleets only)	5.6	6.2	6.7	6.0	5.8	5.5	5.6	6.8
2012 (large fleets only)	5.3	5.8	6.2	5.5	5.3	5.1	5.2	6.5
2013	5.1	5.5	5.7	5.1	4.9	4.7	4.8	6.1
2014	4.9	5.1	5.2	4.7	4.5	4.3	4.4	5.7
2015	4.6	4.8	4.8	4.3	4.1	3.9	4.0	5.3
2016	4.4	4.4	4.3	3.8	3.6	3.5	3.6	4.9
2017	4.2	4.1	3.8	3.4	3.2	3.1	3.2	4.5
2018	4.0	3.7	3.3	3.0	2.8	2.7	2.7	4.1
2019	3.7	3.4	2.8	2.6	2.3	2.3	2.3	3.8
2020	3.5	3.2	2.4	2.2	1.9	1.9	1.9	3.4

2. **Diesel PM Fleet Average** - For each compliance date, a large or medium fleet must demonstrate that its Diesel PM Index was less than or equal to the calculated Diesel PM Target Rate.

The equation for calculating Diesel PM Target Rate is below:

Diesel PM Target Rate = [SUM of (*Max Hp* for each engine in fleet multiplied by *Target* for each engine in fleet) for all engines in fleet] divided by [SUM of (Max *Hp*) for all engines in fleet]

where Target is the Diesel PM target in g/bhp-hr from Table 2. To find the Target for each engine, read the value for the appropriate row based on the compliance year and the appropriate column based on the engine's maximum power from Table 2.

The equation for calculating Diesel PM Index is below:

Diesel PM Index = [SUM of (*Max Hp* for each engine in fleet multiplied by PM *Emission Factor* for each engine in fleet) for all engines in fleet] divided by [SUM of (Max *Hp*) for all engines in fleet]

Table 2 shows the targets used to calculate the Diesel PM Target Rate for each compliance date for large and medium fleets. The Emission Factors are defined in Attachment A.

Table 2 – Large and Medium Fleet PM Targets For Use in Calculating PM Target Rates [g/bhp-hr]

	PM Targets for each Max Hp Group							
Compliance Date: March 1 of Year	**25-49 hp**	**50-74 hp**	**75-99 hp**	**100-174 hp**	**175-299 hp**	**300-599 hp**	**600-750 hp**	**>750 hp**
2010 (large fleets only)	0.46	0.60	0.62	0.33	0.23	0.18	0.20	0.30
2011 (large fleets only)	0.46	0.60	0.62	0.33	0.23	0.18	0.20	0.30
2012 (large fleets only)	0.39	0.43	0.46	0.26	0.16	0.14	0.14	0.24
2013	0.39	0.43	0.46	0.26	0.16	0.14	0.14	0.24
2014	0.29	0.23	0.24	0.18	0.11	0.11	0.11	0.18
2015	0.29	0.23	0.24	0.18	0.11	0.11	0.11	0.18
2016	0.21	0.18	0.19	0.14	0.08	0.08	0.08	0.11
2017	0.21	0.18	0.19	0.14	0.08	0.08	0.08	0.11
2018	0.12	0.12	0.13	0.10	0.06	0.06	0.06	0.08
2019	0.12	0.12	0.13	0.10	0.06	0.06	0.06	0.08
2020	0.08	0.08	0.07	0.06	0.03	0.03	0.03	0.06

(B) **Fleet Average Requirements for Small Fleets**
Small fleets must meet a PM fleet average beginning in 2015. Small fleets are not required to meet a NOx fleet average. To meet the PM fleet average, for each compliance date, a small fleet must demonstrate that its Diesel PM Index was less than or equal to the calculated Diesel PM Target Rate.

The equations for calculating Target Rates and Diesel PM Index are below:

Diesel PM

Target Rate = [SUM of ((Max Hp for each engine in fleet multiplied by Target for each engine in fleet)] divided by [SUM of (Max *Hp*) for all engines in fleet]

where Target is the PM target in g/bhp-hr from Table 3. To find the Target for each engine, read the value for the appropriate row based on the compliance year and the appropriate column based on the engine's maximum power from Table 3.

Diesel PM Index = [SUM of (*Max Hp* multiplied by PM *Emission Factor*) for each engine in fleet] divided by [SUM of (Max *Hp*) for all engines in fleet]

Table 3 shows the targets used to calculate the Diesel PM Target Rate for each compliance date for small fleets. The Emission Factors are defined in Attachment A.

Table 3 – Small Fleet PM Targets
For Use in Calculating PM Target Rates [g/bhp-hr]

	PM Targets for each Max Hp Group							
Compliance Date: March 1 of Year	**25-49 hp**	**50-74 hp**	**75-99 hp**	**100-174 hp**	**175-299 hp**	**300-599 hp**	**600-750 hp**	**>750 hp**
2015	0.46	0.60	0.62	0.33	0.23	0.18	0.20	0.30
2016	0.46	0.60	0.62	0.33	0.23	0.18	0.20	0.30
2017	0.39	0.43	0.46	0.26	0.16	0.14	0.14	0.24
2018	0.39	0.43	0.46	0.26	0.16	0.14	0.14	0.24
2019	0.29	0.23	0.24	0.18	0.11	0.11	0.11	0.18
2020	0.29	0.23	0.24	0.18	0.11	0.11	0.11	0.18
2021	0.21	0.18	0.19	0.14	0.08	0.08	0.08	0.11
2022	0.21	0.18	0.19	0.14	0.08	0.08	0.08	0.11
2023	0.12	0.12	0.13	0.10	0.06	0.06	0.06	0.08
2024	0.12	0.12	0.13	0.10	0.06	0.06	0.06	0.08
2025	0.08	0.08	0.07	0.06	0.03	0.03	0.03	0.06

(C) **Electric and Alternative Fuel Vehicles and Systems Used to Replace Diesel Vehicles** - Fleets with electric or alternative fuel vehicles may include such vehicles in their fleet average index and target rate calculations as follows:

1. **Electric and Alternative Fuel Vehicles Purchased on or after January 1, 2007**
   a. Fleets may include an electric and alternative fuel vehicle purchased on or after January 1, 2007, with a maximum power 25 horsepower or greater (or that replaced a diesel vehicle with maximum power 25

horsepower or greater) in their fleet average if all of the following conditions are met:

i. The owner can demonstrate it serves a function and performs the work equivalent to that of diesel vehicles and is used for a purpose for which diesel vehicles are predominantly used,
ii. The electric or alternative fuel vehicle is used predominantly outdoors,
iii. The electric or alternative fuel vehicle is not already included in the fleet average emission level requirements for large spark ignition engine fleets in title 13, Section 2775.1; and
iv. If the vehicle is an alternative fuel vehicle, the owner must demonstrate it is certified to a NOx standard less than or equal to the Tier 1 NOx standard for the same horsepower in title 13, CCR, Section 2423(b)(1)(A) and is less than or equal to the NOx emissions of a diesel engine of the same model year and horsepower.

