ADVANCED CLEANUP TECHNOLOGIES, INC.

June 21, 2010

California Environmental Protection Agency
Air Resources Board
C/O Clerk of the Board, Air Resources Board
1001 I Street, Sacramento, CA 95814
http://www.arb.ca.gov/listpub/comm/bclist.php

Attention:

**Re:** Request that CARB include ALECS in new proposed Railroad Industry contract agreements.

Dear Board Members,

ACTI requests that CARB include the Advanced Locomotive Emissions Control System (ALECS) in the proposed commitments between ARB and Union Pacific Railroad (UP) and BNSF Railway (BNSF) to further reduce diesel particulate matter (diesel PM) emissions at four high priority railyards. ALECS has already been demonstrated to be viable and cost-effective technology to help reduce diesel PM and is available now for commercial sale and use.

The ALECS captures diesel emissions from multiple locomotives and connects to a centralized emissions treatment system. This technology was developed by Advanced Cleanup Technologies, Inc. (ACTI) and is the same technology that has been successfully demonstrated to treat diesel emissions in oceangoing vessels. ALECS requires no modifications to the locomotive and does not interfere with railyard operations. ALECS can remove PM between cost effectively between $7/lb and $25/lb while also removing $NO_X$, $SO_X$, and VOC's.

The ALECS was successfully demonstrated at the Roseville Rail Yard August 1st, 2006. This demonstration was witnessed and jointly financed by the Placer County APCD, U.S. Environmental Protection Agency (EPA), Sacramento Metropolitan Air Quality Management District (SMAQMD), UPRR, Advanced Cleanup Technologies Inc. (ACTI), the South Coast Air Quality Management District (SCAQMD), the California Air Resources Board (CARB), and the City of Roseville. Also in August of 2006, independent tests were sponsored by the SCAQMD. The report, partially funded by SCAQMD, tests showed a removal efficiency of 98% for $NO_X$, 92% for PM, and 97% for $SO_X$.[1] Additionally, locomotive noise was reduced between 5 and 7 decibels.

The treatment system was subsequently moved to the Port of Long Beach for similar testing on oceangoing vessels. The diesel auxiliary engines on oceangoing vessels are very similar to locomotive engines. Although a different capture system is required for vessels, the treatment system is the same. One June 19, 2008, a public demonstration attended by EPA, SCAQMD, CARB, and others showed AMECS successfully connecting to a chemical tanker. On May 26 and July 16, 2008, system testing was successfully conducted and independent emissions testing were jointly funded by the Ports' Technology Advancement Plan (TAP) program, ACTI, The Port of Long Beach, Metro Ports, and the Southern California Air Quality Management District (SCAQMD) which confirmed emission reductions of more than 95% of particulate matter (PM), 96% volatile organic compounds (VOC's), 99% oxides of sulfur ($SO_X$) and 99% oxides of nitrogen ($NO_X$).[3]

ALECS is an important part of the March 2010 update to the SCAQMD Technology Advancement Office Clean Fuels Program.[6]

Additional testing is planned for the hood and ducting system, also known as the Emissions Capture System (ECS). This testing will focus on automated attachment to three or more locomotives concurrently, emissions capture efficiency, and time-and-motion studies to identify potential operational changes and considerations.

Railyards that have a service, maintenance, and test component would benefit the most from ALECS. These yards include as a minimum: UP Roseville, BNSF Barstow, BNSF Sheila Mechanical, UP Colton, UP Commerce, and UP ICTF.

ALECS is now ready for commercial sale and use and can be tailor designed to specific railyard requirements. Deliveries can be made within nine months from order date.

Thank you for your consideration in this matter.

Sincerely,

Ruben Garcia
President
Advanced Cleanup Technologies, Inc.

# Advanced Locomotive Emissions Control System (ALECS)

## Introduction

The Advanced Locomotive Emissions Control System (ALECS) captures diesel emissions from multiple locomotives at the same time with one centralized emissions treatment system. This technology was developed by Advanced Cleanup Technologies, Inc. (ACTI) and is the identical to the technology that has been successfully demonstrated to treat diesel emissions from oceangoing vessels. ALECS requires no modifications to the locomotive and does not interfere with railyard operations. ALECS can remove PM between cost effectively between $7/lb and $25/lb, depending upon the railyard, while also removing the majority of the $NO_X$, $SO_X$, and VOC emissions.

ALECS was successfully demonstrated at the Roseville Rail Yard August 1st, 2006. This demonstration was witnessed and jointly financed by the California Air Resources Board (CARB), Placer County APCD, U.S. Environmental Protection Agency (EPA), Sacramento Metropolitan Air Quality Management District (SMAQMD), UPRR, Advanced Cleanup Technologies Inc. (ACTI), the South Coast Air Quality Management District (SCAQMD), and the City of Roseville. Also in August of 2006, independent tests were sponsored by the SCAQMD. The report, partially funded by SCAQMD, that documented the results of these tests showed a removal efficiency of 98% for $NO_X$, 92% for PM, and 97% for $SO_X$.[1] Additionally, locomotive noise was reduced between 5 and 7 decibels.

The emissions treatment system was subsequently moved to the Port of Long Beach for similar testing on oceangoing vessels. The diesel auxiliary engines on oceangoing vessels are very similar to locomotive engines. Although a different capture system is required for vessels, the emissions treatment system is the same. One June 19, 2008, a public demonstration attended by EPA, SCAQMD, CARB, and others showed AMECS successfully connecting to a chemical tanker. On May 26 and July 16, 2008, system testing was successfully conducted and independent emissions testing were jointly funded by the Ports' Technology Advancement Plan (TAP) program, ACTI, The Port of Long Beach, Metro Ports, and the Southern California Air Quality Management District (SCAQMD) which confirmed emission reductions of more than 95% of particulate matter (PM), 96% volatile organic compounds (VOC's), 99% oxides of sulfur ($SO_X$) and 99% oxides of nitrogen ($NO_X$).[3]

Additional testing is planned for the hood and ducting system, also known as the Emissions Capture System (ECS). This testing will focus on automated attachment to three or more locomotives concurrently, emissions capture efficiency, and time-and-motion studies to identify potential operational changes and considerations.

Railyards that have a service, maintenance, and test component would benefit the most from ALECS. These yards include as a minimum: UP Roseville, BNSF Barstow, BNSF Sheila Mechanical, UP Colton, UP Commerce, and UP ICTF.

ALECS is now ready for commercial sale and use and can be tailor designed to specific railyard requirements. Deliveries can be made within nine months from order date.

## Background

Advanced Cleanup Technologies, Inc. (ACTI) originally specialized in Hazardous Waste Management and Environmental Emergency Response. The company, founded in 1992, has a highly trained staff experienced in emergency response and waste management services, with the capability to manage multiple incidents. ACTI is a recognized leader in emergency response and decontamination services, particularly on the West Coast, with five offices. ACTI is an approved Oil Spill Response Organization (OSRO) by the United States Coast Guard and the California State Department of Fish & Game, Office of Spill Prevention and Response. ACTI had a large response team assigned to the cleanup effort resulting from the Katrina hurricane disaster in Louisiana.

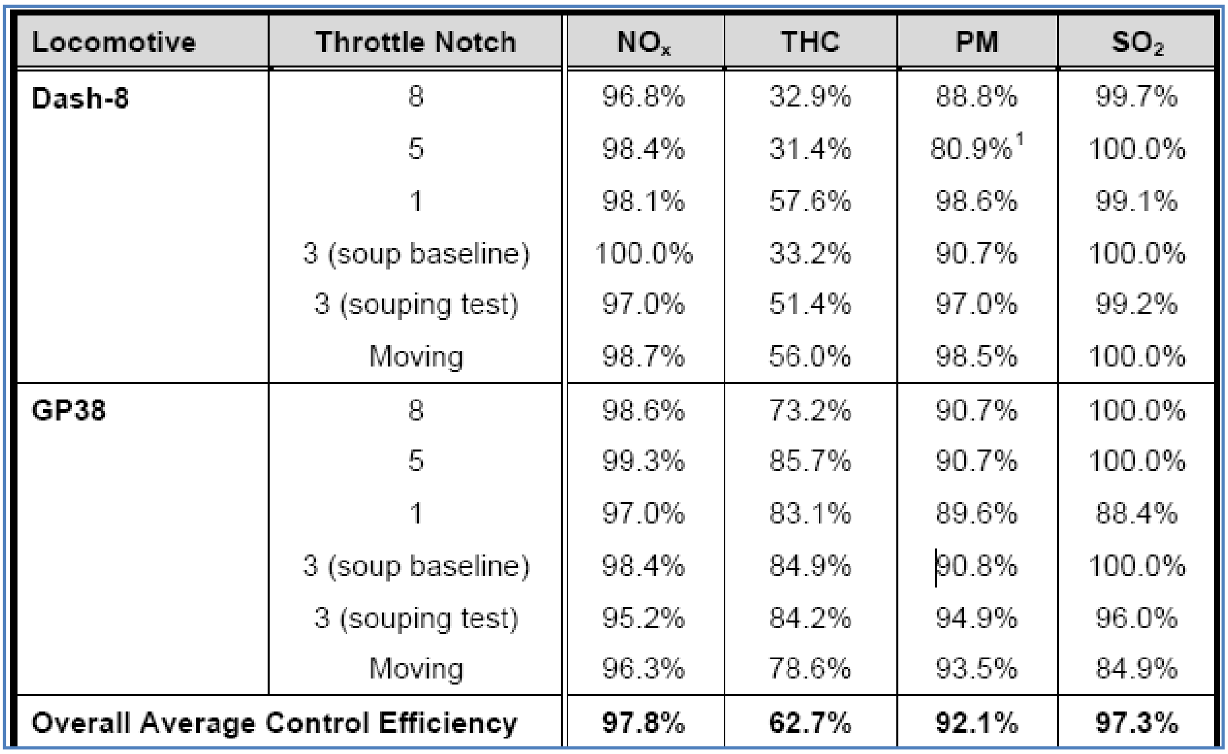
In 2004, ACTI developed a system to remove criteria pollutants from the exhaust gas of ocean going vessels anchored or berthed within seaports. This resulted in the Advanced *Maritime* Emissions Control System (AMECS), with several patents issued and more pending.

ACTI also began working with Placer County Air Pollution Control Distract (APCD) in late 2004 to ascertain if the same technology could also be applied to treat the emissions from railroad locomotives. In response, ACTI developed the Advanced *Locomotive* Emissions Control System (ALECS).

ALECS was successfully demonstrated at the Roseville Rail Yard August 1st, 2006. This demonstration was witnessed and jointly financed by the Placer County APCD, U.S. Environmental Protection Agency (EPA), Sacramento Metropolitan Air Quality Management District (SMAQMD), UPRR, Advanced Cleanup Technologies Inc. (ACTI), the South Coast Air Quality Management District (SCAQMD), the California Air Resources Board (CARB), and the City of Roseville.

Figure 1 - August 1, 2006 – Successful ALECS Demonstration in the Union Pacific Rail Yard in Roseville

Tests were conducted at the Union Pacific Rail Yard in Roseville, California in August 2006 and proved that the ETS effectively reduced pollutants in railroad locomotive diesel engines, which are very similar to ship auxiliary diesel engines.[3] These tests were funded jointly by ACTI, regulatory agencies (CARB, SCAQMD, Placer County APCD, Sacramento Metro APCD and US EPA), and Union Pacific Railroad.



| Locomotive | Throttle Notch | $NO_x$ | THC | PM | $SO_2$ |
|---|---|---|---|---|---|
| **Dash-8** | 8 | 96.8% | 32.9% | 88.8% | 99.7% |
| | 5 | 98.4% | 31.4% | 80.9%[1] | 100.0% |
| | 1 | 98.1% | 57.6% | 98.6% | 99.1% |
| | 3 (soup baseline) | 100.0% | 33.2% | 90.7% | 100.0% |
| | 3 (souping test) | 97.0% | 51.4% | 97.0% | 99.2% |
| | Moving | 98.7% | 56.0% | 98.5% | 100.0% |
| **GP38** | 8 | 98.6% | 73.2% | 90.7% | 100.0% |
| | 5 | 99.3% | 85.7% | 90.7% | 100.0% |
| | 1 | 97.0% | 83.1% | 89.6% | 88.4% |
| | 3 (soup baseline) | 98.4% | 84.9% | 90.8% | 100.0% |
| | 3 (souping test) | 95.2% | 84.2% | 94.9% | 96.0% |
| | Moving | 96.3% | 78.6% | 93.5% | 84.9% |
| **Overall Average Control Efficiency** | | **97.8%** | **62.7%** | **92.1%** | **97.3%** |

Figure 2 - ALECS Test Results at Roseville

Commencing 2005, Metropolitan Stevedore Company (Metro) began working with ACTI on the possibility of utilizing AMECS for use on bulk freighters hotelling at Port of Long Beach (POLB) Berths G212 and G214. In late 2006, the ETS was moved to the Metro docks.

The Bellows Bonnet was proven effective in two separate tests at Metro’s dock in 2007. In these preliminary tests, the ETS was not connected to the duct. Instead, a fan was installed on the dock to provide the motive power to suck the exhaust gas from the bonnet and through the duct.

September 7, 2007 – The first successful preliminary test of the Bellows Bonnet on the Western Seattle, without the ETS, and two hydraulic cranes.

November 11, 2007 – The second successful test of the Bellows bonnet, again on the Western Seattle. This time the “Extended Shroud” was tested for stack sealing.

May 26, 2008 – System testing was successfully conducted on the Queen Lily, a 76,629 DWT Panamax class Bulk Cargo Vessel. This was the first test to also demonstrate the complete system including the ETS and the Emissions Capture System (ECS) with a single tower crane and duct management system. Independent emissions testing were funded by the Ports’ Technology Advancement Plan (TAP) program and the Southern California Air Quality Management District (AQMD).

June 19, 2008 – A public demonstration was held which showed AMECS connecting to and processing exhaust from the Ginga Merlin, a Handysize, 19,999 DWT chemical tanker.

July 16, 2008 – The second successful system test was conducted on the Angela, a Handymax 52,541 DWT bulk cargo vessel. Independent testing during these two tests confirmed that AMECS removes 95% to 99% of harmful emissions.[3]

| | NOx | PM | VOC | $SO_2$ | CO |
|---|---|---|---|---|---|
| **QUEEN LILY** | >99.7% | 98.1% | 95.9% | 99.9% | 43.8% |
| **ANGELA** | >98.6% | 91.8% | 96.8% | 99.8% | ND |
| **Average Control Efficiency** | >99.1% | 95.0% | 96.3% | 99.8% | 43.8% |
| **Adjusted Average Control Efficiency**[1] | >97.6% | 95.0% | 96.3% | 99.8% | 43.8% |

Bellows Bonnet Test
Western Seattle, January 2008

Successful System Test
Queen Lily, May 2008

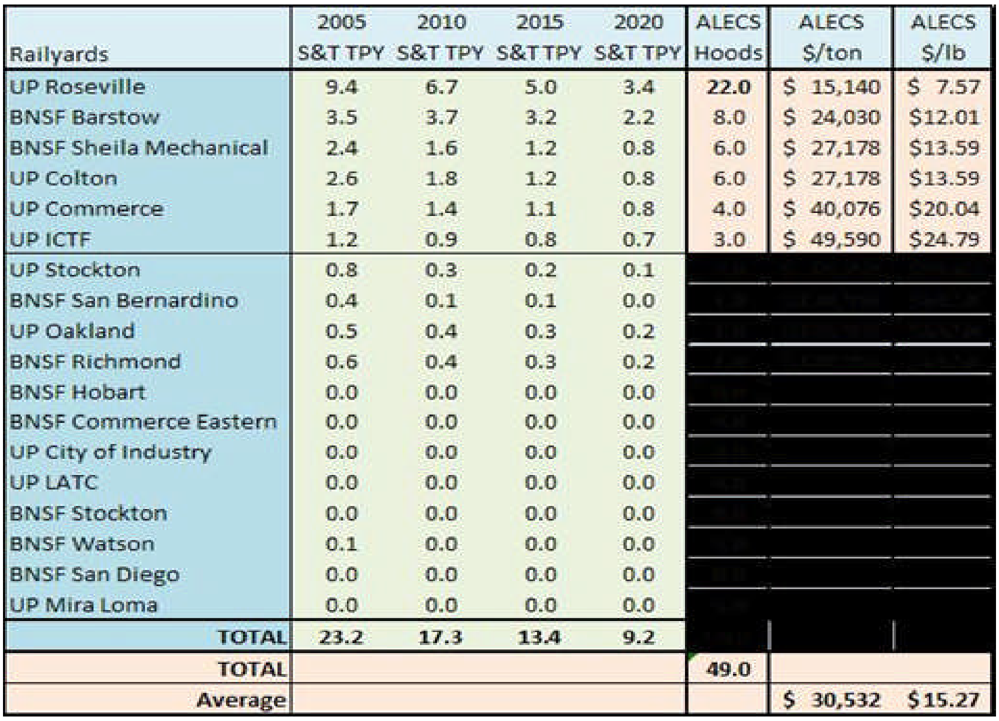
Successful Demonstration
Ginga Merlin, June 2008

