APPENDIX D

REVIEW OF PM EMISSION REDUCTION TECHNOLOGY

In September 2001 and March 2002, staff updated the Board on the status of advanced aftertreatment technology for particulate matter (PM) and oxides of nitrogen (NOx). In this Appendix, staff summarizes and discusses the status of these technologies. The discussion pertains specifically to availability and how retrofit technologies reduce NOx and PM, although other pollutants such as carbon monoxide (CO) and HC may also be significantly reduced through these emission control systems.

AFTERTREATMENT TECHNOLOGY STATUS UPDATE

A. Advanced PM Aftertreatment Technology

There are several available emission control technologies, including engine modifications, that can reduce diesel PM emissions from diesel-fueled engines. Many of these emission control technologies are already being used today in a variety of engine applications to reduce diesel PM emissions. Below is a summary of the emission control technologies that will play a key role in reducing exposures to diesel PM.

1. Diesel Particulate Filter

A diesel particulate filter (DPF) is positioned in the exhaust stream to trap or collect a significant fraction of the particulate emissions while allowing the exhaust gases to pass through the system. Since the volume of particulate matter generated by a diesel engine is sufficient to fill up and plug a reasonably sized filter over time, a means of disposing of the trapped particulate ("regeneration") must be provided. The most common means of disposal is to oxidize or burn the particulate in the filter. To facilitate filter regeneration on diesel engines in real operations, the exhaust gas temperature has to be increased or the soot ignition temperature has to be lowered using a catalyst.

DPFs can incorporate either passive or active regeneration techniques. Passive systems rely on the heat of the exhaust, usually with the aid of a catalyst, to combust the PM at a higher average rate than the rate at which the PM is accumulated. Thus, the applicability of passively regenerating diesel particulate filters may be limited to applications with moderate to low engine-out PM emissions and higher exhaust temperatures. The use of low sulfur fuel (15 parts per million) with DPFs minimizes sulfate formation and in some cases is necessary for proper catalytic operation.

Programs are underway to evaluate the correlation between levels of sulfur in diesel fuels and the effectiveness of retrofit (both PM and NOx) devices. In one demonstration program, BP/ARCO is testing its low sulfur diesel fuel, ECD-1, on catalysts and particulate filters made by Johnson Matthey and Engelhard. ECD-1 contains a maximum of 15 ppm sulfur. The first round of emission results from the BP/ARCO demonstration program indicate that PM, HC, and CO are reduced by greater than 90 percent (LeTavec 2001). A second round of emission tests one year later supports the same conclusion.

The Clean Diesel Demonstration Program conducted by New York City Transit (NYCT) tested the results of using PM retrofits on urban buses (MTA NYCT 2001). The program was designed to test the emissions using these systems: (1) original equipment manufacturer (OEM) diesel oxidation catalyst (DOC) using 350 ppm sulfur diesel fuel; (2) OEM DOC using 30 ppm sulfur diesel fuel; and (3) Johnson Matthey's Continuously Regenerating Technology (CRT™) particulate filter using 30 ppm sulfur diesel fuel.

The conclusions drawn from this study were: (1) the use of the ultra-low sulfur diesel fuel alone resulted in a 76 percent average reduction in the total HC, 29 percent average reduction in CO, and 29 percent average reduction in PM; and (2) the CRT™ resulted in 93-98 percent reductions in total HC, CO, and PM, using the New York Bus Cycle. The CRT™ testing continued until November 2001. Confident in the results of this program, NYCT has contracted for ultra low sulfur diesel fuel for its entire fleet for three years starting from September 2000. NYCT has also committed to retrofitting 100 percent of its fleet of 3500 buses by the end of 2003 (MTA NYCT 2001). Diesel particulate filters have been retrofitted onto 1150 buses as of August 2002. All buses retrofit so far have had 1994 or later model year engines; all remaining buses with pre-1994 engines are expected to be retired by the end of 2003 (Dana Lowell, personal communication, 2002).