b. For the purposes of compliance with sections 2449(d)(1)(A) and (d)(1)(B), electric vehicles shall be credited as follows:
   i. **Max Hp for Electric Vehicles** - For an electric vehicle that replaced a diesel vehicle in the owner's fleet, the maximum power of the diesel vehicle replaced may be used as the electric vehicle's *Max Hp*. Otherwise, the electric vehicle's own maximum power rating should be used.
   ii. **Double Credit for Electric in 2010-2016** - For compliance dates in 2010 through 2016, the *Max Hp* of all electric vehicles purchased on or after January 1, 2007 may be doubled in determining the *Max Hp* that is used in calculating the Diesel PM Index, and as appropriate, NOx Index. An *Emission Factor* of 0 may be used. The *Max Hp* of each electric vehicle is included but not doubled in the calculation of Diesel PM Target Rate and NOx Target Rate.
   iii. **Single Credit for Electric in 2017 and Later** - For compliance dates in year 2017 and later, the *Max Hp* of all electric vehicles purchased on or after January 1, 2007 is used in determining the *Max Hp* that is used in calculating the Diesel PM and NOx Target Rates, Diesel PM Index, and, as appropriate, NOx Index. An *Emission Factor* of 0 may be used.

c. For the purposes of compliance with sections 2449(d)(1)(A) and (d)(1)(B), each alternative fuel vehicle should use an Emission Factor equal to the emission standard to which its engine is certified in g/bhp-hr. If the alternative fuel vehicle is not certified to a NOx or diesel PM emission standard, the owner may provide an appropriate emission factor, as demonstrated to the Executive Officer.

2. **Electric and Alternative Fuel Vehicle Purchased Prior to January 1, 2007**

a. Electric airport GSE vehicles with a maximum power of 25 horsepower or greater (or that replaced a diesel vehicle with maximum power 25 horsepower or greater) purchased prior to January 1, 2007, may be partially counted in the fleet average calculations as follows:
   i. **Max Hp for Electric Vehicles** - For an electric vehicle that replaced a diesel vehicle in the owner's fleet, the maximum power of the diesel vehicle replaced may be used as the electric vehicle's *Max Hp*. Otherwise, the electric vehicle's own maximum power rating should be used.
   ii. Include such vehicle's *Max Hp* times 0.2 as the *Max Hp* in the calculating the Target Rate, Diesel PM Index, and, as appropriate, NOx Index in section 2449(d)(1)(A) and (d)(1)(B), along with an *Emission Factor* of 0.

b. Fleet owners may count a non-GSE electric or alternative fuel vehicle purchased prior to January 1, 2007 in the fleet average calculations if all of the following conditions are met:
   i. The owner can demonstrate it serves a function and performs the work equivalent to that of diesel vehicles and is used for a purpose for which diesel vehicles are predominantly used,
   ii. the electric or alternative fuel vehicle is used predominantly outdoors,
   iii. the vehicle is not already counted toward the fleet average emission level requirements for large spark ignition engine fleets in Title 13, CCR section 2775.1; and
   iv. if the vehicle is alternative fuel vehicle, certified NOx emission levels are lower than the NOx standard for the same model year and horsepower in Title 13, CCR, Section 2423(b)(1) and Title 40, CFR, Part 89.112(a) and Title 40, CFR, Part 1039.101.

3. **Stationary or Portable System Used to Replace Mobile Diesel Vehicle** Fleet owners may include portable or stationary systems that replace mobile diesel vehicles, such as a conveyor system used to replace diesel haul trucks at a mine, in the fleet average calculations. The system may be considered in the fleet average calculations by including the maximum power of the diesel vehicles replaced in the calculations of Target Rate, Diesel PM Index, and NOx Index above, along with an *Emission Factor* of 0. In order to count such a system, all the following conditions must be met:
   a. The owner must demonstrate that it replaced an off-road diesel fueled vehicle subject to this regulation on or after January 1, 2007, and
   b. The system is not already counted toward the fleet average emission level requirements for large spark ignition engine fleets in title 13, CCR section 2775.1 or for portable diesel engine fleets in title 17, CCR section 93116.3.

(D) **Hours in Fleet Average Option** – As an alternative to the formulas for calculating NOx index and diesel PM index in section 2449(d)(1)(A) and (B), fleet owners may opt to include annual hours of operation for all engines in the fleet on the compliance date in the calculation as follows:

NOx Index = [SUM of (*Max Hp* for each engine in fleet on compliance date multiplied by *NOx Emission Factor* for each engine in fleet on compliance date multiplied by *Annual Hours of Operation* for each engine in fleet on compliance date since the previous year's compliance date)] divided by [SUM of (Max *Hp* for each engine in fleet on compliance date multiplied by *Annual Hours of Operation* for each engine in fleet on compliance date since the previous year's compliance date)]

Diesel PM Index = [SUM of (*Max Hp* for each engine in fleet on compliance date multiplied by PM *Emission Factor* for each engine in fleet on compliance date multiplied by *Annual Hours of Operation* for each engine in fleet on compliance date since the previous year's compliance date)] divided by [SUM of (Max *Hp* for each engine in fleet on compliance date multiplied by *Annual Hours of Operation* for each engine in fleet on compliance date since the previous year's compliance date)]

Fleets that choose this option must include hours in all index calculations for the compliance date.

(2) **BACT Requirements** – Each year, each fleet must determine if it will be able to meet the fleet average requirements for the next March 1 compliance date, and if not, the following BACT requirement must be met. If a fleet does not meet the NOx target rate in 2449(d)(1), it must meet the BACT turnover requirements in 2449(d)(2)(A) below. If a fleet does not meet the Diesel PM target rate in 2449(d)(1), it must meet the BACT Retrofit Requirements in 2449(d)(2)(B). Fleets that fail to meet both the NOx and Diesel PM target rates in 2449(d)(1) in a compliance year must first meet the BACT turnover requirements in 2449(d)(2)(A) below in that year and then meet the BACT Retrofit Requirements in 2449(d)(2)(B) in that year.

(A) **Turnover Requirements for Fleets Not Meeting NOx Target Rate** – A fleet may meet the turnover requirements by retiring a vehicle, designating a vehicle as a low-use vehicle, repowering a vehicle, or applying a VDECS verified to achieve NOx reductions. If repowering a vehicle, the new engine must be Tier 2 or higher and must be a higher tier than the engine replaced. The method for counting VDECS verified to achieve NOx reductions is specified in 2449(d)(2)(A)8.

1. **Turnover Rate** –
   If a fleet does not meet the NOx Target Rate in 2449(d)(1) on a compliance date on or before March 1, 2015, it must demonstrate on the applicable compliance date that it has turned over 8 percent of the total maximum power of the fleet that existed on March 1 of the previous year since March 1 of the previous year. If a fleet does not meet the NOx Target Rate in 2449(d)(1) on a compliance date after March 1, 2015, it

must demonstrate on the applicable compliance date that it turned over 10 percent of its total maximum power that existed on March 1 of the previous year since March 1 of the previous year. Any carryover turnover credit previously accrued may be applied towards the turnover required in a later year.