Successful System Test
Angela, July 2008

October 2, 2009 – ACTI receives the AQMD Clean Air award.[4]

## Cost Effectiveness

The ALECS cost effectiveness is proportional to the number of hoods at each railyard. Depending on the railyard, the PM alone cost effectiveness ranges between $7.57/lb to $24.79/lb for the top six railyards in California with an average of $15.27/lb. Additionally, ALECS removes $NO_X$, $SO_X$, and VOC's which makes it even more cost effective. The most advantageous railyards for ALECS in California are UP Roseville, BNSF Barstow, BNSF Sheila Mechanical, UP Colton, UP Commerce, and UP ICTF.



| Railyards | 2005 S&T TPY | 2010 S&T TPY | 2015 S&T TPY | 2020 S&T TPY | ALECS Hoods | ALECS $/ton | ALECS $/lb |
|---|---|---|---|---|---|---|---|
| UP Roseville | 9.4 | 6.7 | 5.0 | 3.4 | **22.0** | $ 15,140 | $ 7.57 |
| BNSF Barstow | 3.5 | 3.7 | 3.2 | 2.2 | 8.0 | $ 24,030 | $12.01 |
| BNSF Sheila Mechanical | 2.4 | 1.6 | 1.2 | 0.8 | 6.0 | $ 27,178 | $13.59 |
| UP Colton | 2.6 | 1.8 | 1.2 | 0.8 | 6.0 | $ 27,178 | $13.59 |
| UP Commerce | 1.7 | 1.4 | 1.1 | 0.8 | 4.0 | $ 40,076 | $20.04 |
| UP ICTF | 1.2 | 0.9 | 0.8 | 0.7 | 3.0 | $ 49,590 | $24.79 |
| UP Stockton | 0.8 | 0.3 | 0.2 | 0.1 | [redacted] | [redacted] | [redacted] |
| BNSF San Bernardino | 0.4 | 0.1 | 0.1 | 0.0 | [redacted] | [redacted] | [redacted] |
| UP Oakland | 0.5 | 0.4 | 0.3 | 0.2 | [redacted] | [redacted] | [redacted] |
| BNSF Richmond | 0.6 | 0.4 | 0.3 | 0.2 | [redacted] | [redacted] | [redacted] |
| BNSF Hobart | 0.0 | 0.0 | 0.0 | 0.0 | [redacted] | [redacted] | [redacted] |
| BNSF Commerce Eastern | 0.0 | 0.0 | 0.0 | 0.0 | [redacted] | [redacted] | [redacted] |
| UP City of Industry | 0.0 | 0.0 | 0.0 | 0.0 | [redacted] | [redacted] | [redacted] |
| UP LATC | 0.0 | 0.0 | 0.0 | 0.0 | [redacted] | [redacted] | [redacted] |
| BNSF Stockton | 0.0 | 0.0 | 0.0 | 0.0 | [redacted] | [redacted] | [redacted] |
| BNSF Watson | 0.1 | 0.0 | 0.0 | 0.0 | [redacted] | [redacted] | [redacted] |
| BNSF San Diego | 0.0 | 0.0 | 0.0 | 0.0 | [redacted] | [redacted] | [redacted] |
| UP Mira Loma | 0.0 | 0.0 | 0.0 | 0.0 | [redacted] | [redacted] | [redacted] |
| **TOTAL** | **23.2** | **17.3** | **13.4** | **9.2** | [redacted] | [redacted] | [redacted] |
| **TOTAL** | | | | | **49.0** | | |
| **Average** | | | | | | **$ 30,532** | **$15.27** |

Figure 3 - PM Cost effectiveness at various yards

In practice, the cost effectiveness may actually be better than shown here. Some locomotives may produce more emissions, especially in service areas. For example, the independent testing in Roseville indicated much higher (double) emissions than EPA Tier 0 even after accounting for deterioration. Additionally, load testing is actually increasing in an effort to meet the new requirements.

Modifying procedures is very cost effective because there are no additional costs. For example, load testing in Roseville at night is now done at a remote site in order to minimize the noise pollution to nearby neighborhoods. It is actually easier to keep the locomotives in the service area for load testing.

The ETS scales back energy usage based on demand which maximizes efficiency and retains cost effectiveness during low periods. In addition, improvements have been made recently including a low temperature (400F) catalyst and a high efficiency heat exchanger (80%) which will improve cost effectiveness further.

## Planned Testing

Additional testing is planned for the hood and ducting system, also known as the Emissions Capture System (ECS). This testing will focus on automated attachment to three or more locomotives concurrently, emissions capture efficiency, and time-and-motion studies to identify potential operational changes and considerations.

Also, the Port of Long Beach, ACTI, and Metropolitan Stevedore will soon be conducting a 30-vessel durability study. This study will determine how the technology can be integrated into daily terminal operations, to determine actual labor costs, understand waste disposal generation and costs, assess the durability of the system and measure the cost effectiveness of the AMECS technology.

## ACTI Qualifications

Starting with nothing but an idea, and within a short period of time (2 years), ACTI conceived, designed, manufactured, installed, and successfully demonstrated ALECS at the Union Pacific Railroad's J.R. Davis rail yard in Roseville, California in the summer of 2006. Since then, ACTI has continued to demonstrate its ability to design and build systems for vessels as well in several tests and demonstrations.

This technology has been enthusiastically supported by all of the governmental agencies including EPA, CARB, and SCAQMD. The support from the Port of Long Beach and Metropolitan Stevedore in hosting AMECS operations demonstrates the interest of the ports and the terminal operators.

On December 8, 2009, the EPA determined that AMECS qualifies as an Emerging Technology.

The $SO_X$ & PM Scrubber and the Selective Catalytic Reduction (SCR) technologies are proven and have been in use in industrial applications for decades.

The California Air Resources Board (CARB) has reviewed and is in general agreement with ACTI's claim that AMECS is 1/3 to 1/5 the cost of Shore Power and has the potential to be twice as effective.

A Risk Assessment report was published by Det Norske Veritas on December 7, 2009 which states "The bonnet installation and removal process presents a nominal or low perceived risk to the vessel personnel and equipment."

ACTI has filed several patents applications on ALECS and AMECS with several being granted thus far.

## ALECS System Description

ALECS consists of the following two major systems: The Emissions Capture System (ECS) and the Emissions Treatment System (ETS).

### Exhaust Capture System

The Exhaust Capture System (ECS) collects exhaust gas from the locomotive and delivers it to the ETS. The hood is automatically positioned over and attached to the exhaust stack of the locomotive by an articulating arm. It is not necessary to have railyard personnel for this or any other part of the operation. The exhaust gases from the locomotives flow from the hood through the ducting into the centrally-located ETS where the criteria pollutants are removed.

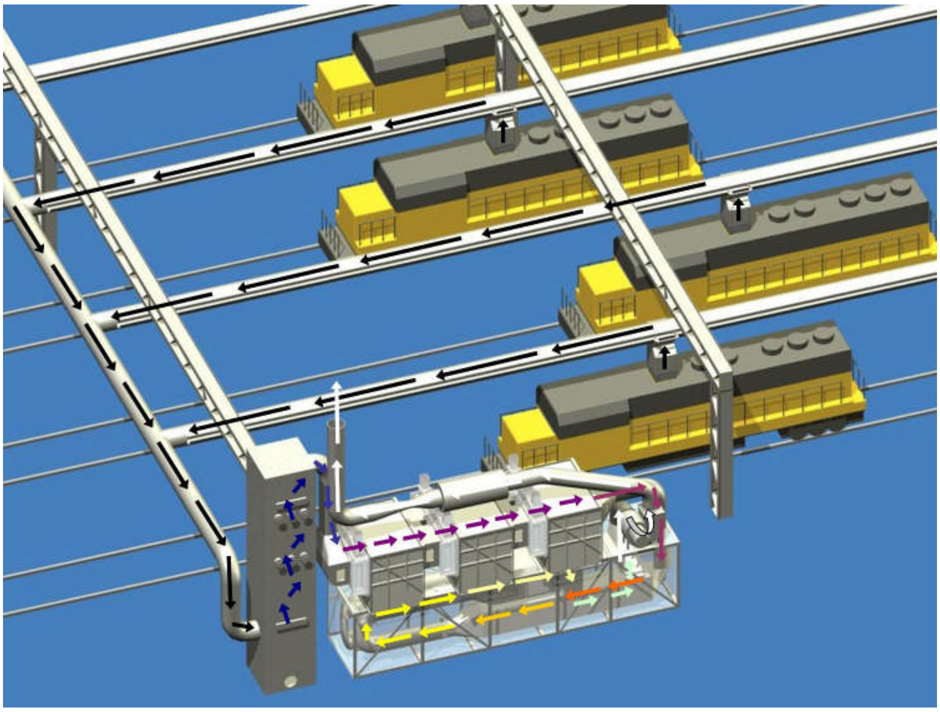


Figure 4 - The ALECS Emissions Capture System (ECS) delivers exhaust from multiple locomotives to a centralized treatment system.

The hood consists of a rectangular box that is sized to fit a wide variety of locomotives. A pressure relief damper assures that the locomotive engine is not subjected to any over/under pressure that could affect the locomotive.

A fan in the ETS maintains a slight vacuum within the hood. This ensures that the exhaust gases are delivered through the duct into the ETS.

The same arm that will be used on future AMECS systems can also be used on ALECS. This increases the economy of scale, reduces development costs, and increases reliability and maintainablility. The only difference is that there is no tower and ALECS hood would be used instead of the AMECS bonnet.

## Zone Locomotive Detection and Operation

The ALECS Arm is designed with maximum extention of 150 feet and each Arm covers its own zone which ranges from 80 to 150 feet in length. Each zone is monitored by a video camera with shape detection software. When a locomotive moves into a zone, it is detected by video shape detection. When the software determines that the locomotive has stopped for a period of time, then the Arm positions itself over the exhaust stack and connects. If the locomotive moves, the hood is immediately removed, and the Arm moves to the clear position.

## Multiple Zone Operation

The zone approach can easily be adapted to any railyard. As many zones as required are placed in the service, maintenance, and test areas. The base pedestal only requires a three foot diameter area on either side of the track, or it can be mounted on an overhead structure, depending on the layout of the yard. The arm can even be programmed to follow a curved track, thus maximizing flexibility.

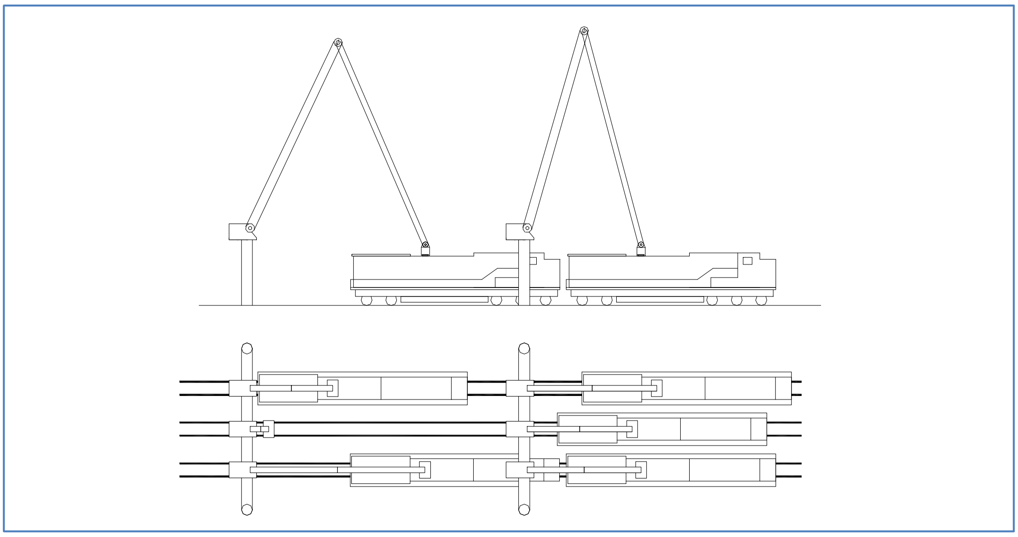


Figure 5 - Six-Zone Example

## ECS Operations

- The ALECS capture system is completely automatic, and does not require an operator and does not affect operations.
- The system effectiveness can be increased if the railyard concentrates more locomotives into the vicinity of the cells, which is a procedural change with little or no impact to the railyard.

## ECS Safety

- Each ALECS Arm can be locked-out/tagged-out if personnel would be working on top of the locomotive. In addition, a light curtain will shut the zone off if anyone steps onto the roof.
- The hood on the arm is free to swing, so if the locomotive moves before the arm is moved, it simply swings out of the way.

- The Arm is designed with stops to prevent it from dipping below a safe level. As a redundant feature, the Arm is designed to break loose if there is a collision, thus protecting the locomotive and the mechanical integrity of the support structure.
- If there is a power loss, then the Arm reverts to its default clear position.
- The system is designed to present a slightly less than atmospheric pressure to the exhaust stack. The locomotive will therefore not experience exhaust backpressure. If the pressure in the hood exceeds atmospheric pressure, than a simple safety damper opens.

### ECS Reliability

- The synergism of using the same Arm for AMECS and ALECS means that developmental improvements on one system benefit the other.
- The Arm is designed for the most hostile environments, which includes outdoor, salt/ocean, and dusty railyard applications. No electronics or controls are located near the severe, hot locomotive environment.

### ECS Cost Effectiveness

- Because AMECS and ALECS use the same arm, developmental costs are reduced.
- The AMECS/ALECS Arm reduces the extent of the overhead structure which lowers costs.
- The AMECS/ALECS Arm is designed so the arm structure also serves as the duct, reducing costs.

## Emissions Treatment System

The ETS consists of six major components: 1) the Preconditioning Chamber (PCC) that removes $SO_x$ and an some hydrocarbons (THC), 2) the $SO_X$ and PM Scrubber (SPS) that removes PM, 3) the Thermal Management System to increase operating efficiency, 4) the Selective Catalytic Reduction (SCR) Reactor for removal of $NO_x$, 5) the Control System and 6) the Continuous Emissions Measuring System (CEMS).

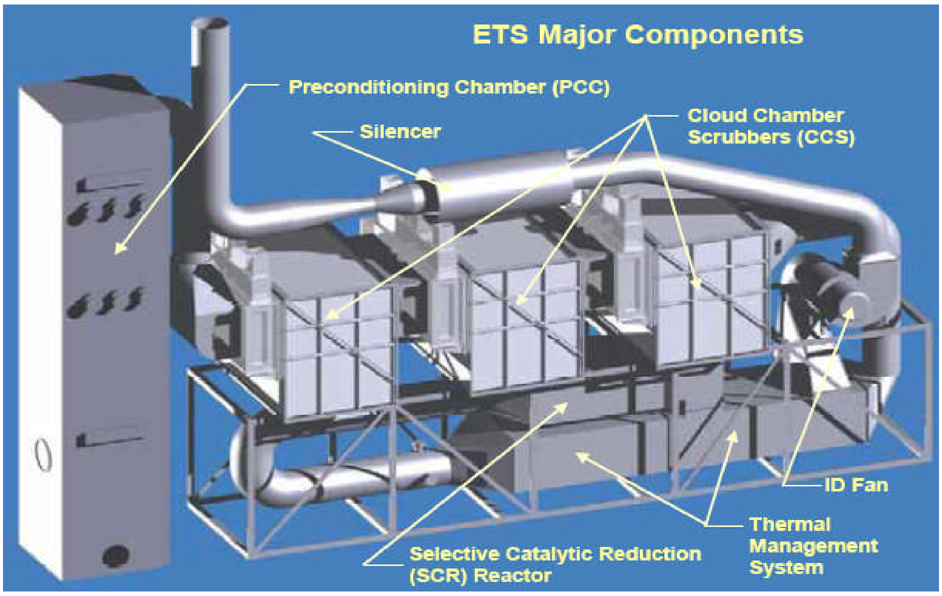


Figure 6 - Emissions Treatment System (ETS)

First, the hot exhaust gas from the vessel is passed through a scrubber, where the gas is cooled by a water spray. A caustic solution is added to the water to remove the $SO_2$ in the gas stream.

The second phase of treatment is the PM scrubber.

The third phase of emissions removal is a Selective Catalytic Reducer (SCR) where $NO_X$ is removed. This stage includes a waste heat recovery system. The gas is reheated to the SCR operating temperature using a heat exchanger and heater. The heat exchanger scavenges about 85% of the heat from the gas stream exiting the SCR and uses it to preheat the gas stream entering the SCR. Liquid urea is used as the NOx reactant. Urea is converted to ammonia when it mixes with the hot gas within the system ducting downstream of the heater and prior to entering the SCR, where the reaction takes place that reduces the NOx to nitrogen gas and water vapor.