Another issue that has arisen with regards to passive DPFs is that in these systems, the catalyst oxidizes NO to NO_2 and uses the produced NO_2 as an oxidant to remove the PM trapped in the filter material. Measurements of NO_X emissions (NO and NO_2) from heavy-duty diesel vehicles equipped with passive catalyzed filters have shown an increase in the NO_2 fraction, though total NO_X emissions remain approximately the same. Passive catalyzed filters oxidize NO to NO_2, which burns soot captured in the filter. More NO_2 is created than is actually used in the regeneration process; and the excess is emitted. In fact, the NO_2 to NO_X ratios could range from 20 to 70 percent, depending on factors such as the diesel particulate filter systems, sulfur level in diesel fuel, and the duty cycle (DaMassa, 2002). To minimize the possible effects on population exposure to ozone and NO_2, the ARB has established a cap of 20 percent of NO_2 to NOx emission ratio for all diesel emission control technologies. To ensure that the cap does not penalize retrofit strategies that reduce total NOx emissions, the 20 percent cap is determined from the baseline (pre-control) emissions.

The applicability of passively regenerating diesel particulate filters may be limited to applications with moderate to low engine-out PM emissions and higher exhaust temperatures, because passive DPF systems rely on the heat of the exhaust, to combust the PM at a higher average rate than the rate at which the PM is accumulated. Thus, although these conditions typically encompass latemodel buses, they do not include all buses. For example, older two-stroke engines are likely to require different control strategies. For those and other applications in which the engine-out PM level is relatively high and the exhaust temperatures are relatively cool, actively regenerating systems are more appropriate. Active systems typically use an external source of heat to oxidize the particulate matter. The most common methods involve electrical regeneration by passing current through a heating element, injecting fuel to provide additional heat for particle oxidation, or the use of a fuel-borne catalyst or other reagent to initiate regeneration. Off-road applications of these active systems have been implemented in Europe since the early 1990's (Mayer and Wyser 2001). However, it should be recognized that passive systems are more attractive from a user's standpoint as they are expected to require less maintenance and to be less expensive.

2. Diesel Oxidation Catalyst

A diesel oxidation catalyst (DOC) converts pollutants into harmless gases by promoting chemical oxidation. The catalyst, which is similar in design to catalysts used on passenger cars, oxidizes CO, gaseous HC, and the liquid HCs adsorbed on the carbon particles present in diesel exhaust gases. The liquid and gas phase HCs are referred to as the soluble organic fraction (SOF). The SOF is one component of the total PM in exhaust emissions. Oxidation catalysts can reduce the SOF by 90 percent under certain operating conditions (MECA 1998), and according to staff estimates, could reduce total particulate emissions by greater than 30 percent.

Additional benefits of the DOC include oxidation of several HC-derived emissions, such as aldehydes or polynuclear aromatic hydrocarbons (PAHs), as well as reduction or elimination of the diesel exhaust odor. The DOC also oxidizes sulfur dioxide (SO_2), which is present in diesel exhaust from the combustion of sulfur containing fuels, generating sulfate particles and may increase total particulate emissions. Reducing the sulfur content of the fuel will reduce the sulfate particles formed. Oxidation catalysts have proven effective in achieving modest PM emission reductions on older buses. Under the U.S. EPA's urban bus rebuild/retrofit program, five manufacturers (Detroit Diesel Corporation, Engelhard, Johnson Matthey, Twin Rivers Technologies, and Engine Control Systems) have certified diesel oxidation catalysts as providing at least a 25 percent reduction in PM emissions (U.S. EPA 2001; MECA 1998).

The Diesel Emission Control – Sulfur Effects (DECSE) Program is a joint government/industry program created to investigate the effects of diesel fuel sulfur levels on emission control systems such as diesel oxidation catalysts. Two DOCs (low and high temperature catalysts) were tested before, during, and after a 250-hour aging cycle using four different sulfur level diesel fuels (DECSE 2001). The reduction efficiencies for HC, CO, and PM were evaluated. Results from this study indicated that fuel sulfur level does not significantly affect performance degradation. Some performance loss, however, was noted as early as 250 hours after initial installation. Other results from the same study showed that low sulfur diesel fuel is needed if a DOC is to be used as an efficient emission control device.