2. **Carryover turnover credit** –
   a. **Beginning** – All fleets other than those meeting the criteria in (i) or (ii) below begin with zero carryover turnover credit on March 1, 2009. All fleets may begin accumulating carryover turnover credit on March 1, 2010.
      i. **Credit for Early Repowers** - Fleets that have repowered their vehicles with Tier 1 or higher engines before March 1, 2009 begin with a carryover turnover credit (indicated as a percentage) equal to: 100 multiplied by the maximum power of Tier 1 or higher repower engines installed in affected vehicles before March 1, 2009 divided by the total maximum power of fleet on March 1, 2009. The credit can only be claimed for engines that remain in the fleet. To claim credit, fleets must keep adequate records as described in 2449(h).
      ii. **Credit for Early Retirement** – Fleets that have retired their Tier 0 vehicles at an average rate greater than 8 percent of maximum power per year between March 1, 2006 and March 1, 2009 begin with carryover turnover credit (as a percentage) equal to: 100 multiplied by the [(Total maximum power of Tier 0 vehicles retired between March 1, 2006 and March 1, 2009) minus (Total maximum power of Tier 0 vehicles added between March 1, 2006 and March 1, 2009)] divided by (Total maximum power of fleet on March 1, 2009) minus 24. Tier 0 vehicles repowered with newer engines are counted under (i) above and should not be counted under (ii). To claim such credit, fleets must keep adequate records as described in 2449(h).
   b. **Accumulating carryover turnover credit** –
      i. **2010-2015** - From March 1, 2010 through March 1, 2015, a fleet accumulates carryover turnover credit each year it turns over more than 8 percent of its maximum power. The amount accumulated is the percent of maximum power turned over in excess of 8 percent in the 12 months prior to March 1 of the year in which the carryover is calculated.
      ii. **After 2015** - After March 1, 2015, a fleet accumulates carryover turnover credit each year it turns over more than 10 percent of its maximum power. The amount accumulated is the percent of maximum power turned over in excess of 10 percent in the 12 months prior to March 1 of the year in which the carryover is calculated.

c. **Using carryover turnover credit** - Accumulated carryover turnover credit may be applied to meeting the turnover requirements of section 2449(d)(2)(A)1 in a later year. The amount of carryover turnover credit used to meet the turnover requirements in any one year is subtracted from the carryover turnover credit total available in subsequent years. The amount of actual turnover plus the amount of carryover turnover credit used must equal the minimum BACT turnover rate required by 2449(d)(2)(A)1.

3. **Order of turnover** – All engines in a fleet that were not subject to a PM standard for new engines (Tier 0 and Tier 1 with no PM standard, i.e., Tier 1 engines between 50 and 174 horsepower) must be turned over before turnover of any other higher tier engines may be counted toward the turnover requirements in 2449(d)(2)(A) or toward accumulating carryover turnover credit.
4. **Exemptions** – Vehicles meeting the criteria below are exempt from the turnover requirement. A fleet is exempt from the turnover requirement in 2449(d)(2)(A)1. if all its vehicles meet one of the criteria below:
   a. Vehicles less than 10 years old – If all vehicles in a fleet will be less than 10 years old on the compliance date, no turnover is required.
   b. Specialty vehicles if all the following criteria are met:
      i. The fleet has turned over all other vehicles first,
      ii. No repower is available for the specialty vehicle, as demonstrated to the Executive Officer,
      iii. A used vehicle with a cleaner engine is not available to serve a function and perform the work equivalent to that of the specialty vehicle, as demonstrated to the Executive Officer, and
      iv. The specialty vehicle has been retrofit with highest level VDECS.
   c. A vehicle retrofit within the last six years with a Level 2 or 3 VDECS that was highest level VDECS at the time of retrofit.
   d. A vehicle with a Tier 4interim engine or Tier 4 final engine.
5. **Delay Tier 1 turnover** - All vehicles with a Tier 1 or higher engine are exempt from the turnover requirement until March 1, 2013, provided that all Tier 0 vehicles in the owner's fleet that do not qualify for an exemptions under section 2449(d)(2)(A)4. have been turned over.
6. **Designating vehicle as low-use** – A fleet may designate a vehicle that was formerly used 100 hours or more per year as low-use by limiting its use to less than 100 hours per year and committing to keep its use less than 100 hours per year.
   a. Only vehicles formerly used 100 hours or more per year may be so designated. Vehicles so designated may be counted toward the turnover requirements.
   b. Once designated as low-use, a vehicle may never again be used more than 100 hours per year by the fleet unless the vehicle meets the adding vehicles requirements in section 2449(d)(7).
   c. A fleet is not obliged to designate a vehicle whose use drops below 100 hours per year as low-use, nor to count it toward the turnover

requirements. If such a vehicle is not designated as low-use, its use may increase beyond 100 hours per year in subsequent years.

7. **Rounding** - If the horsepower required to be turned over under section 2449(d)(2)(A) is less than half of the maximum power of the lowest horsepower engine in the fleet that is subject to the turnover requirements, the next engine is not required to be turned over. However, on the next year's compliance date, any horsepower not turned over due to this rounding provision must be added to the required turnover under section 2449(d)(2)(A). Once the required horsepower to be turned over equals or exceeds half of the maximum power of the next engine in the fleet that is subject to the turnover requirements, the next engine must be turned over.
8. **Turnover Credit for NOx Retrofits** – VDECS that have been verified as achieving NOx reductions may be used to satisfy the turnover requirements in section 2449(d)(2)(A)1 on each compliance date as follows:
   Turnover credit for NOx retrofits (as a percentage) equals 100 multiplied by (Verified Percent NOx Reduction divided by 60 percent) multiplied by (Maximum power on which VDECS verified to achieve NOx reductions was installed in last 12 months) divided by (Total maximum power of fleet on compliance date). Turnover credit for NOx retrofits may be applied to meet the turnover requirements of section 2449(d)(2)(A)1 or to accumulate carryover turnover credit.

(B) **PM Retrofit Requirements for Fleets Not Meeting Diesel PM Target Rate**

1. **PM Retrofit Rate -** If a fleet does not meet the Diesel PM Target Rate in 2449(d)(1), it must demonstrate that it retrofit 20 percent of its total maximum power (not including specialty vehicles retrofitted and exempted from turnover in section 2449(d)(2)(A)4.b.) with highest level VDECS since March 1 of the previous year. Any carryover retrofit credit previously accrued may be applied toward the 20 percent retrofit required.
2. **Carryover PM retrofit credit** –
   a. **Beginning** - All fleets other than those meeting the criteria in (i) below begin with zero carryover retrofit credit on March 1, 2009. All fleets may begin accumulating carryover retrofit credit on March 1, 2010.
      i. **Double Credit for Early PM Retrofits** – Fleets that have installed the highest level VDECS on their vehicles before March 1, 2009 begin with a carryover retrofit credit (calculated as a percentage) equal to: 200 multiplied by Ttotal maximum power of engines on which highest level VDECS was installed before March 1, 2009 divided by Total maximum power of fleet on March 1, 2009.
   b. **Accumulating carryover PM retrofit credit** – A fleet accumulates carryover retrofit credit each year it retrofits more than 20 percent of its maximum power. The amount accumulated is the percent of maximum power retrofit in excess of 20 percent in the past 12 months prior to March 1.

c. **Using carryover PM retrofit credit** - Accumulated carryover retrofit credit may be applied to meeting the retrofit requirements of section 2449(d)(2)(B)1. in a later year. The amount of carryover retrofit credit used to meet the retrofit requirements in any one year is subtracted from the carryover retrofit credit total available in subsequent years. The amount of actual retrofit plus the amount of carryover retrofit credit used must equal the minimum BACT retrofit rate required by 2449(d)(2)(B)(1).