The entire system is automated; startup requires only the push of one button. All important functions can be monitored and adjusted on a touch screen in the control room. Safeguards and redundancies are built into the system for failsafe operation and safe shutdown in an emergency.

Figure 7 - ETS processing vessel exhaust at the Port of Long Beach.

## References

1. “Evaluation of the Advanced Locomotive Emissions Control System (ALECS), ALECS Proof-of-Concept Testing at the Union Pacific J.R. Davis Rail Yard in Roseville, California”, Dated April 2, 2007, Prepared by TIAX LLC. www.placer.ca.gov/departments/.../**ALECS**FinalReport2007%20pdf.ashx
2. “Roseville Rail Yard Study”, California Environmental Protection Agency Air Resources Board, October 14, 2004, http://www.placer.ca.gov/Departments/Air/railroad.aspx
3. “Evaluation of the Advanced Maritime Emissions Control System (AMECS), AMECS Demonstration at the Port of Long Beach, California”, Report to SCAQMD, dated 11/18/08, Prepared by TIAX LLC.
4. ACTI receives AQMD Clean Air Award, “Advancement Of Air Pollution Technology Award”, http://www.aqmd.gov/news1/2009/2009cleanairawardspr.htm
5. Letter, Robert Fletcher, California Air Resources Board. “…staff expects the AMECS system to be capable of meeting the requirements of the Regulation to Reduce Emissions from Diesel Auxiliary Engines on Ocean-Going Vessels While At-Berth at a California Port.”
6. “Develop & Demonstrate Stationary Emission Control System for Marine Vessels (AMECS)”, SCAQMD Technology Advancement Office Update, March 2010

Innovation since 1886

# Evaluation of the Advanced Locomotive Emissions Control System (ALECS)

## ALECS Proof-of-Concept Testing at the Union Pacific J. R. Davis Rail Yard in Roseville, California

**Report to**
**Placer County Air Pollution Control District**
**3091 County Center Drive, Suite 240**
**Auburn, California 95603**

**Date: April 2, 2007**

**Prepared by**
**Michael Chan**
**Michael D. Jackson**
**TIAX LLC**
**1601 S. De Anza Blvd., Suite 100**
**Cupertino, California 95014-5363**
**Tel 408-517-1550**
**Fax 408-517-1553**

**Contract # 25249**
TIAX Case D0392

## Acknowledgments

Although TIAX is the author of this report, the project team provided invaluable contributions. TIAX would like to acknowledge the follow organizations and people:

Placer Country Air Pollution Control District: Tom Christofk for his leadership in developing this proof-of-concept project. Don Duffy for his program management skills to implement this project, and for providing the many suggestions on the drafts of this document. Bruce Springsteen for his help in developing the emissions testing protocol.

Union Pacific Railroad Company: Lanny Schmid, Michael Steel (Pillsbury Winthrop Shaw Pittman LLP), and Gary Rubenstein (Sierra Research) for their support of the project and many thoughtful comments on the test protocol and draft report. We also want to acknowledge the Union Pacific Railroad staff at the Roseville rail yard whose support was indispensable during testing.

Advanced Cleanup Technologies Inc.: Ruben Garcia, Sal Caro, John Powell, Bob Sharp and the entire ACTI team for their input on the Advanced Locomotive Emission Control System (ALECS) capital/operating costs and for their tireless efforts to design, build, and successfully test the first proof-of-concept system at the Roseville rail yard. Tri-Mer Corporation was a major subcontractor with the responsibility for design, fabrication, and operation during testing of the emissions control equipment. Thanks to Rod Gravely, Jody Farley and their team for their long hours in starting up and operating the equipment during testing.

Engine, Fuel, and Emissions Engineering, Inc.: Chris Weaver and his team for developing the test plan for this project and successfully implementing this plan for the first ALECS.

South Coast Air Quality Management District's Michael Bogdanoff and Sacramento Metropolitan Air Quality Management District's Larry Sherwood. SCAQMD funded the emissions testing and SMAQMD provided partial funding for TIAX's analyses and reporting.

Finally, many people from the above organizations contributed to this project to design and test a novel system to capture and treat exhaust emissions from locomotives. We would like to acknowledge the efforts of these staff.

## Table of Contents

## List of Tables

## List of Figures

## Executive Summary

The Union Pacific Railroad's J.R. Davis Rail Yard in Roseville, California, is a major center for locomotive maintenance and repair, as well as for assembling and reassembling trains of freight cars. Over 90 percent of all Union Pacific rail traffic in Northern California goes through the yard. Locomotive operations at the rail yard have been determined to be a significant source of emissions of diesel particulate matter (PM) and other pollutants. An agreement between the Placer County Air Pollution Control District (PCAPCD) and the Union Pacific Railroad Company (UPRR) includes a mitigation plan for reducing PM emissions from the rail yard. Part of this plan is an assessment of the use of stationary air pollution control equipment to capture and treat emissions from motionless locomotives while idling or undergoing engine load tests during maintenance.

The Advanced Locomotive Emission Control System (ALECS) comprises a set of stationary emissions control equipment connected to an articulated bonnet. The bonnet is designed to capture locomotive exhaust, delivering it to the ground-based emission control system via ducting. The hood remains attached while the locomotive is moving slowly along the track to the extent of the ducting. The emission control equipment comprises a sodium hydroxide wash to remove sulfur dioxide ($SO_2$), a triple cloud chamber scrubber for PM removal, and a Selective Catalytic Reduction (SCR) reactor to reduce oxides of nitrogen ($NO_x$). The ALECS is designed to treat exhaust flows between 2,000 and 12,000 standard cubic feet per minute (scfm). The former is approximately the exhaust flow from a locomotive at idle, while the latter is approximately the exhaust flow from a line-haul locomotive at throttle notch 8 (full power).

The ALECS proof-of-concept was a public-private collaborative project involving the PCAPCD, U.S. Environmental Protection Agency (EPA), Sacramento Metropolitan Air Quality Management District (SMAQMD), UPRR, Advanced Cleanup Technologies Inc. (ACTI), the South Coast Air Quality Management District (SCAQMD), the California Air Resources Board (CARB), and the City of Roseville. Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) was contracted by the SCAQMD to conduct emission measurements before and after the ALECS.

Emission measurements were performed on two locomotives: a General Motors Electro-Motive Division GP38 and a General Electric C39-8 (Dash 8). The GP38 has a 2000 horsepower two-stroke diesel engine, and is typically used for switching and local service. The Dash-8 has a 3900 horsepower four-stroke engine, and is normally used for line-haul freight service. Tests were performed with the locomotives motionless at notch 1, notch 3, notch 5, and notch 8 power settings, and while moving slowing back and forth along a small section of track.

Table 1 summarizes the overall average control efficiencies resulting from the proof-of-concept tests. Using these control efficiencies, estimates were made of the reduction in emissions that may result from use of one ALECS in a rail yard situation. The emission reductions are highly dependent on the specific operation addressed in a rail yard. Table 2 presents the range of emission reductions estimated for two very different applications in a rail yard. One case addresses all idling Tier 2 locomotives; while the other case utilizes Tier 0 locomotives addressing some load and diagnostic testing, with the remainder of the capacity servicing idling locomotives. These cases are meant to define the low and high end of possible emissions for the

ALECS. Actual rail yard installation will most likely yield emission reductions somewhere in between these two assumptions, depending on the specific application.

**Table 1. Summary of Pollutant Control Efficiencies**

| | $NO_x$ | HC | PM | $SO_2$ |
|---|---|---|---|---|
| **Overall Average Control Efficiency**[1] | 97.8% | 62.7% | 92.1% | 97.3% |

[1] ALECS demonstration at Roseville rail yard

**Table 2. Range of Estimated Emission Reductions (tons/yr)**

| | $NO_x$ | HC | PM |
|---|---|---|---|
| **Mixed Loads Tier 0 Emissions** | 83.4 | 8.44 | 2.53 |
| **Idling Only Tier 2 Emissions** | 40.0 | 2.49 | 1.29 |

The fully loaded total initial capital cost of the ALECS (for an estimated 12 bonnet system) is $8,680,126 with an annual operational cost of $899,926. The 12 bonnet system is sized to cover an area of the rail yard that allows for at least six locomotives to be connected and running at all times.

Cost effectiveness of the ALECS has been estimated using the total life cycle costs based upon annualizing (and adjusting for the time value of money) the capital investment and the net present value (discounted cash flow) of future operation and maintenance costs for the range of pollutants removed by the two rail yard operating scenarios. The estimated cost effectiveness curve for the total weighted pollutants reduced over the 20 year life of ALECS is illustrated in Figure 1. Pollutants considered in this estimate are $NO_x$, HC, and PM. Oxides of sulfur ($SO_x$) emissions that are reduced were not included in this cost effectiveness calculation. The PM emissions were weighted by a factor of 20 as is the practice with the current Carl Moyer Incentive Program guidelines. This weighting was used in calculating cost effectiveness because of the toxicity level of PM. ALECS was estimated to be in full operation 96 percent of the time. The cost effectiveness ranged between $18,437/ton in the all idling mode to $7,297/ton of weighted pollutant reduced in the mixed mode of a combination of locomotives at idle and at loads during maintenance testing.

Noise measurements where made on some high power runs to assess possible noise reductions due to the bonnet attached over the locomotive exhaust stack. Measurements with, and without the bonnet attached yielded noise reductions of 5.3 to 6.8 decibels, representing noise energy reductions of 70 to 79 percent.

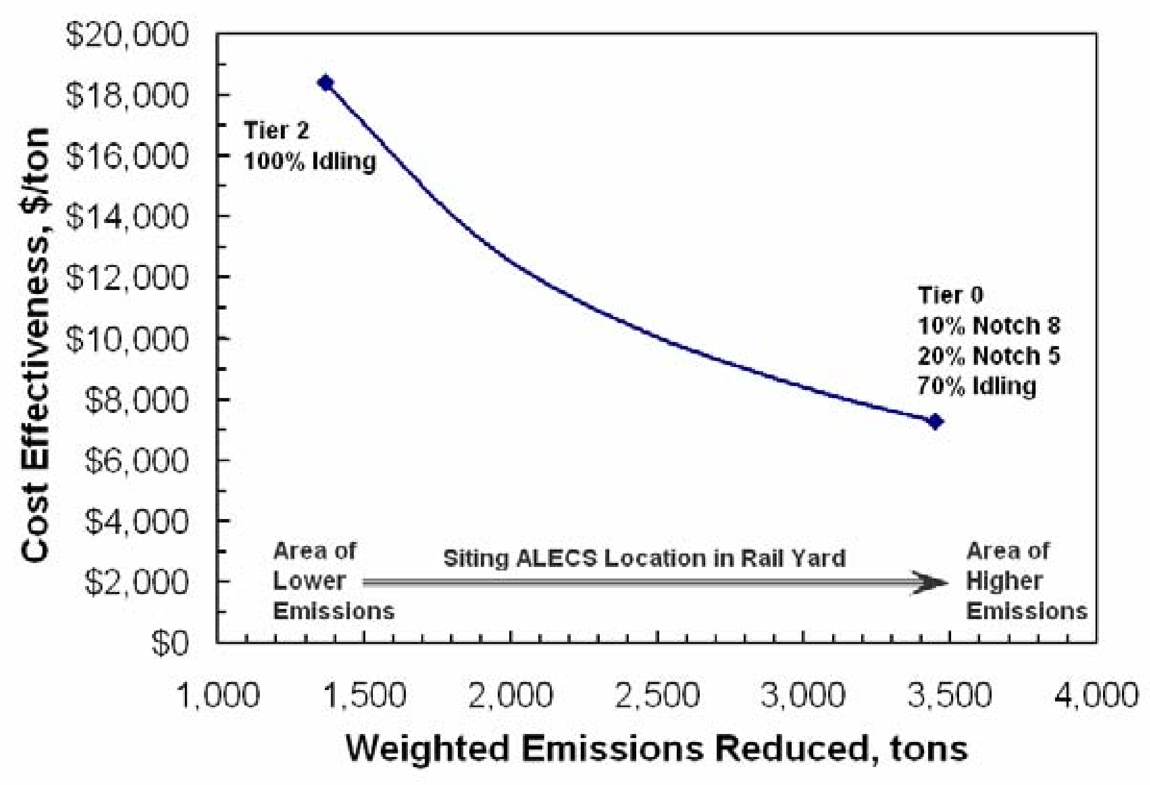


**Figure 1. ALECS Cost Effectiveness**

While the ALECS proof-of-concept tests met most of the project objectives and yielded valuable information confirming that the system is capable of capturing and treating locomotive emissions, there remains additional work in selected areas in order to support fielding a cost effective system in a rail yard application. The emissions capture subsystem, which includes the bonnet over the locomotive stack and the ducting that routes the exhaust to the emissions control subsystem, was designed to accommodate a single locomotive. The full-scale subsystem capable of capturing and transporting emissions from multiple locomotives was not tested. A number of follow-on actions are recommended, including public policy leadership, internal rail yard analyses with respect to optimal siting situations as well as positive and negative impacts to rail yard operations, demonstrating the emissions capture subsystem for multiple locomotives, developing financial mechanisms for the funding of systems, and community outreach.

# 1. Introduction

## 1.1 Project Background and Overview

Placer County Air Pollution Control District (PCAPCD) led a public-private collaborative project in a technology proof-of-concept test of a new concept to clean locomotive diesel exhaust. As a result of public concern over health risk from locomotive diesel emissions emanating from the J. R. Davis Rail Yard in Roseville, California, the PCAPCD arranged for the California Air Resources Board (CARB) to perform a detailed health risk analysis of locomotive diesel exhaust from the rail yard. Diesel exhaust was designated a toxic air contaminant by the CARB in 1998. This yard is one of the largest rail facilities in the western United States and serves as a maintenance and repair hub for locomotives. Over 90 percent of all Union Pacific rail traffic in Northern California moves through the yard (Union Pacific Railroad website, January 2007). The following lists some of the features of the rail yard (see Figure 2 for an aerial overview of the facility).

- Encompasses 915 acres
- 6 miles long
- 55 bowl tracks
- 136 miles of track
- 247 switches
- 2 main lines
- 6,500 rail car capacity
- 1,800-2,300 cars per day classification ability
- Over 30,000 locomotives stop annually
- Additional 15,000 locomotives pass through without stopping
- 21,500 locomotives receive service, maintenance, and/or repair per year
- 9,600 locomotives refueled only for fast turn-around per year
- Locomotives are fueled with 2.8 million gallons of diesel fuel per month

The effort was a public-private collaborative project involving the U.S. Environmental Protection Agency (EPA), California Air Resources Board, three Air Districts, one city government, and two corporations. The purpose of the project was to demonstrate the effectiveness of the stationary control equipment in capturing and treating locomotive exhaust, and to generate the information on capital and operating costs. The CARB Roseville Rail Yard Study (CARB, October 14, 2004) concluded “Computer modeling predicts potential cancer risks greater than 500 in a million (based on 70 years of exposure) northwest of the Service track area and the Hump and Trim area. The area impacted is between 10 to 40 acres.” These are the areas of the rail yard where servicing, fueling, and maintenance testing of locomotives occurs. Subsequent to the health risk findings, the PCAPCD negotiated an agreement with Union Pacific Railroad Company (UPRR) that included a number of measures to reduce diesel emissions. One measure was to investigate the use of stationary control equipment to clean up diesel exhaust captured from motionless or slow moving locomotives in service areas of the rail yard where numbers of locomotives are run for diagnostics and testing.

**Figure 2. Aerial View of the J. R. Davis Rail Yard**

In response to this measure, the PCAPCD organized and led a technology proof-of-concept test of an innovative new concept to capture locomotive diesel exhaust and remove the air pollutants using conventional stationary source techniques. This project is innovative in that conventional stationary source technology is applied to a mobile source through a novel bonnet type exhaust capture device (see Figure 3). Conventional emissions control equipment includes the Preconditioning Chamber, cloud chamber scrubbers and Selective Catalytic Reduction (SCR) to remove approximately 95 percent of oxides of nitrogen ($NO_x$), oxides of sulfur ($SO_x$), and particulate matter (PM). The novel bonnet device consists of a duct structure mounted above the locomotive track and a remotely guided bonnet that fits over the exhaust stack and can move with the locomotive to the extent of the overhead duct structure.