Some potential adverse environmental impacts of DOCs have been identified. First, as is the case with most processes that incorporate catalytic oxidation, the formation of sulfates increases at higher temperatures. Depending on the exhaust temperature and sulfur content of the fuel, the increase in sulfate particles may offset the reductions in SOF emissions. Using low sulfur (15 parts per million) diesel fuel can minimize this effect. Second, a DOC could be considered a "hazardous waste" at the end of its useful life depending on the material(s) used in the catalytic coating. However, DOCs can be manufactured with catalytic coatings such that the product would not be considered a hazardous waste. Finally, because the oxidation process converts NO to $NO_{2,}$, the emissions of NO_2 could increase. However, these concerns are relatively minor, and DOCs have been successfully used as original equipment in numerous diesel engines for many years.

3. Fuel Additives

Fuel additives are substances added to the fuel to reduce the total mass of PM, with variable effects on CO, NOx and HC production. When additives are used alone, the PM reduction range from 15 percent to 50 percent, although reduction as high as 99 percent can be seen when additives are used with a DPF. Some additive-based systems reduce polynuclear aromatic hydrocarbons by around 80 percent.

Fuel-borne catalysts (FBCs) are fuel additives added to diesel fuel to aid in soot removal in diesel particulate filters by decreasing the ignition temperature of the carbonaceous exhaust. Additionally, FBC can improve fuel economy, aid other retrofit systems, and decrease mass PM emissions. FBC/DPF systems are widely used in Europe for on-road and off-road, mobile and stationary applications. Typical FBC materials include cerium, platinum, iron, strontium, and sodium. Most additives act to reduce soot combustion temperature, thereby facilitating filter regeneration and potentially preventing excessive filter loading and/or uncontrolled regeneration. Additives can be used with both passive and active systems.

The additive is added to the fuel in one of three methods: dosing the bulk fuel, incorporating an on-board dosing system in the vehicle, or allowing consumers to add the additive directly. The last method is least attractive due to high likelihood of user error, thus allowing for situations where the vehicle may run with an inappropriate additive dose. The formulation concentration of the additive, as well as the actual base constituent of the additive, will profoundly affect the behavior of the FBC. When used with a DPF, approximately 1% of metal consumed is emitted in the tailpipe exhaust. Although some similarities exist among FBCs, it is inappropriate to draw generalizations between additives. Additionally, additives with similar active ingredients can have significant differences.

A question left unanswered about FBCs is the potential long-term health effect of metals used in FBCs. When FBCs are used at high treatment rates without filters, there is a potential for high levels of metal emissions and an increase in ultra-fine particles. Other concerns associated with the use of FBCs include incompatibility with other applications and interference with normal engine functioning. Further investigations are needed to address these potential concerns.

4. Alternative Diesel Fuels

Alternative diesel fuels, such as biodiesel, synthetic diesel, and water emulsions, have also shown to reduce diesel PM emissions. Biodiesel fuel, a renewable energy source, is derived from vegetable oils or animal fats. Biodiesel can be used for combustion in a diesel engine either in the pure state or blended with diesel fuel. Biodiesel fuel blends that include oxygenate additives can decrease PM emissions, but can also increase NOx emissions. In addition, in some cases biodiesel may not be compatible with alloys and elastomers commonly used in diesel engines necessitating special engine material design considerations.

Synthetic diesel fuels are manufactured using carbon-containing feedstocks, such as natural gas or coal. The most widely known synthetic diesel fuel technology is the Fischer-Tropsch process. Synthetic diesel fuels are attractive because they do not require modifications to existing diesel engines. The fuels can be designed to provide both good engine performance and emission reductions. The high cetane numbers and low sulfur content of synthetic fuels promote emission reductions of several diesel exhaust pollutants. Significant reductions in diesel emissions, including NOx and PM, have been reported when using synthetic fuel. Because the sulfur content is very low, synthetic fuels are compatible with a range of sulfur-sensitive aftertreatment technologies, such as lean NOx catalysts or passive filters.