3. **Order of PM Retrofit –** No Level 2 VDECS may be counted toward the retrofit requirements in 2449(d)(2)(B) until all engines in vehicles older than 5 years for which the highest level VDECS available is a Level 3 VDECS have been retrofit, except for specialty vehicles utilizing the exemption in Section 2449(d)(2)(A)4.b. for which Level 2 is the highest level VDECS.
4. **Exemptions –** The following exemptions from the retrofit requirement apply, provided that retrofits have been or are being applied to all other engines in the owner's fleet not subject to these exemptions. A fleet is exempt from the retrofit requirement in 2449(d)(2)(B)1. if all its vehicles' engines meet one of the criteria below:
   a. Engines in vehicles less than 5 years old,
   b. Engines for which there is no highest level VDECS (i.e., for which there is no Level 2 or 3 VDECS, or for which there is a Level 2 or 3 VDECS which cannot be used without impairing the safe operation of the vehicle as demonstrated per section 2449(e)(8)),
   c. Engines equipped with an original equipment manufacturer diesel particulate filter that came new with the vehicle, or
   d. Engines already retrofit with a Level 2 or 3 VDECS that was the highest level VDECS available at time of installation. An engine with a Level 2 VDECS that was not the highest level VDECS at time of installation does not qualify for this exemption.
5. **Rounding** - If the horsepower required to be retrofit under section 2449(d)(2)(B) is less than half of the maximum power of the lowest horsepower engine in the fleet that is subject to the retrofit requirements, the next engine is not required to be retrofitted. However, on the next year's compliance date, any horsepower not retrofit due to this rounding provision must be added to the required retrofit under section 2449(d)(2)(B). Once the required horsepower to be retrofit equals or exceeds half of the maximum power of the next engine in the fleet that is subject to the retrofit requirements, the next engine must be retrofitted.

(3) **Idling** - The idling limits in section 2449(d)(3)(A) shall be effective and enforceable immediately upon this regulation being certified by the Secretary of State. Fleets must meet the following idling limits.

(A) **Idling Limit** - No vehicle or engines subject to this regulation may idle for more than 5 consecutive minutes. Idling of a vehicle that is owned by a rental

company is the responsibility of the renter or lessee, and the rental agreement should so indicate. The idling limit does not apply to:

1. idling when queuing,
2. idling to verify that the vehicle is in safe operating condition,
3. idling for testing, servicing, repairing or diagnostic purposes,
4. idling necessary to accomplish work for which the vehicle was designed (such as operating a crane),
5. idling required to bring the machine system to operating temperature, and
6. idling necessary to ensure safe operation of the vehicle.

(B) **Written Idling Policy** - As of March 1, 2009, medium and large fleets must also have a written idling policy that is made available to operators of the vehicles and informs them that idling is limited to 5 consecutive minutes or less.

(C) **Waiver** - A vehicle owner may apply to the Executive Officer for a waiver to allow additional idling in excess of 5 consecutive minutes. The Executive Officer shall grant such a request upon finding that the vehicle owner has provided sufficient justification that such idling is necessary.

(4) **Changing Fleet Size** –

(A) Small fleets that become medium fleets must meet the medium fleet requirements on the reporting date two years subsequent.

(B) Large fleets that become medium fleets must meet the medium fleet requirements on the next reporting date.

(C) Medium fleets that become small fleets must meet the small fleet requirements on the next reporting date.

(5) **New Fleets** – New fleets must meet the fleet average requirements in section 2449(d)(1) within three months of purchasing vehicles subject to the regulation or bringing such vehicles into the State of California for the first time after March 1, 2009. New fleets do not have the option of complying with the BACT requirements in section 2449(d)(2). New fleets must comply with the idling requirements in section 2449(d)(3) immediately upon purchasing vehicles subject to the regulation or upon bringing such vehicles into the State. New fleets must report vehicles subject to the regulation to ARB within 30 days of purchasing or bringing such vehicles into the State, in accordance with the requirements in section 2449(g).

(6) **Fleet Ownership Transferred** – If ownership of an entire fleet that was meeting the BACT requirements in lieu of the fleet average requirements is transferred to a new fleet owner who did not own a fleet before the transfer of ownership, the fleet may continue to meet the BACT requirements. That is, transfer of ownership to a new owner who did not own a fleet before does not automatically require the fleet to begin meeting the fleet average requirements in section 2449(d)(1). Existing fleet may acquire other entire fleets without condition if both fleets were in compliance with the individual fleet requirements. If existing fleets acquire portions of fleets or entire fleets that did not previously comply with the regulation, however, they must meet the requirements for adding vehicles in section 2449(d)(7) when adding the entire fleet.

(7) **Adding Vehicles –**

(A) **Beginning March 1, 2009** - After March 1, 2009 a fleet may not add a vehicle with a Tier 0 engine to its fleet.

(B) **Between the First and Final Compliance Dates** – The following requirements apply between March 1, 2010 and March 1, 2020 for large fleets, between March 1, 2013 and March 1, 2020 for medium fleets, and between March 1, 2015 and March 1, 2025 for small fleets.

1. **Fleets Meeting the Target Rates** - If a fleet met the fleet average target rates in 2449(d)(1) on the previous compliance date, when it adds a vehicle to its fleet, the fleet must demonstrate that the fleet still meets the fleet average target rates within three months of adding the vehicle. That is, fleets may not add vehicles that cause them to exceed the most recent fleet average target rates. The added vehicle also must be included in the fleet average demonstration on the next compliance date.
2. **Fleets Not Meeting the Fleet Average Targets** - If a fleet did not meet the fleet average requirements in 2449(d)(1) on the previous compliance date, the fleet may not add a vehicle to its fleet that would further increase its emissions above the fleet average target rate, as described below.
   a. **Large and Medium Fleets** - A large or medium fleet that met the BACT requirements in section 2449(d)(2) instead of the fleet average requirements in section 2449(d)(1) on the most recent compliance date may not add a vehicle to its fleet unless all of the following conditions are met:
      i. The engine is Tier 2 or higher. (For the purposes of this requirement, a vehicle may be assumed to meet the new engine emission standard tier in effect for the model year unless the engine is a flexibility engine certified January 1, 2007 or later to the implementation flexibility standards 13 CCR 2423(d), in which case the emission standard tier to which the engine is certified should be used.)
      ii. The vehicle engine's PM Emission Factor (after being adjusted for any VDECS) is less than or equal to the PM Target in Table 2 for engines in the same horsepower group for the most recent compliance date, and
      iii. The vehicle engine's NOx Emission Factor (after being adjusted for any VDECS) is less than or equal to the NOx Target in Table 1 for engines in the same horsepower group for the most recent compliance date.
   b. **Small Fleets** – A small fleet that met the BACT requirements in section 2449(d)(2) instead of the fleet average requirements in section 2449(d)(1) on the most recent compliance date may not add a vehicle to its fleet unless both the following conditions are met:
      i. The vehicle engine is Tier 2 or higher. (For the purposes of this requirement, a vehicle may be assumed to meet the new engine emission standard tier in effect for the model year unless the engine is a flexibility engine certified January 1, 2007 or later to the implementation flexibility standards 13 CCR 2423(d), in which case

the emission standard tier to which the engine is certified should be used.)

ii. The vehicle engine's PM Emission Factor (after being adjusted for any VDECS) is less than or equal to the PM Target in Table 3 for engines in the same horsepower group for the most recent compliance date.