The cost of this collaborative project was covered by direct funding, a grant, in-kind contributions, and corporate product development. The contributing project participants were:

- U.S. Environmental Protection Agency (EPA)
- California Air Resources Board (CARB)
- Placer County Air Pollution Control District (PCAPCD)
- Sacramento Metropolitan Air Quality Management District (SMAQMD)
- South Coast Air Quality Management District (SCAQMD)
- City of Roseville
- Union Pacific Railroad Company (UPRR)
- Advanced Cleanup Technologies, Inc. (ACTI)

07/31/2006 09:21

**Figure 3. Locomotive under the Exhaust Capture Bonnet**

## 1.2 Project Objectives/Motivations

The Advanced Locomotive Emission Control System (ALECS) proof-of-concept test project was a year and a half effort involving the development of locomotive-specific interfaces, temporary installation of emissions control equipment at the Roseville rail yard and testing motionless and slow-moving locomotives to determine the possible effectiveness of the control equipment.

The original objectives of the proof-of-concept test project are listed below (they will be compared to accomplishments later in this report):

> **Objective 1: Demonstrate the Possible Effectiveness of Stationary Control Equipment on Locomotive Exhaust:** This proof-of-concept test of the ALECS equipment should quantify the overall capture and control efficiency of particulate matter (PM), $NO_x$, $SO_x$, and total hydrocarbons (THC) with actual locomotive exhaust in a rail yard environment. Locomotive engines in common use come in two distinct technologies; two-stroke and four-stroke. This proof-of-concept test will test one engine of each technology; a GP38 two-stroke locomotive operating on ultra-low sulfur (15 ppmw) fuel, and a Dash-8 four-stroke locomotive operating on a fuel with a sulfur content between 200 ppmw and 500 ppmw. Sound measurements will be taken with and without the control equipment to determine the extent of noise reduction due to the control equipment (sound measurements added during the project).

Emissions testing will be conducted according to a test protocol developed for this project. The test protocol should prescribe accepted test methods appropriate to the pollutants being measured. The protocol will be reviewed by the air districts, CARB, and EPA. The testing will be conducted on the locomotive before the control equipment and upon exit from the control equipment to determine the emissions on a concentration and mass basis.

**Objective 2: Demonstrate the Attachment Scheme between the Locomotive and the Stationary Control Equipment:** Since a rail yard is a busy place where efficiency of operations is important, the attachment of the emissions control equipment to the locomotive must be quick, simple, and safe to the operating personnel. The operation of the ALECS must absolutely not impede the fluidity of normal railroad operations in any manner. Attachment, detachment, and capture efficiency will be demonstrated on locomotives with one and two emission stacks. During the emissions testing phase of this project, multiple attachments and disconnects shall be performed to demonstrate this capability. Rail yard personnel shall be given a chance to operate the attachment controls.

**Objective 3: Demonstrate the Capability of Some Locomotive Movement While Connected to the Control Equipment:** One of the design features of the ALECS is to allow movement of the locomotive along the track for a prescribed distance while connected to the emissions control equipment. During emissions testing, some portion of the testing on each locomotive shall be conducted with the locomotive connected to the stationary control equipment and the locomotive moving to demonstrate this capability while fully capturing the exhaust from the engine in the locomotive.

**Objective 4: Develop Improved Information on Capital Cost, Operating Procedures, and Operating Costs:** The underlying purpose of this proof-of-concept test project is to provide information on performance, operation and cost of using stationary emissions control equipment to treat locomotive exhaust in rail yards that will enable the railroad and equipment suppliers to make business decisions on moving forward in deploying this type of equipment. During the installation and operation of the ALECS, information shall be collected and recorded that will enable capital and life cycle costs to be generated. Rail yard facility requirements for infrastructure and support utilities will be defined. These cost estimates shall be documented in the final report. Railroad personnel shall be instructed on operation and maintenance of the ALECS during the proof-of-concept project, and will provide to the PCAPCD estimates for all costs for impacts to yard or system operations (either capital or operating) are included in the final accounting. These cost estimates will be included in the project final report.

The ALECS to be used for this proof-of-concept test is borrowed from another project where the equipment size was optimized for another application. As part of this objective, the cost of equipment appropriately sized and ALECS designed to serve the J. R. Davis Rail Yard will be estimated.

**Objective 5: Document Test Results and Project Findings in a Final Report:** Since this proof-of-concept test project has, as one purpose, the generation of information on performance and operation of the ALECS sufficient to allow railroads to make business decisions on use of this stationary control equipment on their rail yards, the project results will be documented in a final report.  The final report will include, as a minimum, details of the locomotives tested, configuration of the test setup, test equipment, test conditions, and test methods, logistic and operation issues identified during project implementation, and emission (and noise) test results before and after the control equipment.

# 2. Description of Technology

## 2.1 Overall Description

ACTI's ALECS is designed to capture railroad locomotive exhaust emissions and direct them to an emissions treatment system for removal of harmful pollutants.

ALECS is comprised of two major subassemblies, the Emissions Capture Subsystem (ECS) and the Emissions Treatment Subsystem (ETS). The Emissions Capture Subsystem is the system used to capture the exhaust emissions from the locomotive and transport the captured exhaust to the Emissions Treatment Subsystem where a substantial amount of the harmful pollutants are removed.

## 2.2 Emissions Capture Subsystem

The Emissions Capture Subsystem (ECS) is designed to capture the exhaust emissions from locomotives while motionless or moving slowly within designated areas within a rail yard. The system is designed to capture the exhaust emissions from multiple locomotives. Locomotive exhaust is captured at the exhaust stack and directed through an Overhead Manifold to an emissions treatment system for removal of harmful pollutants.

The ECS is comprised of four major components: the Support Structure, Overhead Manifold, Emissions Intake Bonnet (EIB) and Control Software. The ECS is designed to provide the railroad with the maximum flexibility practical without interfering or impacting railroad operations.

System backpressure on the locomotive engine is controlled by a pressure sensor located within the bonnet, which in turn controls a damper located at the top of the bonnet. Backpressure is controlled between atmospheric and minus 0.25 inch of water gauge pressure, which puts the exhaust system under a slight vacuum. This vacuum essentially captures all of the locomotive's exhaust and may also add some dilution air from the surrounding atmosphere into the capture system.

### 2.2.1 Proof-of-Concept Test Configuration

For the proof-of-concept test, a scaled down version of the ECS was designed to show that exhaust emissions can be captured from various types of railroad locomotives with different exhaust flows and temperatures, stack configurations, and while immobile or moving within a designated area. Figure 4 shows the proof-of-concept test configuration. Capturing locomotive exhaust emissions was accomplished with the EIB located over the targeted locomotive and lowered around the locomotive exhaust stack (Figure 5 shows two bonnets lowered onto a locomotive).

The captured exhaust was then directed through an overhead manifold to the Emissions Treatment Subsystem. The proof-of-concept test overhead structure and intake manifold can be seen in Figure 6.

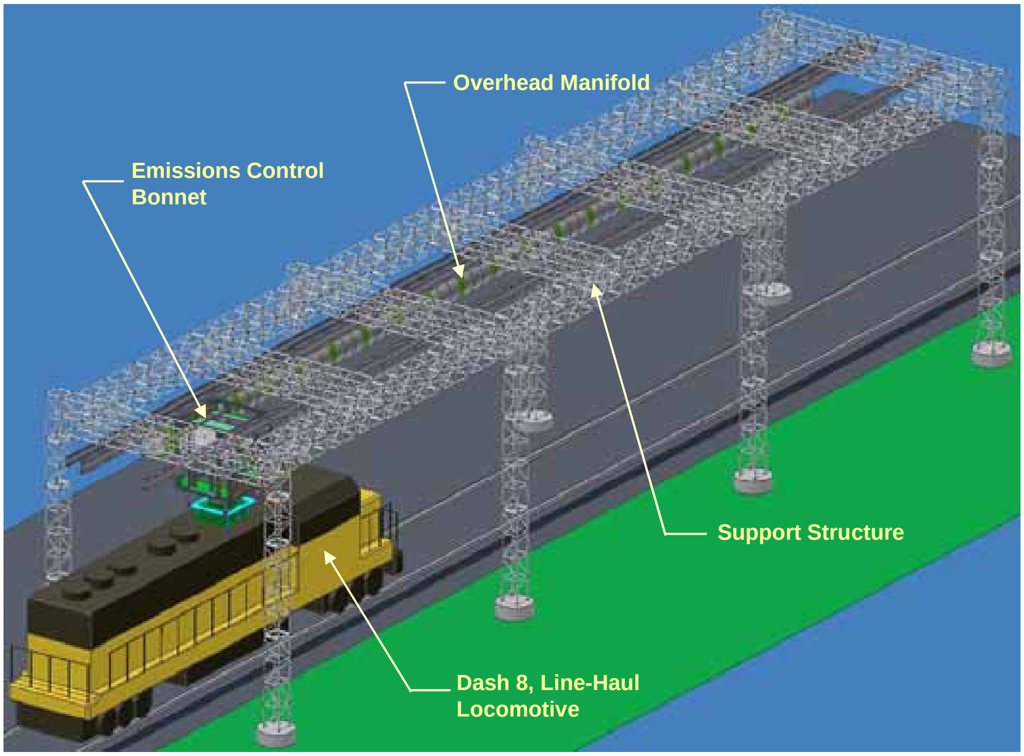


Figure 4. Proof-of-Concept Test Configuration of Emissions Capture Subsystem

Figure 5. Emissions Intake Bonnets Lowered onto a Locomotive

Figure 6.  Overhead Structure and Intake Manifold

The short-term proof-of-concept test design of this project could only process the emissions from a single locomotive at a time.  The full scale deployment design will need to cover multiple tracks and be able to receive emissions from multiple locomotives and direct the captured exhaust emissions to the Emissions Treatment Subsystem.

One of the functions of the ECS is to reduce or eliminate emissions of locomotives that may require maintenance.  Figure 7 shows the visible smoke for a locomotive with high PM emissions. On occasion, visible exhaust emissions as shown in this figure have been observed from the stack of locomotives during engine startup, full power testing, and engine malfunction (invisible emissions can depend upon the atmospheric conditions, cold start of the engine, or throttle notch changes and may become less visible as equilibrium of the engine is attained).

### 2.2.2 Future Full Scale Deployment Concept

The future full scale deployment concept of the ECS was designed (for costing purposes) to be a versatile system that can be arranged to accommodate many rail yard configurations using common components.  These components can be used to tailor a system to an area of the rail yard with varying numbers of parallel tracks of different lengths  For the economic analysis, an ECS covering an estimated 1,200 feet of track was selected.  The track can be three 400 foot sections side-by side, two 600 foot sections side-by-side or one continuous track at 1,200 feet in length, servicing 12 locomotives.

Figure 7. Visible Locomotive Exhaust Emissions

Shown in Figure 8 is an example of a future typical deployment of the ECS. Figure 9 depicts the system connected to the ETS, with arrows showing the path of the captured exhaust. Note that the system is designed to handle consist (multiple locomotives attached together to power a train) and standalone locomotives. However, the system that was tested in this project used only a single locomotive design.

The Support Structure is the metal framework that supports the Overhead Manifold and Emissions Intake Bonnets. It is comprised of steel Support Piers, Transverse Support and Longitudinal Support Beams.

The Overhead Manifold is the medium that directs the captured exhaust emissions to the ETS. It is comprised of an Intake Outer (Stainless Steel) Tube, an EIB Interface Inner-Connection (Stainless Steel) Tube, a Trolley Support Rail and Power Strip, and Control Cable Harness.

The EIB Interface Connection tube slides within the Intake Outer Tube to allow for automatic positioning of the bonnet over the selected locomotive exhaust stack.

The ECS will monitor exhaust flow rates from multiple locomotives and the exhaust from those locomotives producing the highest exhaust flow will be directed to the treatment system. This will selectively process the exhaust from the locomotives having the highest emissions (operating at the highest throttle notch), thereby optimizing the treatment systems effectiveness and efficiency in reducing the amount of harmful pollutants introduced into the surrounding atmosphere.

Figure 10 is a depiction of the Overhead Manifold, and shown in Figure 11 is a transparent view of the EIB Interface Connection Tube for the full scale, conceptual ECS design.