Water-fuel emulsions are a third type of alternative diesel fuel. The various emulsifying technologies being developed utilize chemical additives (surfactants), high pressures, or electrical phenomena and have 20-30% water in their formulations. NOx and PM emissions have been reduced 40-50% using water-fuel emulsions. One drawback to this method is the increase of HC and CO emissions. However, this increase can be mitigated by the use of a DOC. Although water emulsions appear to be a promising diesel emission control technology, they have been known to alter the fuel lubricity and corrosion properties. The stratification of the emulsified fuel during storage is another problem associated with technology. Further development is needed to eliminate these undesirable properties of the fuels.

B. Technology Evaluation

1. Retrofit Requirements

Following is the summary of the urban transit bus fleet rule requirements for retrofitting diesel bus engines to reduce diesel PM emissions in use, which are being proposed for modification. Title 13, CCR, section 1956.2 (f) requires that older engines be retrofitted to reduce diesel PM earlier than newer engines. Specifically, 100 percent of pre-1991 MY (Tier 1) diesel engines must be retrofitted with technology that will reduce diesel PM by 85 percent by January 1, 2003. The same requirement applies to a lower percentage of MY 1991 through 1995 (Tier 2) engines by January 1, 2003, under a phase-in period. The deadline for full compliance for all 1995 and older models is January 1, 2004, for transit agencies on the diesel path and January 1, 2005, for transit agencies on the alternative-fuel path.

For Tier 3, or 1996 through 2002 MY, engines, the rule specifies that these be retrofitted under a phase in schedule as follows: for diesel path transit agencies, 20 percent by January 1, 2005; 75 percent by January 1, 2006; and 100 percent by January 1, 2007. Transit agencies on the alternative-fuel path have two additional years to begin and conclude retrofits, as follows: 20 percent by January 1, 2007; 75 percent by January 1, 2008; and 100 percent by January 1, 2009. Included in the retrofit requirements are the following exemptions:

(1) MY 1990 and earlier engines that were originally certified to 0.6 g/bhp-hr PM and have been retrofitted to 0.1 g/bhp-hr PM with an ARB certified retrofit device are exempt from further retrofits;

(2) Tier 2 and 3 buses, operated by transit agencies on the alternative fuel path, that are within two years of retirement are exempt from the retrofit requirements; and

(3) Tier 2 and 3 buses, operated by transit agencies on the diesel path, that are within one year of retirement are exempt from the retrofit requirements.

2. Requirements for Technology Verification

Prior to its use in any transit bus, ARB requires that a retrofit device be verified to reduce diesel particulate matter emissions by 85 percent or, alternatively, to levels of 0.01 g/bhp-hr or below (title 13, CCR, section 1956.2(f)(7)). The ARB staff is developing regulations regarding the evaluation of retrofit devices. In recognition of the major role that retrofit technologies must play in the reduction of public exposure to diesel PM, the Board has adopted a verification procedure to verify emission reductions.

The verification process is intended to ensure that retrofit devices provide the necessary reductions while remaining durable. Prior to a device being verified, the manufacturer must provide a general description of the emission control system, including the principles of operation; effects on engine performance and fuel consumption; any fuel requirements (e.g., diesel fuel with a sulfur level of 15 ppm or less); and maintenance requirements. In addition, the manufacturer must provide emissions test data (including NO_2 measurements), and durability data. Devices intended for heavy-duty engines, such as those used in transit buses, must show a durability of 50,000 miles or 1,000 hours.

Installation of emission control equipment in the exhaust system of a vehicle may result in increases in backpressure. The manufacturer must therefore demonstrate that the resulting backpressure is within the engine manufacturer's specified limits, or will not result in any damage to the engine. Acknowledging this, the verification procedure requires that a backpressure monitor be installed for all filter-based systems.