(C) **After the Final Compliance Date** - Commencing respectively on March 1, 2020 for large and medium fleets, and March 1, 2025 for small fleets, no fleet owner may add a vehicle to his fleet, unless the vehicle is equipped with an engine meeting the Tier 3, Tier 4 interim, or Tier 4 final emission standards. If the engine did not come with an original equipment manufacturer diesel particulate filter, it must be equipped with the highest level VDECS within 3 months of acquisition.

(8) **VDECS Installation**– Before installing a VDECS on a vehicle, the vehicle owner must:

(A) Ensure that the VDECS is verified for use with the engine and vehicle, as described in the Executive Order for the VDECS.

(B) Ensure that use of the vehicle is consistent with the conditions of the Executive Order for the VDECS.

(C) Ensure that the diesel emission control strategy is installed in a verified configuration.

(D) Ensure that the engine to be retrofit is tuned up so that it meets engine manufacturer's specifications prior to VDECS installation.

(9) **VDECS Maintenance -** The owner of a vehicle retrofit with a VDECS must ensure all maintenance on the VDECS and engine is performed as required by the respective manufacturers.

(10) **Compliance After the Final Compliance Date** –

(A) Commencing respectively on March 1, 2020, if a large or medium fleet does not meet the NOx fleet average target rate for the final compliance date in section 2449(d)(1), the fleet must continue to meet the BACT turnover requirements in Section 2449(d)(2)(A) and report annually each year until it does so.

(B) Except as provided below, commencing respectively on March 1, 2021 for large and medium fleets, and March 1, 2026 for small fleets, all vehicles in each fleet must be equipped with the highest level VDECS. The following engines and vehicles are exempt from this requirement:

1. Low-use vehicles,
2. Engines for which there is no highest level VDECS (i.e., for which there is no Level 2 or 3 VDECS, or for which there is a Level 2 or 3 VDECS which cannot be used without impairing the safe operation of the vehicle as demonstrated per section 2449(e)(8)),
3. Engines equipped with an original equipment manufacturer diesel particulate filter that came new with the vehicle,
4. Engines already retrofit with a Level 2 or 3 VDECS that was the highest level VDECS available at time of installation, and

5. Vehicles in large and medium fleets that have not yet met the NOx fleet average target rate for the final compliance date in section 2449(d)(1).

(e) **Special Provisions/ Compliance Extensions**

(1) **VDECS Failure:** In the event of a failure or damage of a VDECS, the following conditions apply:

(A) **Failure or Damage During the Warranty Period.** If a VDECS fails or is damaged within its warranty period and it can not be repaired, the owner must replace it with the same level VDECS or higher for the vehicle within 90 days of the failure.

(B) **Failure or Damage Outside the Warranty Period.**

1. **Before Final Compliance Date -** If a VDECS fails or is damaged outside of its warranty period before March 1, 2021 for large and medium fleets, or before March 1, 2026 for small fleets and it can not be repaired and the fleet would not meet the fleet average target rates in 2449(d)(1) for the most recent compliance date if the VDECS that failed were removed, then within 90 days of the failure, the owner must replace it with the highest level VDECS available for the engine at time of failure.
2. **After Final Compliance Date** - If a VDECS fails or is damaged outside of its warranty period on or after March 1, 2021 for large and medium fleets, or on or after March 1, 2026 for small fleets and it can not be repaired, then within 90 days of the failure, the owner must replace it with the highest level VDECS available for the engine at time of failure, regardless of whether the fleet met the fleet average requirements in 2449(d)(1) for the most recent compliance date.

(2) **Fuel-based Strategy VDECS:**

(A) If a fleet owner determines that the highest level VDECS for a large percentage of his fleet would be a Level 2 fuel verified as a diesel emission control strategy, and implementation of this VDECS would require installation of a dedicated storage tank, then the fleet owner may request prior approval from the Executive Officer to allow use of the level 2 fuel-based strategy across its fleet.

(B) Extension for Discontinuation of Fuel Verified as a Diesel Emission Control Strategy. If a fleet owner who has relied upon a fuel verified as a diesel emission control strategy to meet the fleet average requirements in 2449(d)(1) discontinues use of the fuel due to circumstances beyond the fleet owner's control, the owner may apply to the Executive Officer no later than 30 days after discontinuation for up to two years additional time to come back into compliance with the fleet average requirements in 2449(d)(1). The Executive Officer then has 30 days to act upon the request. Fleets that did not meet the fleet average requirements in 2449(d)(1) in the most recent compliance year may not apply for this extension.

(3) **Exemption for Vehicles Used for Emergency Operations:** Vehicles used solely for emergency operations are exempt from the performance requirements in section 2449(d) but still must be labeled and reported in accordance with

sections 2449(f) and (g). Vehicles used solely for emergency operations need not be included when calculating fleet average indices or target rates, when determining fleet size, or when calculating the required horsepower for the BACT turnover and retrofit requirements in section 2449(d)(2).

Owners of vehicles brought into California for emergency operations that last longer than three months must report such entry to ARB and request an equipment identification number within three months of entering the state. Vehicles used solely for emergency operations and that stay in California for less than three months do not have to be labeled. For vehicles used both for emergency operations and for other purposes, hours of operation accrued when the vehicle is used for emergency operations do not need to be included when determining whether the vehicle meets the low-use vehicle definition.

(4) **Special Provisions for Snow Removal Vehicles:** Dedicated snow removal vehicles are exempt from the performance requirements in section 2449(d) but still must be labeled and reported in accordance with sections 2449(f) and (g). Dedicated snow removal vehicles need not be included when calculating fleet average indices or target rates, when determining fleet size, or when calculating the required horsepower for the BACT turnover and retrofit requirements in section 2449(d)(2). Publicly owned vehicles used exclusively to support snow removal operations (such as a loader without a special snow removal attachment), but which do not meet the dedicated snow removal vehicle definition, are exempt from the performance requirements in section 2449(d) but still must be labeled and reported in accordance with sections 2449(f) and (g).

(5) **Use of Experimental Diesel Emission Control Strategies:** If a fleet owner wishes to use an experimental, or non-verified, diesel emission control strategy, the owner must first obtain approval from the Executive Officer for a compliance extension. To obtain approval, the owner must demonstrate either that (A) a VDECS is not available or not feasible or not safe for their vehicle or application, or (B) that use of the non-verified strategy is needed to generate data to support verification of the strategy. The owner or operator shall keep documentation of this use in records as specified. The application must include emissions data and detailed control technology description demonstrating the experimental control achieves at least a Level 2 diesel PM emission reduction. If the application demonstrates that the device achieves at least 50 percent reductions in diesel PM, it may be treated like a Level 2 VDECS. If the application demonstrates that the device achieves at least 85 percent reductions in PM, it may be treated like a Level 3 VDECS. If the application demonstrates that the device achieves a NOx reduction over 15%, the NOx reduction may be counted.