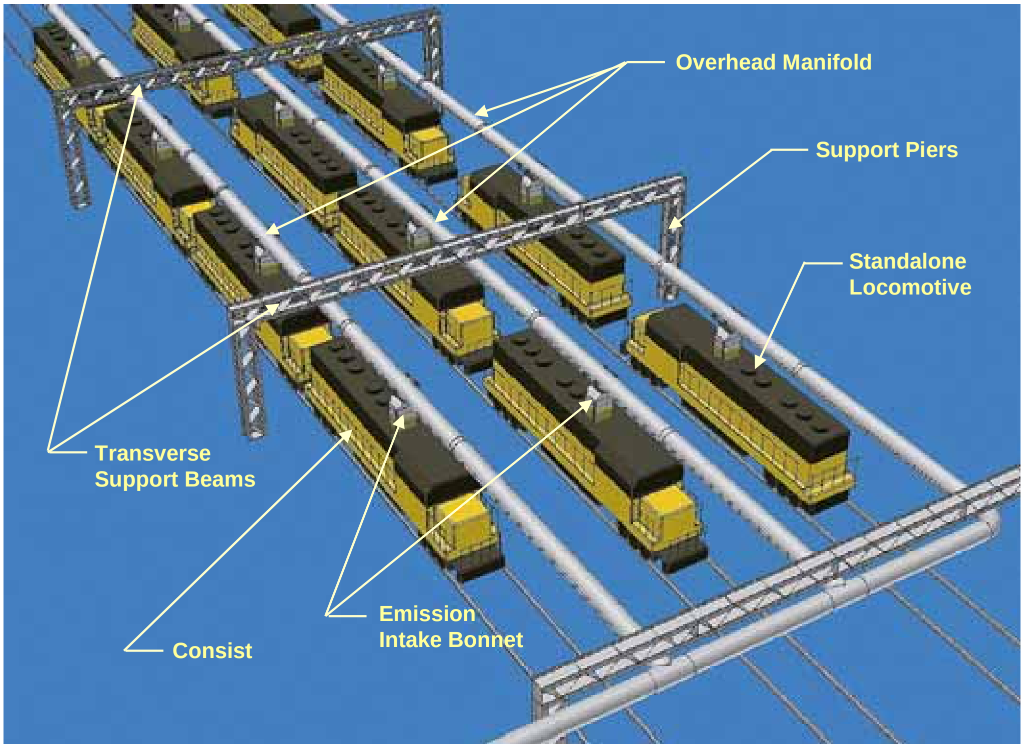


Figure 8. Conceptual Example Deployment of Emissions Capture Subsystem

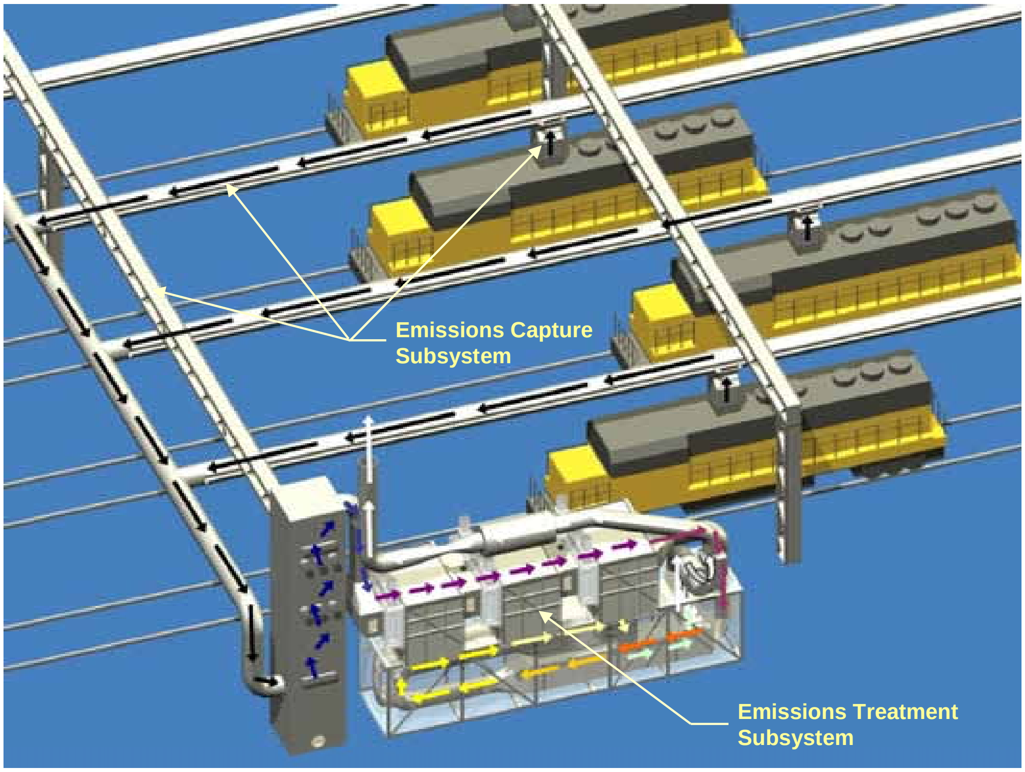


Figure 9. Conceptual Emissions Capture Subsystem Attached to the ETS

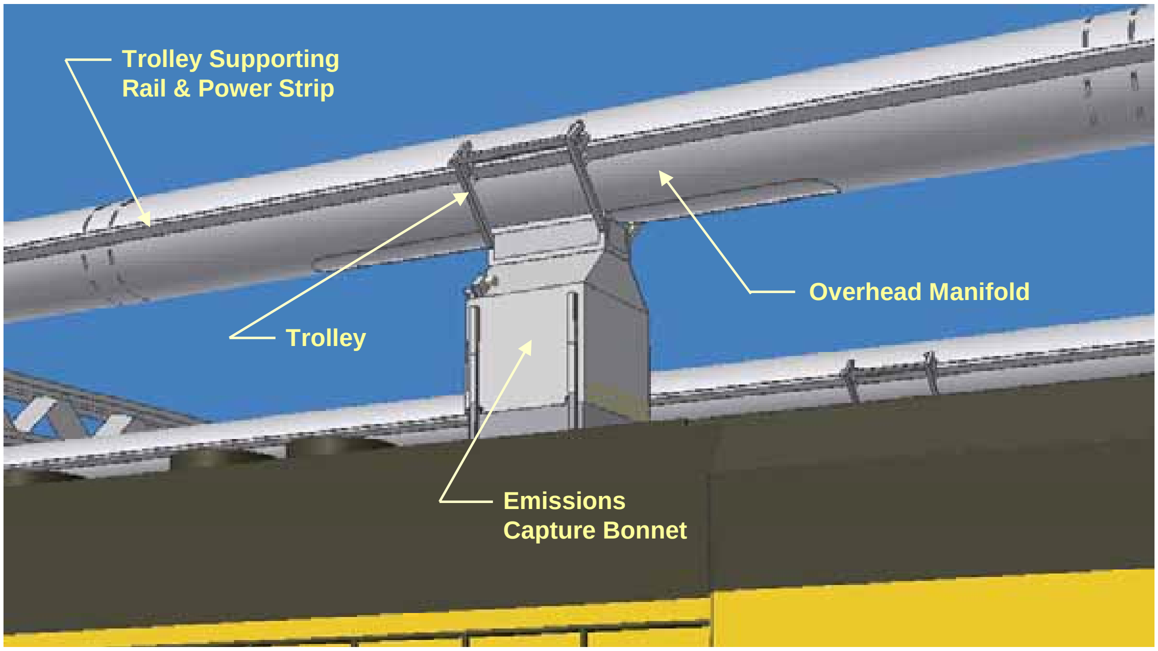


**Figure 10. Conceptual Overhead Manifold and Emissions Control Bonnet**

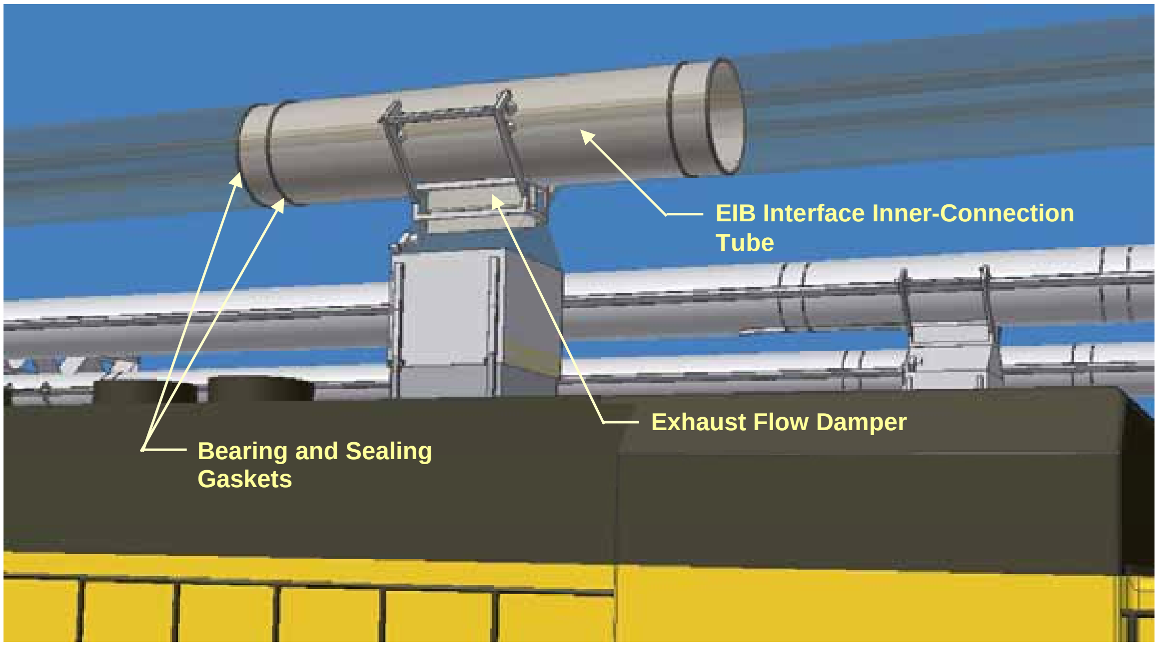


**Figure 11. Conceptual Emissions Intake Bonnet and Interface Connection Tube**

The EIB is the component that captures the exhaust emissions from locomotives by enclosing the exhaust stack and directing the exhaust emissions into the Overhead Manifold. The EIB is comprised of two components, the Intake Bonnet and the Trolley. The Trolley positions the Intake Bonnet over the locomotive's stack, and the stack lowering mechanism lowers the bonnet around the stack. For a conceptual depiction of the EIB Trolley see Figure 12.

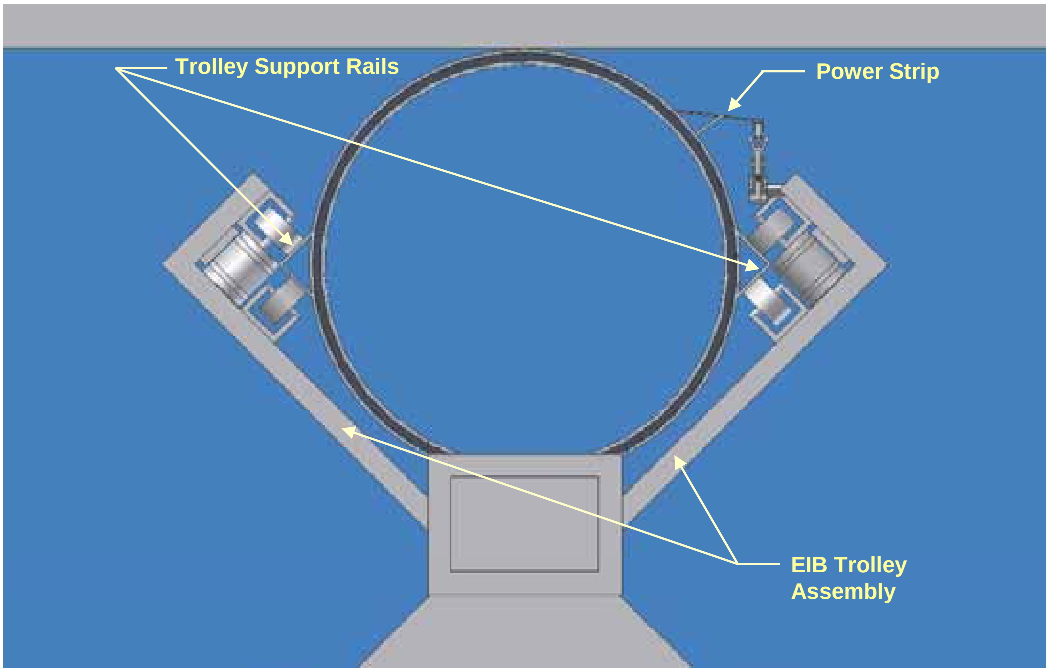


**Figure 12. Conceptual Emissions Intake Bonnet Trolley**

The ECS Control System will be programmed to automatically locate and connect to the locomotive stack. The system will detect when a locomotive enters the zone of operation. When the system determines that the locomotive has stopped, then a bonnet will be deployed. When the locomotive begins to move out of the zone, then the bonnet will automatically be retracted.

The ECS control system will also work to maximize the capture efficiency by prioritizing higher throttle notch levels over idling locomotives. As previously stated, each bonnet is connected through a control damper to the intake manifold. When a bonnet disconnects from a locomotive, the damper is completely closed to airflow. When a bonnet is connected to the locomotive, the damper is used to modulate the flow to keep the pressure within a negative ¼ inch of water pressure. When a higher exhaust flow rate of one or more of the locomotives is detected, the higher flow locomotive is prioritized over the lower notch and/or idling locomotives, which are temporarily disconnected from the system. The system also automatically connects as many locomotives as required to maintain the maximum flow rate of the ETS.

The bonnets are programmed to failsafe to the disengaged mode. Under any fault condition (e.g. loss of power, over/under pressure, over temperature) the system will disconnect from the locomotives and notify the technician on duty both locally in the Operational Control Unit (OCU) of the ETS and remotely by pager. In the event of an emergency or a failure, emergency stop pushbuttons can disconnect all bonnets, and bring the system to a safe operating condition.

## 2.3 Emissions Treatment Subsystem

The ETS consists of six major components: a Preconditioning Chamber (PCC) that removes $SO_x$ and an amount of hydrocarbons (THC), a Cloud Chamber Scrubber (CCS) that removes PM, a Thermal Management System to increase operating efficiency, a Selective Catalytic Reduction

(SCR) Reactor for removal of $NO_x$, a Control System and the Continuous Emissions Measuring System (CEMS).

The ETS and the relative location of its components are shown in Figure 13 and are described further below. The Control system and CEMS descriptions follow these ETS major component descriptions.

The first component the exhaust gas encounters as it enters the system is the Preconditioning Chamber (PCC) which serves several functions. First, it cools the gas adiabatically through a counterflow water spray and in the process increases the water vapor content to near saturation. This feature is required by the following stage, which cannot accept hot gas. Secondly, it removes most of the soluble hydrocarbons and other water soluble compounds. Third, the water is rendered caustic by means of a metered injection of sodium hydroxide to remove 95 to 99 percent of the $SO_2$, depending on the inlet concentration. The fourth function of the PCC is to cause the nanometer size PM particles to agglomerate into larger particulate globules, which facilitates their removal in the next stage

The path of the exhaust emissions flow through the ETS, along with the relative positions of the major components is shown in Figure 14.

The gas exits the PCC at a temperature of about 140°F. This gas is directed to the first of three Cloud Chamber Scrubbers (CCS). These vessels are empty, except that they are filled with a fog of minute water droplets generated by an array of spray nozzles collinear with the exhaust gas stream. Each droplet is charged to a high voltage immediately after leaving its nozzle. This charge causes particulate matter in the gas stream to be attracted to and adhere to the water droplets, with each of the billions of water droplets collecting many particles. The droplets fall to the bottom of the CCS to a collection reservoir. Droplets entrained in the gas stream are removed by a mist eliminator.

The particles thus collected in the water reservoir are flushed through a solids removal system where they are collected for subsequent removal from the premises and disposal using approved regulatory means. The removal system consists of a solids separation device for inline solids removal, water extraction, and compaction.

The Selective Catalytic Reduction (SCR) Reactor requires a temperature of approximately 600°F to operate. The exhaust gas exiting the CCS is cooled to about 140°F and stripped of $SO_2$, PM, soluble hydrocarbons, and condensed (particulate) hydrocarbons and sulfates. This clean but cool gas must then be reheated. This is accomplished by a Thermal Management System (Burner & Heat-Exchanger) that is connected to the system in a wraparound arrangement. In this scheme, the hot exhaust from the SCR Reactor is used to heat the cold gas entering the SCR Reactor. Approximately 80 percent of the available heat is recovered from the hot gas leaving the SCR Reactor by this heat exchanger. The additional heat increment required to bring the gas stream up to 600°F is provided by a natural gas or propane-fired burner.

The exhaust emissions flow through the Thermal Management System with the relative positions of the components shown below in Figure 15.