To ensure acceptability to the user, the manufacturer must provide a warranty that covers defects and damage to the vehicle. In addition, the manufacturer must clearly specify in the owner's manual the following information:

- Warranty statement including the warranty period over which the manufacturer is liable for any defects;
- Installation and maintenance requirements;
- Fuel consumption penalty, if any;
- Fuel limitations, if any (e.g., sulfur content);
- Contact information for the manufacturer of replacement components and maintenance supplies.
- Safety considerations.

3. Verified Technologies

As of August, 2002, the ARB staff has verified the following particulate control strategies for retrofit use:

Level 3 - 85 percent or greater PM reduction

- Clean Air Partners - diesel particulate filter for use with specific Power Systems Associates natural gas/diesel bi-fuel engines and Caterpillar engines which have been converted to bi-fuel operation using the Power Systems Associates and Clean Air Partners bi-fuel retrofit systems.

- Engelhard - DPX™ diesel particulate filters for use with most 1994-2002 model year diesel engines in on-road applications using 15 ppm or less sulfur fuel. All of these engines are four-stroke, turbocharged, and were certified in California to the 0.1 gram per brake horsepower-hour (g/bhp-hr) PM emission standard when new.

- Johnson Matthey - CRT™ diesel particulate filters for use with most 1994-2002 model year diesel engines in on-road applications using 15 ppm or less sulfur fuel. All of these engines are four-stroke, turbocharged, and were certified in California to the 0.1 gram per brake horsepower-hour (g/bhp-hr) PM emission standard when new.

Level 3 - 85 percent or greater PM reduction with 25 percent NOx reduction

- Cleaire - Flash and Catch™ system for use with specific 1994 through 1998 model year Cummins M11 engines, for steady state application (long haul truck), operating on low-sulfur fuel in on-road applications. The nature of the control place additional restrictions on the calibrations for which the controls will function. These other restrictions are detailed in the verification letters, which may be found on the ARB web site at http://www.arb.ca.gov/diesel/verifieddevices/verdev.htm.

Level 1 - 25 percent or greater PM reduction with 25 percent NOx reduction

- Cleaire - Flash and Match™ oxidation catalyst system for use with specific 1994 through 1998 model year Cummins M11 engines, for steady state application (long haul truck), in on-road applications. The nature of the control place additional restrictions on the calibrations for which the controls will function. These other restrictions are detailed in the verification letters, which may be found on the ARB web site at http://www.arb.ca.gov/diesel/verifieddevices/verdev.htm.

4. Availability of PM Emission Reduction Technology

At this time, two particulate control devices that achieve 85 percent control are available and ARB-verified for urban bus use (the Engelhard DPX™ and the Johnson Matthey CRT™). Those devices are verified only for 1994 and newer four-stroke engines. The devices are passive diesel particulate filters that utilize exhaust gas heat and a catalyst to regenerate. No system has been verified as of August 1, 2002, to reduce diesel PM emissions from older and two-stroke bus engines, at any level of PM reduction. In general, two-stroke bus engines are more technologically challenging to retrofit with a passive DPF because PM emissions tend to be higher than four-stroke engines. Furthermore, the exhaust gas temperature may not meet the minimum temperature required for spontaneous regeneration. Perhaps as importantly, the number of engines that are available to be retrofitted is relatively small and unlikely to grow, thus providing a disincentive for manufacturers to bring such a technologically challenging product to market.

Staff reported to the Board in March 2002 that the technology to reduce diesel PM emissions by 85 percent would not be available for pre-1994 MY engines in time to meet the January 2003, regulatory deadline. As a result, staff's proposal in this report revises the current PM retrofit requirement to allow transit agencies more flexibility to reduce in-use diesel PM emissions to the same level as envisioned by the original regulation. Transit agencies would use the funds already earmarked for the retrofit of the Tier 1 and Tier 2 engines to reduce their diesel PM emissions.