Each vehicle engine retrofit with the experimental strategy will be considered to be in compliance for the duration of the experiment, until it expires. The owner must bring the fleet into compliance prior to the expiration of the experimental diesel emission control strategy extension.

(6) **Compliance Extension for Equipment Manufacturer Delays:** An owner or operator who has purchased new equipment (including VDECS) or vehicles in order to comply with this regulation, will be excused from immediate compliance if the new equipment or vehicles have not been received due to manufacturing delays as long as the following conditions are met:

(A) The equipment or vehicle was purchased, or the owner and seller had entered into contractual agreement for the purchase, at least six months prior to the required compliance date; and

(B) Proof of purchase, such as a purchase order or signed contract for the sale, including engine specifications for each applicable piece of equipment, must be maintained by the owner and provided to an agent or employee of ARB upon request.

(C) The new equipment or vehicles are immediately placed into operation upon receipt.

(7) **Exemption for Low-Use Vehicles:** Low-use vehicles are exempt from the performance requirements in section 2449(d) but still must be labeled and reported in accordance with sections 2449(f) and (g). Low-use vehicles need not be included when calculating fleet average indices or target rates, when determining fleet size, or when calculating the required horsepower for the BACT turnover and retrofit requirements in section 2449(d)(2).

Vehicles that formerly met the low-use vehicle definition, but whose use increases to 100 hours per year or greater must meet the BACT requirements or be included in the fleet average calculation by the next compliance date. For example, a formerly low-use engine that exceeds 100 hours per year between March 1, 2013 and February 28, 2014 must be included in the fleet average indices and target rates reported in 2014.

(8) **VDECS That Impairs Safe Operation of Vehicle**: A fleet owner may request that the Executive Officer find that a VDECS should not be considered the highest level VDECS available because (A) it cannot be safely installed or operated in a particular vehicle application, or (B) its use would make the use of another existing retrofit device that is required for occupational safety and health reasons, such as a diesel oxidation catalyst, impossible. The requesting party shall provide documentation to support its claims. Documentation must include reports and findings of federal, state or local government agencies, independent testing laboratories, engine or equipment manufacturer studies, or other equally reliable sources. The request will only be approved if the requesting party has made a thorough effort to find a safe method for installing and operating the VDECS, including considering the use of mirrors, various locations for VDECS mounting, and use of an actively regenerated VDECS. The Executive Officer shall review the documentation submitted and any other reliable information that he or she wishes to consider and shall make his or her determination based upon the totality of the evidence. The Executive Officer shall send a written determination letter to the requesting party within 60 days of the request being submitted.

(9) **Compliance Flexibility for Delays in Availability of Tier 4 Vehicles**: If the Executive Officer finds that there is a delay in availability of vehicles with engines meeting the Tier 4 interim or final emission standards so that vehicles with Tier 4 interim or final engines to meet a fleet's needs are not available or not available in sufficient numbers or in a sufficient range of makes, models, and sizes, then the Executive Officer may grant an extension to the fleet from the requirements in 2449(d)(1) and 2449(d)(2). If such a delay affects a group of fleets, the Executive Officer may issue an extension to all fleets with certain characteristics. Any such delay must be documented based on verifiable information from the fleet regarding its vehicle needs and/or verifiable information from the equipment manufacturer, engine manufacturer, distributor, and/or dealer regarding the unavailability of appropriate vehicles with Tier 4 interim or final engines.

(10) **Exemption for Vehicles Awaiting Sale** - Vehicles in the possession of dealers, financing companies, or other entities who do not intend to operate the vehicle nor offer the vehicle for hire, that are operated only to demonstrate functionality to potential buyers or to move short distances while awaiting sale or for maintenance purposes are exempt from all requirements in section 2449.

(11) **Exemption for Vehicle Used Over Half the Time for Agriculture** - A vehicle that is used by its owner for agricultural operations for over half of its annual operating hours but that is not used exclusively for agricultural operations is exempt from the performance requirements in section 2449(d) but still must be labeled and reported in accordance with sections 2449(f) and (g). Vehicles used exclusively for agricultural operations are completely exempt from the performance, labeling, and reporting requirements. A vehicle that is rented or leased for use by others is exempt only if it is exclusively used for agricultural operations.

(f) **Labeling** – All vehicles with engines subject to the regulation must be labeled with an ARB-issued equipment identification number (EIN). ARB will issue unique EIN to the fleet owner for each vehicle subject to the regulation in response to the initial reporting described in Section 2449(g)(1) and the annual reporting described in Section 2449 (g)(2). All owners of vehicles subject to the regulation must comply with the following labeling requirements.

(1) Application for EIN for added vehicle – Notwithstanding the requirements for vehicles used for emergency operations in section 2449(e)(3), if a fleet owner adds a vehicle to his California fleet or brings a vehicle into California from outside the state, the owner has 30 days from the date of purchase or the date the vehicle enters California to apply to ARB for an EIN or, if the vehicle already has an EIN, to inform ARB of the purchase. If the reporting date under Section 2449(g)(2) occurs before 30 days after purchase, the annual reporting may serve as the application for an EIN.

Applications for an equipment identification number should be submitted electronically per the guidelines approved by the Executive Officer for electronic data reporting, or mailed or delivered to ARB at the address listed immediately below:

California Air Resources Board
Mobile Source Control Division (In-Use Off-road Diesel)
P.O. Box 2815
Sacramento, CA 95812.

(2) Affixing Equipment Identification Number – Within 30 days of receipt of the ARB-issued EIN, owners shall permanently affix or paint the EIN(s) on the vehicle in clear view according to the following specification:
(A) The EIN shall be white on a red background.
(B) The EIN shall be located in clear view on the right (starboard) side of the outside of the vehicle approximately 5 feet above the ground, or, if the vehicle is not 5 feet tall, lower on the vehicle.
(C) Each character shall be at least 3 inches (7.6 centimeters) in height and 1.5 inches (3.8 centimeters) in width.
(D) The EIN shall be maintained in a manner that retains its legibility for the entire life of the vehicle.

(g) **Reporting** – Reporting is required for each and every fleet. Large and medium fleets may report separately for different divisions or subsidiaries of a given company or agency. Fleet owners must submit reporting information using forms approved by the Executive Officer However, in engine data required to be reported is unknown, such engines are assumed to be 1900-1969 vehicles for fleet average.
(1) Initial reporting – All fleet owners must submit the information in section 2449(g)(1)(A) through (C) to ARB by their initial reporting date. In the initial reporting, fleet owners must report information regarding each vehicle subject to this regulation in their fleet as of March 1, 2009. The initial reporting date for large fleets is April 1, 2009. The initial reporting date for medium fleets is June 1, 2009. The initial reporting date for small fleets is August 1, 2009. Reports should include the following:
(A) **Owner Contact Information** – Responsible person name, corporate parent (if applicable), company or agency name, street address, phone number, email address (if available), and taxpayer identification number.
(B) **Vehicle List** – A list of each vehicle subject to this regulation along with the following information for each vehicle.
1. Vehicle type;
2. Vehicle manufacturer;
3. Vehicle model;
4. Vehicle model year;
5. Whether the vehicle is a low-use vehicle;
6. Whether the vehicle is a specialty vehicle;
7. Whether the vehicle is a dedicated emergency vehicle;
8. Whether the vehicle is a dedicated snow removal vehicle;
9. Whether the vehicle is used for agricultural operations for over half of its annual operating hours;
10. Whether the vehicle is an electric vehicle that replaced a diesel vehicle;

11. Whether the vehicle is one that the owner intends to retire within one year; and
12. For each engine that propels the vehicle, the engine manufacturer, engine family (if any), engine serial number, engine model year, engine maximum power, type of retrofit emission control equipment installed (if any), date installed, and its verification level.