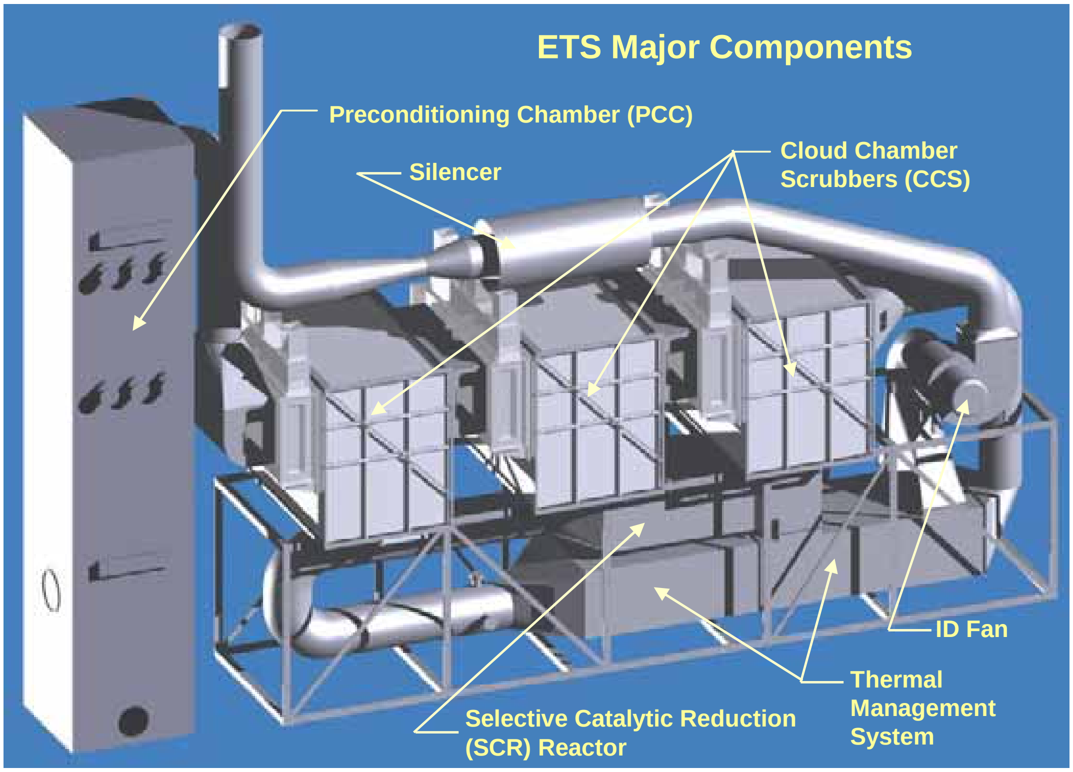


Figure 13.  ETS with Relative Locations of Its Components

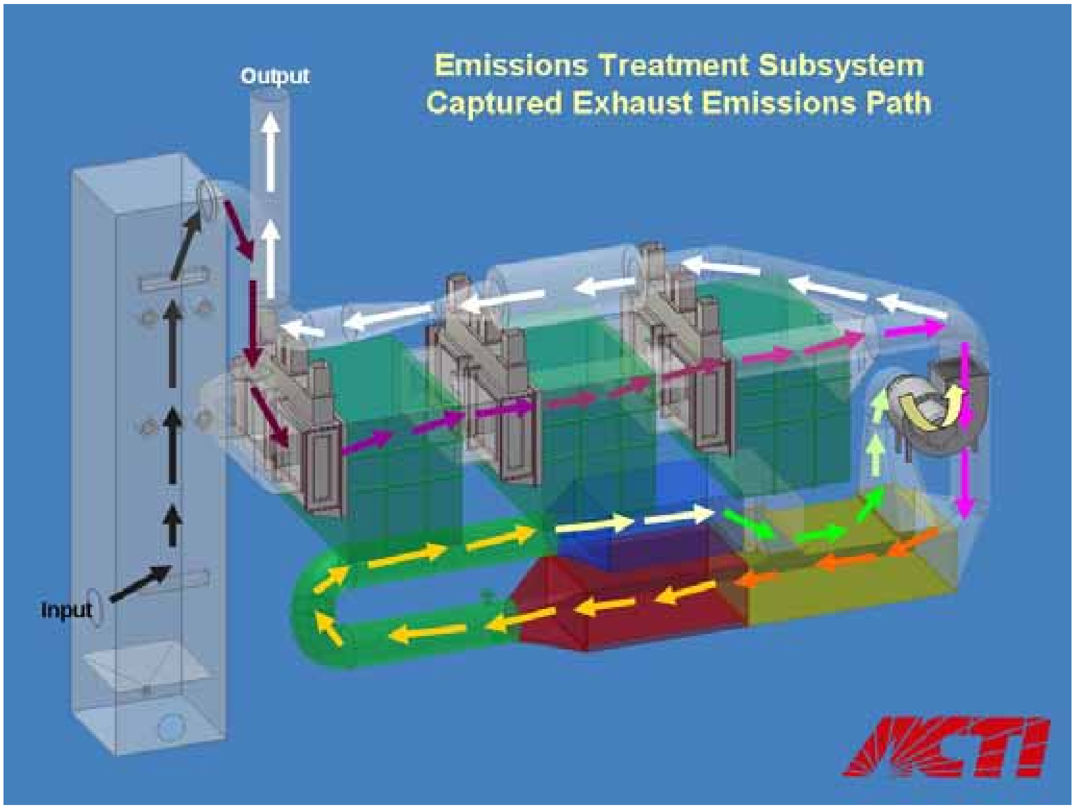


Figure 14.  Emissions Treatment Subsystem Captured Exhaust Emissions Path

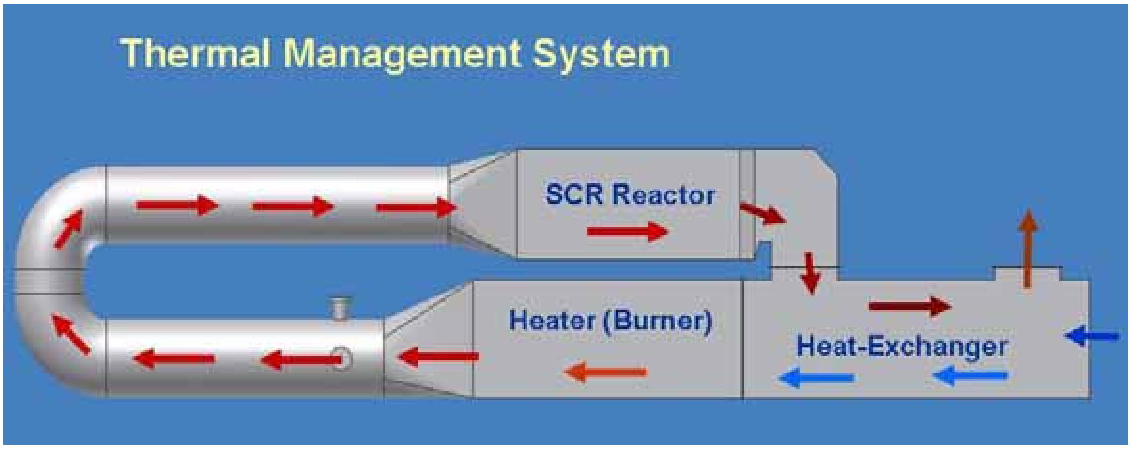


Figure 15. ETS Thermal Management System

The reheated gas at 600°F is passed through the SCR Reactor for $NO_x$ removal. In the SCR Reactor, ammonia combines chemically with NO in the presence of the catalyst, converting the NO and ammonia ($NH_3$) into water vapor and nitrogen gas. Urea is the reagent this system uses as the source of ammonia. The urea is injected into the system immediately after the burner. Special atomizer nozzles and flow modification devices ensure uniform distribution, and a long mixing duct assures complete conversion of urea to ammonia.

An Induced Draft (ID) fan is located downstream of the SCR Reactor and Thermal Management System, and a silencer is located downstream of the ID fan. This fan draws the exhaust gas from the locomotive through the ducting into the ETS. The flow and pressures are controlled by dampers and the fan's variable speed drive motor.

In addition to the silencer, which acts as a muffler, the downstream ducting and fan housing are acoustically insulated to ensure that the systems operating noise level is reduced to an acceptable level.

Figure 16 shows the ETS in Roseville, California (it was not connected to the ECS yet).

### Control System Description

The ALECS Control System is an integrated network which automatically operates and monitors all aspects of the ALECS operation. The ETS has its own Operational Control Unit (OCU), which controls all the ETS processes including any attached ECS. The ETS can be monitored and controlled locally (in the OCU) and remotely. The OCU houses all sensing, monitoring, recording and control system functions for ALECS. These systems acquire, monitor, store and transmit the data required to maintain efficient emissions control operations as well as to document emissions reduction performance during acceptance testing and certification. The OCU operates automatically, adjusting for the wide range of variables in the number of locomotives and their operating characteristics, compensating for changes in real-time.

Figure 16. Emissions Treatment Subsystem in Roseville Rail Yard

Failsafe strategies are built into the control system. This system keeps all ECS and ETS operational parameters within design limits, makes automatic adjustments where appropriate, switches to redundant components or systems in the event of a malfunction or out-of-spec condition, and records significant parameters to verify performance.

As part of the control system, measured data will be recorded in a Microsoft SQL relational database by locomotive identification number.

### Continuous Emissions Monitoring System (CEMS)

The CEMS measures the following parameters:

- At the ETS inlet (source measurement)
    - $NO_x$
    - $SO_x$
    - $O_2$
    - PM (time shared with the outlet)
    - Flow
    - Temperature

- At the ETS outlet (discharge to atmosphere)
    - $NO_x$
    - $SO_x$
    - $O_2$
    - THC
    - $NH_3$ (ammonia)
    - PM (time shared with the inlet)

- Flow
- Temperature

PM is measured at the inlet and outlet using a Dekati Mass Measuring system with a single instrument. This arrangement uses a three-way valve to allow time sharing between the inlet and the outlet by switching the instrument input between sample lines.

### Instrumentation Description

The gaseous instrumentation is a Horiba Instruments model ENDA-4000 stack gas analysis system. It uses chemiluminescent analysis for $NO_x$, non-dispersive infrared (NDIR) for $SO_x$, and magnetopneumatic analysis for the oxygen ($O_2$) measurements. A Horiba FIA-236 flame ionization analyzer is used to measure total hydrocarbons. $NH_3$ is measured by converting the $NH_3$ to NO in dual stream heated probes with an electrically heated filter chamber in the probe heated to 320°C. $NH_3$ is determined by measuring the NO thus produced and comparing it to the level without the $NH_3$ contribution to NO. The $NH_3$ system includes a built-in Horiba CLA-510 chemiluminescent $NO_x$ analyzer for the $NH_3$ measurement.

The sample conditioning system includes a solid state thermoelectric pre-cooler with stainless steel impingers, a solid state thermoelectric sample cooler, primary and secondary particulate filters, an acid mist catcher, magnetically coupled sample pump and booster pump, temperature controller for the heated sample line, temperature controller for the sample probe primary filter, automatic temperature and pressure control, and automatic system calibration.

The sampling system consists of a stainless steel sample probe with heated primary filter and automatic blowback, and a heat traced multiple tube sample umbilical. The probe assembly consists of a probe pipe, heated primary filter and NEMA 4X enclosure. Connections route calibration gas upstream of the primary filter. The sampling system on the downstream side of the ETS adds dual stream heated probe heads with integral $NH_3$ converters and a 2 micron ceramic filter element heated to 320°C.

The sample system is shown in simplified form in Figure 17. Figure 18 is a picture of the CEMS utilized in the proof-of-concept testing.

PM is measured with the Dekati DMM-230 Mass Monitor manufactured by Dekati, Ltd. in Finland. This instrument gives one second data points of particle size as well as other particle statistics. The DMM operation principle is based on measuring particle electrical mobility and aerodynamic size. These two parameters are compared in real time to determine total mass.

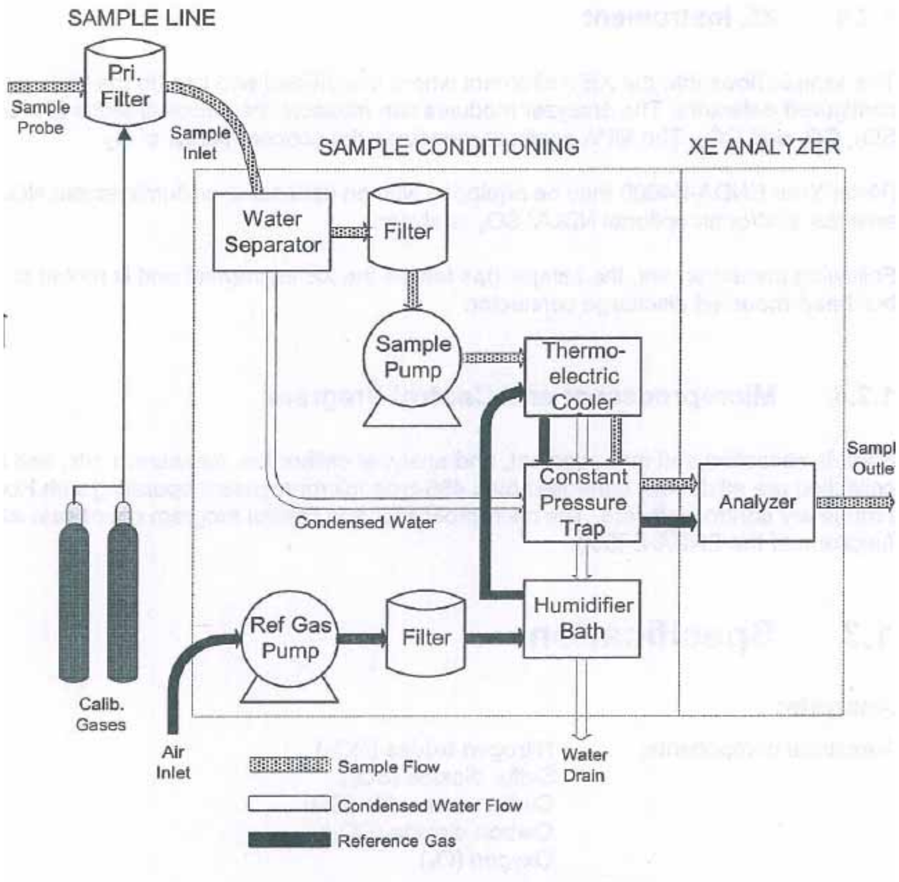


Figure 17. Simplified Diagram of the CEMS Sample System

Figure 18. ALECS CEMS

## 2.4 Site Preparation and System Installation for Proof-of-Concept Tests at Roseville

Prior to the system being shipped to Roseville, a site was selected that would not interfere with railroad operations and that was safe for operational personnel and visitors. Figure 19 shows an aerial view of the approximate location of the ALECS proof-of-concept test site in the Roseville rail yard. The site was readied by pouring a concrete pad, and as the location did not have easy access to electrical power lines or natural gas, a temporary diesel generator using a Tier 2 engine and a propane engine driven generator were bought in to supply electricity and temporary propane tanks were installed to provide fuel for the burner and propane generator.

Figure 19. Aerial View of the Site Where the ALECS was Installed

The entire system was shipped to the site on flatbed trucks from the various fabrication locations where the components were manufactured and tested. The system was then assembled, tested and readied for demonstration and testing.

With the exception of visitors, all non-railroad personnel underwent rail yard safety training.

# 3. Testing of System

## 3.1 Overall Test Plan/Matrix

The test program consisted of testing two locomotives made available by the Union Pacific Railroad that are representative of common high-use locomotives at the Roseville rail yard; one a line-haul locomotive and the other a switcher locomotive. These two locomotives were carefully selected to provide a range of design parameters seen in the locomotive technologies prevalent at Roseville.

Development of the proof-of-concept test plan was a collaborative effort by members of the project team and the emissions testing contractor. Organizations active in this plan development were PCAPCD, ACTI, EPA, CARB, SCAQMD, UPRR's consultant Sierra Research, TIAX, and EF&EE. The goal of the plan development was to demonstrate the ALECS performance over a range of locomotive variations with limited funding available for the testing. A challenge was to come up with test methods suitable for a system that contained a stationary source and a mobile source. Table 3 summarizes the conditions and the number of tests listed in the test plan for the two locomotives to be used with the ALECS.

The resulting test protocol defined the exhaust parameters to be measured and recorded, the sampling locations, the test methods, and the locomotive configurations and throttle settings to be tested. The complete test protocol is included as Appendix A.

**Table 3. Summary of Planned Tests**

| Locomotive | Throttle Notch | Number of Tests per Location | Location of Tests | | |
|---|---|---|---|---|---|
| | | | Locomotive Stack | ALECS Inlet | ALECS Outlet |
| **Dash-8** | 8 | 3 | X | X | X |
| | 5 | 3 | X | X | X |
| | 1 | 3 | X | X | X |
| | 3 (soup baseline) | 3 | X | X | X |
| | 3 (souping test) | 3 | X | X | X |
| | Moving | 3 | X | X | X |
| **GP38** | 8 | 3 | X | X | X |
| | 5 | 3 | X | X | X |
| | 1 | 3 | X | X | X |
| | 3 (soup baseline) | 3 | X | X | X |
| | 3 (souping test) | 3 | X | X | X |
| | Moving | 3 | X | X | X |

Each locomotive was tested in a motionless condition and also moving slowly over a 50-foot section of track. The immobile locomotive testing was conducted at four throttle settings; notch 1, notch 3, notch 5 and notch 8. The moving test was conducted at low throttle settings to continuously move the locomotive back and forth along 50 feet of track while connected to the overhead ducting. Three tests were conducted for each individual condition.

The test program included emission measurements at three locations; in the locomotive stack(s), in the inlet ducting to the ground-mounted emission treatment system (Figure 20 shows the ducting between the emissions capture system and the emissions treatment system where measurements were taken), and at the outlet from the emission treatment system (Figure 21 shows the exhaust stack outlet measurement location as well as the inlet measurement location).

Pollutants measured included PM, $NO_x$, CO, $SO_2$, and THC. Test procedures for these pollutants conformed to ISO standard 8178. Ammonia ($NH_3$) was measured only at the inlet and outlet of the emission control system, following EPA Method 320.

Noise measurements were made for each locomotive at notch 8, both with and without the bonnet attached to the exhaust stack. These tests were conducted to evaluate the level of noise reduction that can be attributed to use of the ALECS.

**Figure 20. Ducting between the ECS and the ETS**

Figure 21.  Exhaust Stack of the Emissions Treatment Subsystem

### 3.2 Locomotives Tested (GP38 and Dash-8)

The larger of the two locomotives tested was a General Electric (GE) C39-8 locomotive (representative of the Dash-8 series) used primarily for line-haul freight service and was equipped with a four-stroke, turbocharged, GE FDL-16 engine.  This 16 cylinder engine produces 3,900 tractive horsepower, and discharges exhaust through a single rectangular stack connected directly to the turbocharger outlet.  The maximum exhaust flow rate at full power is approximately 12,000 scfm.  The test locomotive was identified with the serial number 9143 (see Figure 22).

The smaller locomotive tested was a General Electric Electro-Motive Division (EMD) GP38 (Figure 23).  At Roseville, this type of locomotive is used primarily for switching and local service.  It was equipped with a two-stroke, Roots-blown, EMD 16-645E engine.  The engine has 16 cylinders and is rated at 2,000 tractive horsepower.  It is equipped with two exhaust stacks, fed by the front eight and rear eight cylinders, respectively.  The maximum exhaust flow rate at full power is approximately 6,000 scfm.  The test locomotive was identified with the serial number 604.  Table 4 summarizes the locomotive characteristics.

Immobile locomotive tests consisted of triplicate tests of each locomotive running at throttle notch 1, notch 5, notch 8, souping baseline at notch 3, and the souping test at notch 3. “Souping” is the term used for material buildup (such as oils and PM) in the exhaust system at light loads which burns off at higher loads. The souping baseline test is a test run at a throttle setting that is high enough where souping does not occur (notch 3) in order to evaluate steady state emissions. The souping test is run immediately after the notch 1 test to measure the soup that accumulated during the notch 1 test and is burned off in a higher notch run, and then compared to the souping baseline emissions rate.

Figure 22.  Single Stack Line-haul Dash-8 Locomotive

Figure 23.  Double Stack Switcher GP38 Locomotive

Table 4. Locomotive Characteristics

| | Locomotive | |
|---|---|---|
| | **Dash-8** | **GP38** |
| **Locomotive Service Class** | Line-haul | Switcher |
| **Locomotive Model** | GE C39-8 | EMD GP38 |
| **Locomotive Identification Number** | 9143 | 604 |
| **Engine Model** | GE FDL-16 | EMD 16-645E |
| **Engine Type** | Four-stroke | Two-stroke |
| **Number of Cylinders** | 16 | 16 |
| **Rated Power Output (horsepower)** | 3,900 | 2,000 |
| **Number of Exhaust Stacks** | 1 | 2 |
| **Maximum Exhaust Flow Rate** | 12,000 scfm | 6,000 scfm |

Locomotive noise measurements were performed using a hand-held noise meter. Measurements were made at a point 30 meters away from the locomotive along a line passing through the center of the locomotive perpendicular to the track. Noise measurements were taken at the throttle notch 8 operating condition with the bonnet attached and unattached. Noise measurements on a moving locomotive were deemed not necessary due to the low throttle notch settings.

The triplicate moving tests were conducted with the bonnet(s) attached to the locomotive stack(s) and each locomotive moved back and forth under its own power within the 50 feet of test section. The moving tests were conducted for 30 minutes of continuous back and forth motion in which the locomotive throttle was set at notch 1 and the drive was engaged to move and then disengaged from the drive using the brakes to stop.

Additional information on the test conditions can be found in Appendix A and B which contains the test plan and emission test report respectively.

### 3.3 Emission Measurements

The emissions testing contractor, Engine, Fuel, and Emissions Engineering (EF&EE), used their patented Ride-Along Vehicle Emissions Measurement (RAVEM) sampling system to perform the PM emissions measurements. The RAVEM uses the isokinetic partial flow dilution method specified as one option under ISO 8178. Separate RAVEM samplers were used to sample the exhaust at the locomotive stack, at the inlet to the ALECS (see Figure 24), and in the outlet stack from the ALECS.

The RAVEM system located at the ALECS inlet was configured to measure $NO_x$, CO, and $CO_2$ continuously, as well as collecting integrated bag samples of the dilute gas to be analyzed after the end of each test. The RAVEM samplers at the outlet and at the locomotive stack collected integrated bag samples only. These were analyzed at the end of each test by the analyzers of the first RAVEM system.

Figure 24.  RAVEM Setup at the Inlet to the Emissions Treatment Subsystem

The ALECS system itself includes continuous emission monitoring systems (CEMS) for $NO_x$, $SO_2$, and $O_2$ at both the inlet and the outlet, and for THC and $NH_3$ at the outlet only.  For these tests, EF&EE provided another THC analyzer for the inlet.  Table 5 shows the equipment (EF&EE or ALECS CEM) used to measure emissions by sampling location.

Table 5.  Source of Measurements by Sampling Location

| | Locomotive Stack | ALECS Inlet | ALECS Outlet |
|---|---|---|---|
| **$NO_x$** | E | A, E | A, E |
| **THC** | — | E | A |
| **CO** | E | E | E |
| **$CO_2$** | E | E | E |
| **$SO_2$** | — | A | A |
| **$NH_3$** | — | E | A, E |
| **$N_2O$** | — | E | E |
| **PM** | E | E | E |

A =  ALECS CEM system equipment
E = EF&EE system equipment

## 4. Test Results

All of the data taken at the ETS inlet and outlet locations by EF&EE with their RAVEM are presented here (PM, $NO_x$, CO, and $CO_2$). $NO_x$ data taken by the ALECS' CEMS will not be presented here because only the $NO_x$ data taken by EF&EE will be used. Although the $NO_x$ data from ALECS's CEMS were not used, there was a good correlation with the RAVEM $NO_x$ data (see the emission test report in Appendix B for comparisons of the two sets of data). However, the $SO_2$, THC, and $NH_3$ data taken by the ALECS' CEMS will be presented (EF&EE did not perform these measurements).

The original intent of sampling and analyzing the exhaust at the locomotive stack location was to see if the ducting to the inlet of the ALECS changed any of the results. Unfortunately, the measures at the locomotive stack were influenced by non uniform flow which introduced uncertainties that rendered these data unusable. Also, the nitrous oxide ($N_2O$) data were too low to be reported by EF&EE. Therefore the data for the locomotive stack location and $N_2O$ data will not be addressed in this report (see the emission test report in Appendix B for a more thorough explanation of the details).

### 4.1 Emissions Results

Table 6, Table 7, and Table 8 presents the inlet and outlet emission results to the Emission Treatment System (ETS) measurements performed by EF&EE's RAVEM system for the motionless Dash-8, motionless GP38, and moving locomotives respectively.

Table 9, Table 10, and Table 11 are the inlet and outlet emissions results from ALECS' CEMS for the pollutants not measured by EF&EE. They are for the immobile Dash-8, immobile GP38, and moving locomotive tests respectively. The ammonia slip from the use of urea in the SCR system was very low. The average ammonia slip ranged from 0 up to 1.3 g/min (around 3 ppm for an exhaust flow rate of 12,000 scfm).

The $CO_2$ and CO results show that there are more of these pollutants coming out of the system than what entered (this is reflected in the negative control efficiency values). The increase in CO and $CO_2$ are attributed to the propane fuel burned to reheat the exhaust gas before the SCR system.

The overall emission control efficiency of the major pollutants of interest is presented in Table 12.

## Table 6. ALECS Inlet/Outlet Emissions — RAVEM Data for the Motionless Dash-8

| | Inlet Emissions | | | | Outlet Emissions[1] | | | |
|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | CO | $NO_x$ | PM | $CO_2$ | CO | $NO_x$ | PM |
| **Notch 8 Average (g/min)** | 30,207 | 119 | 648 | 25.5 | 33,808 | 146 | 20.4 | 2.9 |
| Coefficient Of Deviation | 2.5% | 6.5% | 3.9% | 7.9% | 5.0% | 8.0% | 25.9% | 6.2% |
| Control Efficiency | | | | | **-11.9%** | **-22.0%** | **96.8%** | **88.8%** |
| **Notch 5 Average (g/min)** | 18,111 | 128 | 427 | 6.4 | 21,073 | 151 | 6.7 | 1.2 |
| Coefficient Of Deviation | 3.7% | 10.8% | 2.7% | 8.9% | 8.2% | 18.0% | 71.9% | 12.9% |
| Control Efficiency | | | | | **-16.4%** | **-18.1%** | **98.4%** | **80.9%** |
| **Notch 1 Average (g/min)** | 3,785 | 17 | 97 | 4.6 | 3,623 | 18 | 1.9 | 0.1 |
| Coefficient Of Deviation | 6.0% | 45.6% | 8.4% | 6.5% | 3.8% | 6.0% | 107% | 2.9% |
| Control Efficiency | | | | | **4.3%** | **-3.0%** | **98.1%** | **98.6%** |
| **Souping Baseline Ave. (g/min)** | 11,020 | 37 | 267 | 3.8 | 12,069 | 48 | 0.0 | 0.4 |
| Coefficient Of Deviation | 1.6% | 11.6% | 1.6% | 18% | 12.0% | 29.5% | 141% | 22.0% |
| Control Efficiency | | | | | **-9.5%** | **-28.5%** | **100%** | **90.7%** |
| **Souping Test Average (g/min)** | 10,841 | 41 | 257 | 18.2 | 12,509 | 58 | 7.7 | 0.5 |
| Coefficient Of Deviation | 8.0% | 19.8% | 5.3% | 64% | 7.0% | 8.7% | 101% | 65.4% |
| Control Efficiency | | | | | **-15.4%** | **-42.6%** | **97.0%** | **97.0%** |

[1] Negative control efficiencies are due to the increase of $CO_2$ and CO from burning propane fuel to reheat the exhaust before entering the SCR.

## Table 7. ALECS Inlet/Outlet Emissions — RAVEM Data for the Motionless GP38

| | Inlet Emissions | | | | Outlet Emissions[1] | | | |
|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | CO | $NO_x$ | PM | $CO_2$ | CO | $NO_x$ | PM |
| **Notch 8 Average (g/min)** | 19,411 | 37 | 466 | 6.6 | 21,466 | 45 | 6.8 | 0.6 |
| Coefficient Of Deviation | 6.0% | 18.2% | 0.8% | 16% | 3.5% | 6.5% | 129% | 27.8% |
| Control Efficiency | | | | | **-10.6%** | **-24.0%** | **98.6%** | **90.7%** |
| **Notch 5 Average (g/min)** | 9,869 | 3 | 205 | 4.7 | 11,150 | 14 | 1.4 | 0.4 |
| Coefficient Of Deviation | 1.5% | 77.3% | 2.0% | 16% | 2.6% | 32.3% | 101% | 6.2% |
| Control Efficiency | | | | | **-13.0%** | **-324%** | **99.3%** | **90.7%** |
| **Notch 1 Average (g/min)** | 1,518 | (1) | 27 | 0.32 | 2,257 | 4 | 0.8 | 0.03 |
| Coefficient Of Deviation | 11.0% | 638% | 2.6% | 34% | 1.5% | 31.7% | 194% | 9.4% |
| Control Efficiency | | | | | **-48.7%** | **#N/A** | **97.0%** | **89.6%** |
| **Souping Baseline Ave. (g/min)** | 5,630 | 1 | 106 | 1.7 | 6,347 | 8 | 1.6 | 0.2 |
| Coefficient Of Deviation | 7.2% | 159% | 7.1% | 14% | 6.4% | 18.9% | 79.8% | 6.4% |
| Control Efficiency | | | | | **-12.7%** | **-474%** | **98.4%** | **90.8%** |
| **Souping Test Average (g/min)** | 5,327 | (2) | 99 | 2.9 | 5,817 | 8 | 4.8 | 0.1 |
| Coefficient Of Deviation | 15.0% | 55.5% | 8.4% | 17% | 11.5% | 13.7% | 133% | 14.0% |
| Control Efficiency | | | | | **-9.2%** | **#N/A** | **95.2%** | **94.9%** |

[1] Negative control efficiencies are due to the increase of $CO_2$ and CO from burning fuel to reheat the exhaust before entering the SCR.

## Table 8. ALECS Inlet/Outlet Emissions — RAVEM Data for the Moving Tests

| | Inlet Emissions | | | | Outlet Emissions[1] | | | |
|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | CO | $NO_x$ | PM | $CO_2$ | CO | $NO_x$ | PM |
| **Dash-8 Moving Test Average (g/min)** | 1,797 | 6 | 43 | 3.2 | 2,303 | 12 | 0.6 | 0.0 |
| Coefficient Of Deviation | 40.3% | 97.6% | 35.4% | 71% | 13.9% | 38.9% | 129% | 16.8% |
| Control Efficiency | | | | | **-28.2%** | **-99.4%** | **98.7%** | **98.5%** |
| **GP38 Moving Test Average (g/min)** | 898 | 2 | 22 | 0.2 | 1,661 | 3 | 0.8 | 0.0 |
| Coefficient Of Deviation | 18.6% | 70.9% | 6.5% | 116% | 8.2% | 20.1% | 158% | 66.8% |
| Control Efficiency | | | | | **-84.9%** | **-47.7%** | **96.3%** | **93.5%** |

[1] Negative control efficiencies are due to the increase of $CO_2$ and CO from burning fuel to reheat the exhaust before entering the SCR.

## Table 9. ALECS Inlet/Outlet Emissions — CEMS data for the Motionless Dash-8

| | Inlet | | Outlet | | |
|---|---|---|---|---|---|
| | $SO_2$ | THC | $SO_2$ | THC | $NH_3$ |
| **Notch 8 Average (g/min)** | 27.34 | 9.90 | 0.07 | 6.64 | 1.3 |
| Coefficient Of Deviation | 10.4% | 24.0% | 198.7% | 8.7% | 17.8% |
| Control Efficiency | | | **99.7%** | **32.9%** | |
| **Notch 5 Average (g/min)** | 18.16 | 4.06 | 0.00 | 2.79 | 0.8 |
| Coefficient Of Deviation | 8.3% | 1.3% | 173.2% | 37.7% | 103.9% |
| Control Efficiency | | | **100%** | **31.4%** | |
| **Notch 1 Average (g/min)** | 1.44 | 1.39 | 0.01 | 0.59 | 0.3 |
| Coefficient Of Deviation | 4.3% | 31.5% | 97.4% | 33.4% | 136.0% |
| Control Efficiency | | | **99.1%** | **57.6%** | |
| **Souping Baseline Ave. (g/min)** | 10.87 | 3.90 | 0.00 | 2.60 | 0.0 |
| Coefficient Of Deviation | 14.4% | 2.1% | 0.0% | 13.5% | 115.2% |
| Control Efficiency | | | **100.0%** | **33.2%** | |
| **Souping Test Average (g/min)** | 9.42 | 4.61 | 0.07 | 2.24 | 0.1 |
| Coefficient Of Deviation | 6.6% | 8.7% | 104.9% | 37.0% | 75.5% |
| Control Efficiency | | | **99.2%** | **51.4%** | |

## Table 10. ALECS Inlet/Outlet Emissions — CEMS Data for the Motionless GP38

| | Inlet | | Outlet | | |
|---|---|---|---|---|---|
| | $SO_2$ | THC | $SO_2$ | THC | $NH_3$ |
| **Notch 8 Average (g/min)** | 16.23 | 3.38 | 0.00 | 0.90 | 0.1 |
| Coefficient Of Deviation | 0.2% | 9.3% | 0.00 | 1.7% | 173.1% |
| Control Efficiency | | | **100.0%** | **73.2%** | |
| **Notch 5 Average (g/min)** | 4.70 | 1.62 | 0.00 | 0.23 | 0.0 |
| Coefficient Of Deviation | 1.4% | 7.8% | 0.00 | 2.4% | 99.0% |
| Control Efficiency | | | **100.0%** | **85.7%** | |
| **Notch 1 Average (g/min)** | 0.17 | 0.52 | 0.02 | 0.09 | 0.6 |
| Coefficient Of Deviation | 52.4% | 13.9% | 173.2% | 11.2% | 169.1% |
| Control Efficiency | | | **88.4%** | **83.1%** | |
| **Souping Baseline Ave. (g/min)** | 1.35 | 0.95 | 0.00 | 0.14 | 0.0 |
| Coefficient Of Deviation | 20.9% | 9.7% | 0.00 | 10.6% | 157.3% |
| Control Efficiency | | | **100.0%** | **84.9%** | |
| **Souping Test Average (g/min)** | 1.14 | 0.97 | 0.05 | 0.15 | 0.2 |
| Coefficient Of Deviation | 22.2% | 5.3% | 173.2% | 7.4% | 87.6% |
| Control Efficiency | | | **96.0%** | **84.2%** | |

## Table 11. ALECS Inlet/Outlet Emissions — CEMS Data for the Moving Tests

| | Inlet | | Outlet | | |
|---|---|---|---|---|---|
| | $SO_2$ | THC | $SO_2$ | THC | $NH_3$ |
| **Dash-8 Moving Test Average (g/min)** | 0.75 | 1.27 | 0.00 | 0.56 | 0.000 |
| Coefficient Of Deviation | 36.6% | 35.3% | 0.0% | 60.9% | 100.2% |
| Control Efficiency | | | **100.0%** | **56.0%** | |
| **GP38 Moving Test Average (g/min)** | 0.24 | 0.46 | 0.04 | 0.10 | 0.000 |
| Coefficient Of Deviation | 9.1% | 1.1% | 173.2% | 9.6% | 139.2% |
| Control Efficiency | | | **84.9%** | **78.6%** | |

Table 12. Average Control Efficiencies of the Major Pollutants

| Locomotive | Throttle Notch | $NO_x$ | THC | PM | $SO_2$ |
|---|---|---|---|---|---|
| **Dash-8** | 8 | 96.8% | 32.9% | 88.8% | 99.7% |
| | 5 | 98.4% | 31.4% | 80.9%[1] | 100.0% |
| | 1 | 98.1% | 57.6% | 98.6% | 99.1% |
| | 3 (soup baseline) | 100.0% | 33.2% | 90.7% | 100.0% |
| | 3 (souping test) | 97.0% | 51.4% | 97.0% | 99.2% |
| | Moving | 98.7% | 56.0% | 98.5% | 100.0% |
| **GP38** | 8 | 98.6% | 73.2% | 90.7% | 100.0% |
| | 5 | 99.3% | 85.7% | 90.7% | 100.0% |
| | 1 | 97.0% | 83.1% | 89.6% | 88.4% |
| | 3 (soup baseline) | 98.4% | 84.9% | 90.8% | 100.0% |
| | 3 (souping test) | 95.2% | 84.2% | 94.9% | 96.0% |
| | Moving | 96.3% | 78.6% | 93.5% | 84.9% |
| **Overall Average Control Efficiency** | | **97.8%** | **62.7%** | **92.1%** | **97.3%** |

[1] The anomalous low average PM value (in comparison to the other PM control efficiencies) has been investigated by ACTI, but it could not be explained. The data is included in the overall average calculation for completeness.

## 4.2 Utility, Energy, and Chemical Consumption Rates

ACTI collected operating process data on the ALECS and provided the estimates shown in Table 13 on the utility, energy, and chemical consumption rates per hour of operation. Propane was the fuel used for reheating the exhaust prior to the SCR, but natural gas is the fuel expected to be used in normal operation. The amount of natural gas required to heat the 12,000 scfm of exhaust is 2.60 MMBtu/hr (based upon the measured propane usage during testing, then adjusted using 2,500 Btu/$ft^3$ propane with 1,031 Btu/$ft^3$ natural gas to calculate the natural gas usage). Also, in the proof-of-concept test, diesel engine generators were used to produce the electricity needed, but electricity from the local utility is expected to be used in normal operation. The diesel engine generators and propane were used due to the ALECS installation being temporary only for this proof-of-concept test and being located in a remote area of the rail yard.