(C) **Low-Use Vehicles** – For vehicles that owners intend to define as low-use, report two hour meter readings, one from on or before March 1, 2008 and one from on or after March 1, 2009, and the dates of reading. If using the three-year rolling average definition of low-use, report two hour meter readings, one from on or before March 1, 2006 and one from on or after March 1, 2009.

(D) **Specialty Vehicles** – For vehicles that owners intend to define as specialty vehicles, report demonstration, per criteria approved by the Executive Officer, that no repower is available and no used vehicle with a cleaner engine is available to serve a function equivalent to and perform work equivalent to that of the specialty vehicle.

(E) **Electric Vehicles Replacing a Diesel Vehicle** – For electric vehicles that replace a diesel vehicle, report the following information regarding the diesel vehicle replaced: vehicle type, vehicle manufacturer, vehicle model, vehicle model year, vehicle serial number, engine manufacturer, engine family (if any), engine serial number, engine model year, engine maximum power and date retired.

(2) Annual Reporting and Compliance Certification – All fleet owners must review and update the information submitted under section 2449(g)(1) annually, and submit the information in section 2449(g)(2)(A) through (C) to ARB by the reporting date of each subsequent reporting year. The large fleet reporting date is April 1, the medium fleet reporting date is June 1, and the small fleet reporting date is August 1. Large fleets must report annually each year from 2010 to 2020. Medium fleets must report annually each year 2013 to 2020. Small fleets must report annually each year from 2015 to 2025. Any fleet that fails to meet the fleet average target rate for the final compliance date in section 2449(d)(1) must continue to report annually each year until it does so. Fleets must use forms approved by the Executive Officer for submittal of the required reporting information.

(A) **Compliance Certification** – A certification signed by a responsible official or a designee thereof that the information reported is accurate and that the fleet is in compliance with the regulation. The certification must be submitted on a form approved by the Executive Officer. If a designee signs the compliance certification, a written statement signed by the responsible official designating the designee must be attached to the compliance certification and submitted to ARB. If the fleet is a Captive Attainment Area Fleet, the certification must certify that the fleet's vehicles did not operate outside the counties listed in 2449(c)(5).

(B) **Changes Since Last Reporting** – Any additions, deletions, or changes to the fleet must be reported. Such changes may include vehicles removed from

the fleet, vehicles added to the fleet through purchase or by bringing into California, vehicles newly defined as low-use or specialty vehicles, repowers, and retrofits. If there are no changes, the fleet may indicate there are no changes.

(C) **Low-Use Vehicles** –

1. Vehicles Used Only In California - For vehicles defined as low-use that operate only in California, report the hour meter readings for the last 12 months and the dates of reading. Fleets must report two hour meter readings, one from before or on March 1 of the previous year and one from on or after March 1 of the current year. If using the three-year rolling average option, fleets must report two hour meter readings, one from before or on March 1 of the first year of the three yearperiod, and one from on or after March 1 of the current year.
2. Vehicles Used In and Outside California - For vehicles defined as low-use that operate in and outside California, submit a log that contains the following information:
   a. Each date the vehicle entered California and the hour meter reading upon entry,
   b. Each date the vehicle exited California and the hour meter reading upon exit.

(3) New Fleet Reporting – New fleets must submit the information in section 2449(g)(1)(A) through (C) to ARB for vehicles subject to the regulation to ARB within 30 days of purchase or bringing such vehicles into the State. Beginning the first March 1 that is more than 30 days after the date of purchase or bringing a vehicle into the State, new fleets must comply with the annual reporting requirements in section 2449(g)(2).

(h) **Record keeping** – Fleet owners must maintain copies of the information reported under section 2449(g), as well as the records described in section 2449(h) below, and provide them to an agent or employee of the ARB within five business days upon request. Records must be kept at a location within the State of California.

(1) Changes Since Last Reporting Period - Any additions, deletions, or changes to the fleet since the last reporting.

(2) Vehicles Not Yet Labeled – For newly purchased or acquired vehicles or vehicles recently brought into the state that have not yet been labeled per section 2449(f)(2), records must be kept of the vehicle purchase date or the date the vehicle entered the state.

(3) VDECS Failure – Records of any VDECS failure and replacement.

(4) Fuel-based Strategy – Records of any approval from ARB Executive Officer to use a fuel strategy as in section 2449(e)(2).

(5) Experimental Diesel PM Control Strategy – For fleets using an experimental diesel PM control strategy, approval from the Executive Officer for use of the experimental diesel PM control strategy, the test plan and test data used in the experimental diesel PM control strategy application, etc.

(6) Manufacturer Delay – For any vehicles or VDECS for which the fleet owner is utilizing the equipment manufacturer delay provision in section 2449(e)(6), proof

of purchase, such as a purchase order or signed contract for the sale, including engine specifications for each applicable piece of equipment or vehicle.

(7) Early repowers – Fleets claiming credit for early repower under section 2449(d)(2)(A)2.a.i. shall maintain records of the date the repower was installed, the vehicle in which the repower was installed (vehicle manufacturer, vehicle model, vehicle model year, and vehicle serial number), the engine that was replaced (engine manufacturer, engine family (if any), engine serial number, engine model year, engine maximum power), and the repower engine (engine manufacturer, engine family, engine serial number, engine model year, and engine maximum power).

(8) Early Retirement - Fleets claiming credit for early turnover under section 2449(d)(2)(A)2.a.ii. shall maintain records of the vehicles that were retired including vehicle manufacturer, vehicle model, vehicle model year, and vehicle serial number. If the vehicles were sold, fleets must keep records of the sale including the date, sale price, and buyer.

(9) Record Retention – Each owner shall maintain the records for each vehicle subject to the regulation until it is retired and for the overall fleet as long as the owner has a fleet or March 1, 2030, whichever is earlier. If vehicle ownership is transferred, the seller shall convey the vehicle records to the buyer. If fleet ownership is transferred, the seller shall convey the fleet records to the buyer. Dealers must maintain records of the disclosure of regulation applicability required by Section 2449(j) for three years after the sale.

(i) **Right of Entry** – For the purpose of inspecting off-road vehicles and their records to determine compliance with these regulations, an agent or employee of ARB, upon presentation of proper credentials, has the right to enter any facility (with any necessary safety clearances) where off-road vehicles are located or off-road vehicle records are kept.

(j) **Disclosure of Regulation Applicability** – Any person selling a vehicle with an engine subject to this regulation in California must provide the following disclosure in writing to the buyer on the bill of sale, "When operated in California, any off-road diesel vehicle may be subject to the California Air Resources Board In-Use Off-road Diesel Vehicle Regulation. It therefore could be subject to retrofit or accelerated turnover requirements to reduce emissions of air pollutants. For more information, please visit the California Air Resources Board website at http://www.arb.ca.gov/msprog/ordiesel/ordiesel.htm."

(k) **Penalties** – Any person who fails to comply with the performance requirements of this regulation, who fails to submit any information, report, or statement required by this regulation, or who knowingly submits any false statement or representation in any application, report, statement, or other document filed, maintained, or used for the purposes of compliance with this regulation may be subject to civil or criminal penalties under sections 39674, 39675, 42400, 42400.1, 42400.2, 42402,.2, and 43016 of the Health and Safety Code. In assessing penalties, the Executive Officer will consider factors, including but not limited to the willfulness of the violation, the

length of time of noncompliance, whether the fleet made an attempt to comply, and the magnitude of noncompliance.

Authority and References- This regulatory action is proposed under the authority granted to the ARB in Health and Safety Code sections 39002, 39515, 39516, 39600, 39601, 39602, 39650, 39656, 39658, 39659, 39665, 39667, 39674, 39675, 40000, 41511, 42400, 42400.1, 42400.2, 42402.2, 43000, 43000.5, 43013, 43016, and 43018. This action is proposed to implement, interpret, or make specific Health and Safety Code sections 39002, 39515, 39516, 39600, 39601, 39602, 39650, 39656, 39657, 39658, 39659, 39665, 39667, 39674, 39675, 40000, 41511, 42400, 42400.1, 42400.2,, 42402.2, 43000, 43000.5, 43013, 43016, and 43018.

Attachment A –

Use the values in these tables unless engine is a flexibility engine certified January 1, 2007 or later to the implementation flexibility standards 13 CCR 2423(d), or unless the engine is an engine certified to on-road standards. Engines certified to on-road standards should use the standard to which the engine is certified. Flexibility engines certified January 1, 2007 or later should use the emission standard to which the engine is certified. Engines certified to Family Emission Limits should still use the emission factors in the table below.

For engines that have been retrofit with VDECS, the PM Emission Factor is reduced 50 percent for a Level 2 VDECS, and 85 percent for a Level 3 VDECS; the NOx Emission Factor is reduced by whatever percentage NOx emission reductions are verified. The PM Emission Factor is not reduced for a Level 1 VDECS.

PM Emissions Factors by Horsepower and Year (g/bhp-hr)								
Engine Model Year	Horsepower Group							
	25-49	50-74	75-99	100-174	175-299	300-599	600-750	Over 750
1900-1969	0.950	1.200	1.200	1.100	1.100	0.950	0.950	0.950
1970-1971	0.950	1.200	1.200	0.940	0.940	0.810	0.810	0.810
1972-1987	0.950	1.200	1.200	0.780	0.780	0.680	0.680	0.680
1988	0.950	0.980	0.980	0.540	0.540	0.490	0.490	0.490
1989-1995	0.950	0.980	0.980	0.540	0.540	0.490	0.490	0.490
1996	0.950	0.980	0.980	0.540	0.40	0.40	0.40	0.500
1997	0.950	0.980	0.980	0.600	0.40	0.40	0.40	0.500
1998	0.950	1.090	1.090	0.600	0.40	0.40	0.40	0.500
1999	0.60	1.090	1.090	0.600	0.40	0.40	0.40	0.500
2000	0.60	1.090	1.090	0.600	0.40	0.40	0.40	0.40
2001	0.60	1.090	1.090	0.600	0.40	0.15	0.40	0.40
2002	0.60	1.090	1.090	0.600	0.40	0.15	0.15	0.40
2003	0.60	1.090	1.090	0.22	0.15	0.15	0.15	0.40
2004	0.45	0.30	0.30	0.22	0.15	0.15	0.15	0.40
2005	0.45	0.30	0.30	0.22	0.15	0.15	0.15	0.40
2006	0.45	0.30	0.30	0.22	0.15	0.15	0.15	0.15
2007	0.45	0.30	0.30	0.22	0.15	0.15	0.15	0.15
2008	0.22	0.22	0.30	0.22	0.15	0.15	0.15	0.15
2009	0.22	0.22	0.30	0.22	0.15	0.15	0.15	0.15
2010	0.22	0.22	0.30	0.22	0.15	0.15	0.15	0.15
2011	0.22	0.22	0.30	0.22	0.015	0.015	0.015	0.07
2012	0.22	0.22	0.015	0.015	0.015	0.015	0.015	0.07
2013	0.02	0.02	0.015	0.015	0.015	0.015	0.015	0.07
2014	0.02	0.02	0.015	0.015	0.015	0.015	0.015	0.07
2015 and later	0.02	0.02	0.015	0.015	0.015	0.015	0.015	0.03

NOx Emissions Factors by Horsepower and Year (g/bhp-hr)								
Engine Model Year	Horsepower Group							
	25-49	50-74	75-99	100-174	175-299	300-599	600-750	Over 750
1900 – 1969	7.2	14.8	14.8	15.9	15.9	15.2	15.2	15.2
1970 – 1971	7.2	14.8	14.8	14.8	14.8	14.1	14.1	14.1
1972 – 1979	7.2	14.8	14.8	13.6	13.6	13.0	13.0	13.0
1980 – 1987	7.2	14.8	14.8	12.5	12.5	11.9	11.9	11.9
1988	7.1	9.9	9.9	9.3	9.3	8.9	8.9	8.9
1989 – 1995	7.1	9.9	9.9	9.3	9.3	8.9	8.9	8.9
1996	7.1	9.9	9.9	9.3	6.9	6.9	6.9	8.9
1997	7.1	9.9	9.9	6.9	6.9	6.9	6.9	8.9
1998	7.1	6.9	6.9	6.9	6.9	6.9	6.9	8.9
1999	6.2	6.9	6.9	6.9	6.9	6.9	6.9	8.9
2000	6.2	6.9	6.9	6.9	6.9	6.9	6.9	6.9
2001	6.2	6.9	6.9	6.9	6.9	4.2	6.9	6.9
2002	6.2	6.9	6.9	6.9	6.9	4.2	4.2	6.9
2003	6.2	6.9	6.9	4.3	4.3	4.2	4.2	6.9
2004	4.9	4.9	4.9	4.3	4.3	4.2	4.2	6.9
2005	4.9	4.9	4.9	4.3	4.3	4.2	4.2	6.9
2006	4.9	4.9	4.9	4.3	2.6	2.6	2.6	4.2
2007	4.9	4.9	4.9	2.6	2.6	2.6	2.6	4.2
2008	4.9	3.0	3.0	2.6	2.6	2.6	2.6	4.2
2009	4.9	3.0	3.0	2.6	2.6	2.6	2.6	4.2
2010	4.9	3.0	3.0	2.6	2.6	2.6	2.6	4.2
2011	4.9	3.0	3.0	2.6	1.5	1.5	1.5	2.6
2012	4.9	3.0	2.5	2.5	1.5	1.5	1.5	2.6
2013	3.0	3.0	2.5	2.5	1.5	1.5	1.5	2.6
2014	3.0	3.0	2.5	2.5	0.3	0.3	0.3	2.6
2015 and later	3.0	3.0	0.3	0.3	0.3	0.3	0.3	2.6