Table 13. Utility, Energy, and Chemical Consumption Rates

| Consumables | Quantity | Units |
|---|---|---|
| **Electricity** | 328 | kWh/hr |
| **Natural Gas** | 2.60 | MMBtu/hr |
| **Water** | 180 | gal/hr |
| **Aqueous Urea (40%)** | 0.54 | gal/hr |
| **Sodium Hydroxide (30%)** | 0.0095 | gal/hr |

## 4.3 Waste Characterization

The solid waste produced by the ALECS and collected from the Preconditioning Chamber and the Cloud Chamber discharge was analyzed. The toxic chemicals and Title 22 metal compounds were below the detection limit of the laboratory. The only detectable compounds are shown in Table 14. The complete lab report is included in Appendix D.

**Table 14. Solid Waste Analysis**

| | Units | Sample #1 | Sample #2 |
|---|---|---|---|
| **Oil & Grease** | mg/Kg | 85,000 | 78,000 |
| **Total Recoverable Petroleum Hydrocarbons** | mg/Kg | 88,000 | 80,000 |
| **Zinc** | mg/Kg | 92 | 22 |

Solid waste accumulated from the ETS was estimated to be produced at a peak rate of 2.2 lb/hr. This estimate is based upon data collected by ACTI during the testing. Captured solid waste was stored in drums that hold around 400 pounds of material each. The filled drums were transported by an ACTI truck to an approved disposal site

The liquid wastewater was analyzed and the results are provided (as well as the solid waste analysis) in Appendix D. Liquid wastewater was being produced at a rate of 0.9 gal/hr. Analysis of the wastewater shows it could be considered safe enough to be discharged to a publicly owned treatment works, but local policies specific to each location will need to be identified.

## 4.4 Diesel Fuel Analysis

The test fuel for the GP38 was ultra-low sulfur diesel fuel meeting ARB regulations for sulfur and aromatic content. The sulfur limit is 15 ppm, and the limit on aromatic content is 10 percent unless the fuel is produced according to an approved alternative formulation. The test fuel for the Dash-8 was a diesel fuel that is actually supplied to Union Pacific line-haul locomotives outside California. This fuel was specified with sulfur content between 200 and 500 ppm.

Table 15 shows the results of analyses performed on each fuel sample. EF&EE collected fuel samples from each locomotive’s fuel tank during the test program. The fuel tanks were sealed and labeled to ensure that fuel was not added to the tanks by mistake.

Table 15. Fuel Analyses

| | Method | Dash 8 | GP38 |
|---|---|---|---|
| **Carbon Content** | D-5291 | 86.00% | 86.10% |
| **Hydrogen Content** | D-5291 | 13.33% | 13.73% |
| **Nitrogen Content** | D-5291 | 0.05% | 0.06% |
| **Sulfur Content (ppm)** | D-4294 | 500 | <150[1] |

[1] This test did not have the resolution to verify 15 ppm sulfur content. However, the fuel was taken from the Roseville rail yard fueling system and all fuel dispensed in Roseville at the time met CARB diesel with a sulfur content of 15 ppm or less.

## 4.5 Noise Measurements

The locomotive noise measurements were measured at a point 30 meters perpendicularly away from the side of the locomotive with and without the bonnet attached to the stack(s). The decibel scale is logarithmic rather than linear. Hence a small reduction in decibels results in a fairly large percent reduction in sound energy. Table 16 shows the results of the noise measurements taken.

Table 16. Noise Measurements with and without the Bonnet in Place

| | Average Sound Level (decibels) | | | Percent Reduction In Sound Energy |
|---|---|---|---|---|
| | w/o Bonnet | w/Bonnet | Reduction | |
| **DASH-8: Notch 8** | 87.0 | 81.7 | 5.3 | 70% |
| **DASH-8: Notch 5** | 84.5 | 77.7 | 6.8 | 79% |
| **GP38: Notch 8** | 91.6 | 84.8 | 6.8 | 79% |

## 4.6 Overall System Evaluation

Conventional stationary emission control technology has been demonstrated to be very effective in treating emissions from locomotive sources. The ECS demonstrated the ability to capture emissions from a single locomotive (at a time) while motionless and while moving. The proof–of-concept test utilized a system that was installed to handle a single locomotive at a time; a full-sized emissions capture system (ECS) with multiple locomotives was not tested.

# 5. Life Cycle Cost Analysis

## 5.1 Methodology

The life cycle cost analysis estimates the total cost of the ALECS incurred over the life of the system and is used along with the emission estimates to determine the system cost effectiveness per ton of pollutant reduced. The life cycle cost analysis entails Cost Element Definition, Data Collection, and Evaluation.

## 5.2 Cost Element Definition

Cost elements are broken down into Initial Capital Costs, Operating and Maintenance Costs including Utility/Energy Costs, Repair and Replacement Costs, Downtime Costs, Environmental Costs, and Salvage Value.

A) Initial Capital Costs include engineering and design (drawings and regulatory issues), bidding process, purchase order administration, hardware capital costs, testing and inspection, inventory of spare parts, foundations (design, preparation, concrete and reinforcing), installation of equipment, connection of process piping, connection of electrical wiring and instrumentation, one-time licensing/permitting fees, and the start up (check out) costs.

B) Operating and Maintenance Costs include items such as labor costs of operators, inspections, insurance, warranties, recurring licensing/permitting fees, and all maintenance (corrective and preventive maintenance). Also included are yearly costs of consumables such as the utility/energy costs (electricity, natural gas, and water) and chemical costs (such as sodium hydroxide and urea).

C) Repair and Replacement Costs are the costs of repairing and replacing equipment over the life of the ALECS. This would also include catalyst material replacement.

D) Rail yard impact costs include estimates of costs incurred by the Union Pacific Railroad. An example would be if the ALECS was shut down for repairs and locomotives that normally would be serviced or stored in a specific area needed to be relocated and serviced/stored elsewhere. Rail yard impact costs would also include the costs to change rail yard operations that are different from what is practiced today (including structural changes, if needed, to accommodate ALECS). For example, the additional time and costs (including labor) of rerouting locomotives to the ALECS area if the locomotives may not have been normally required to be moved. Locomotive downtimes can be very expensive to the rail yard and may result in loss of revenue. Costs may also be negative (a benefit to the rail yard) if the implementation of ALECS produced increased efficiencies such as decreased dwell time (time a locomotive is in the rail yard). At the current time, Union Pacific Railroad does not have an estimate (positive or negative) as to the effect ALECS would have on rail yard operations.

E) Environmental Costs are associated with the disposal of wastewater, solid waste, used chemicals, and used parts.

F) The Salvage Value of the system would be the net worth of the ALECS in its final year of the life cycle period. If the system can be moved and salvaged for useful parts/purposes, there would be a reduction in life cycle costs.

The estimates in this report are based upon data and observations taken during the operation and proof-of-concept testing of the ALECS.

### 5.3 Data Collection and Assumptions

Accuracy of input data is important to improve the certainty of the life cycle cost prediction. Data was obtained from stakeholders in this project (such as ACTI, UPRR, EF&EE, and the PCAPCD) to provide the most accurate information available. Where actual data were not available from the stakeholders, literature searches, theoretical calculations, and engineering estimates were utilized. The ETS would be common among installations at different rail yards, however, the ECS would need to be tailored to each specific installation dependent upon the size and activity of locomotives at each rail yard. However, the main ECS components would be common, just arranged to cover a different length or width of the section of rail yard being addressed. For estimating costs, an installation for the Western United States is assumed.

ACTI provided information on the initial capital costs (see Table 17). The costs include burden, markup, and taxes. Taxes do not include provisions for property taxes. The ECS is based upon the full scale deployment design of the concentric tube manifold subsystem shown Section 2.2. The estimates are based upon 12 bonnets installed for an ETS installed at the rail yard. The ETS equipment costs include a semi-automatic solid waste removal system that will replace the bag filter system that was used in the proof-of-concept test. A boost blower has been added to the Roseville proof-of-concept test design in order to compensate for the length of the full-scale ECS design.

The costs are based upon the assumption of reduced prices from multiple production runs of around 20 units, split between rail and marine applications

The Indirect Installation Costs were adjusted based on ACTI's experience in Roseville. As this system is duplicated in many locations, the required Engineering Support will become considerably less on each succeeding application, and most of the non-recurring engineering will only be needed for the first application. This also applies to some extent to the rest of the indirect installation costs as well. The construction, field expenses, and contractor fees are mostly included as part of the Equipment Costs, although a portion of these costs is still required for final placement and integration of these items.

The proof-of-concept test design utilized a filtration system to separate the particulate from the Preconditioning Chamber and Cloud Chamber Scrubber water for disposal. Figure 25 shows the originally white filters (Figure 26) that have turned black with use in the proof-of-concept testing.

The full scale deployment design would incorporate the Solid Waste Semi-Automatic Removal System shown in Figure 27 that would be able to process higher volumes of particulate with less labor and filter material/changes.

## Table 17. ALECS Initial Capital Costs

| | Qty | Units | Cost/Unit | Subtotal | Total |
|---|---|---|---|---|---|
| **Equipment Costs** | | | | | |
| ECS: Overhead Structure | 1,200 | feet | $ 933 | $1,119,901 | |
| ECS: Overhead Manifold | 1,200 | feet | $ 1,077 | $1,292,193 | |
| ECS: Bonnets | 12 | each | $ 57,431 | $ 689,170 | |
| ECS: Boost Blower | 1 | each | $ 19,383 | $ 19,383 | |
| ETS | 1 | each | $3,625,319 | $3,625,319 | |
| Emissions Monitoring | 1 | each | $ 518,378 | $ 518,378 | |
| **Total Equipment Costs (Cp):** | | | | **$7,264,343** | |
| **Shipping** | 3% | Cp | $7,264,343 | **$ 217,930** | |
| | | | | **Purchased Equipment Cost (PEC):** | **$7,482,273** |
| **Direct Installation Costs** | | | | | |
| ECS: Piers | 24 | each | $ 1,436 | $ 34,458 | |
| ECS: Assembly & Erection | 1,200 | feet | $ 144 | $ 172,292 | |
| ECS: Electrical | 1 | each | $ 43,073 | $ 43,073 | |
| ETS: Pads & Foundations | 1 | each | $ 107,683 | $ 107,683 | |
| ETS: Electrical | 1 | each | $ 93,325 | $ 93,325 | |
| ETS: Natural Gas/Propane/CNG | 1 | each | $ 43,073 | $ 43,073 | |
| ETS: Water | 1 | each | $ 1,436 | $ 1,436 | |
| ETS: Sewer (Industrial) | 1 | each | $ 8,615 | $ 8,615 | |
| Permits | 1 | each | $ 50,970 | $ 50,970 | |
| Infrastructure Design & Construction | 1 | each | $ 78,967 | $ 78,967 | |
| Trenching and Coring | 1 | each | $ 8,615 | $ 8,615 | |
| Consumables for Commissioning | 1 | each | $ 31,587 | $ 31,587 | |
| | | | | **Total Direct Costs (TDC):** | **$ 674,094** |
| **Indirect Installation Costs** | | | | | |
| Engineering Support | 0.5% | PEC | $7,482,273 | $ 37,411 | |
| Construction & Field Expenses | 1.0% | PEC | $7,482,273 | $ 74,823 | |
| Contractor Fees | 2.0% | PEC | $7,482,273 | $ 149,645 | |
| Start-up | 0.5% | PEC | $7,482,273 | $ 37,411 | |
| Performance Test | 0.5% | PEC | $7,482,273 | $ 37,411 | |
| Contingencies | 2.5% | PEC | $7,482,273 | $ 187,057 | |
| | | | | **Total Indirect Costs (TIC):** | **$ 523,759** |
| | | | | **Total Initial Capital Investment (TICI):** | **$8,680,126** |

Figure 25.  Some Solid Waste Filters Used During the Demonstrating Testing

Figure 26.  Clean Solid Waste Filter

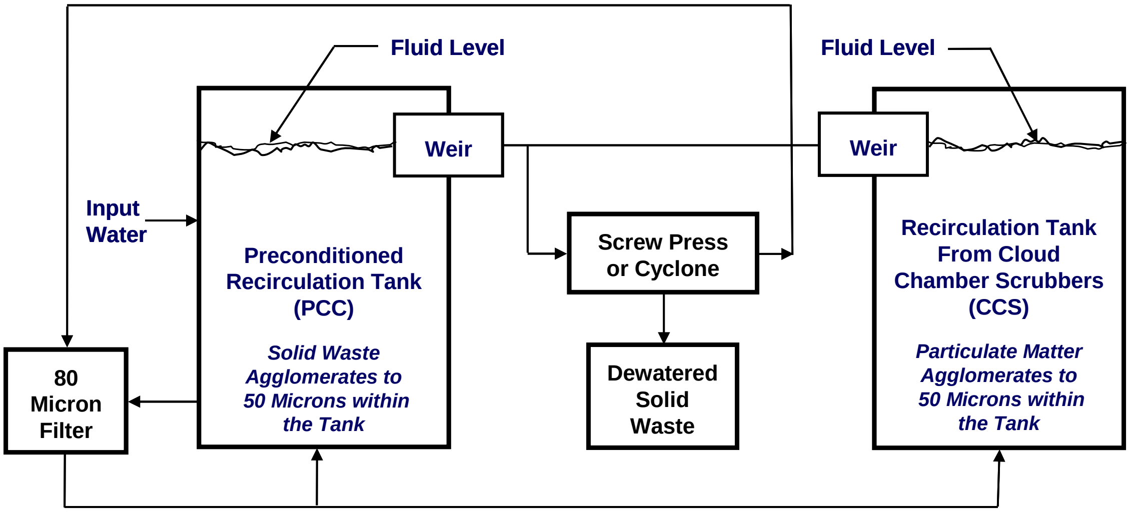


**Figure 27. Solid Waste Semi-Automatic Removal System**

The solid waste and particulate matter collected within the PCC and CCS recirculation tanks are removed (skimmed) from the surface using a Weir. ACTI experience has shown that the solid waste and particulate matter agglomerates within the tanks to a size of approximately 50 microns. Since the water in the tanks is turbulent, material does not tend to accumulate on the bottom.

The removed material is then sent to a screw press or cyclone which automatically removes much of the water. The removed water is returned to the appropriate recirculation tank, the solid material is then deposited into roll bins for removal and disposal. Analysis has shown the solid waste material to be non-hazardous.

The removed water is then filtered through an 80 micron filter prior to being returned to the appropriate recirculation tank. Filters are disposable and will be replaced every other month.

The annually recurring operation and maintenance costs are presented in Table 18. The consumables and utilities are based upon ALECS operating 96 percent of the maximum annual hours (ACTI estimate). The electricity and natural gas prices are based upon the Energy Information Administration’s forecasted 2007 Industrial prices for the Pacific region. The SCR catalyst is estimated to be replaced every five years at a cost (fully loaded) of $86,146. The 5 year life of the catalyst is based upon the removal of sulfur and PM prior to the SCR which extends the life of the catalyst. The catalyst is assumed to not be replaced in the 20th year of the ALECS operation due to the end of its projected 20 year life. This catalyst replacement cost is annualized in the recurring operation and maintenance costs. It is assumed that there will not be a salvage value of the ALECS at the end of its useful life and any salvage value would be offset by any costs associated with shutting down the ALECS.

Burden and profit are not applied to the “Utilities” line items (e.g. electricity, natural gas, and water), as these will be supplied by the rail yard. However, maintenance and labor will be supplied by a third party operator/owner. ALECS will be staffed 24 hours a day, 365 days a year as shown in Table 18.

**Table 18. ALECS Annually Recurring Operation and Maintenance Costs**

| | Usage Rate | | Unit Cost | | $/hr | $/year |
|---|---|---|---|---|---|---|
| **Consumables/Utilities/Fees** | | | | | | |
| Sodium Hydroxide (30%) | 0.0095 | gal/hr | $ 1.65 | /gal | $ 0.02 | $ 132 |
| Aqueous Urea (40%) | 0.54 | gal/hr | $ 1.86 | /gal | $ 1.01 | $ 8,462 |
| Electricity | 328 | kWh/hr | $ 0.0747 | /kWh | $ 24.50 | $ 206,049 |
| Natural Gas | 2.60 | MMBtu/hr | $ 7.20 | /MMBtu | $ 18.69 | $ 157,213 |
| Natural Gas Meter Charge | 1 | meter | $ 11.51 | /meter-day | $ 0.48 | $ 4,201 |
| Water | 180 | gal/hr | $ 1.66 | /1000 gal | $ 0.30 | $ 2,513 |
| Liquid Waste | 0.90 | gal/hr | $ 0.34 | /gal | $ 0.30 | $ 2,563 |
| Solid Waste | 2.19 | lb/hr | $ 0.051 | /lb | $ 0.11 | $ 935 |
| Insurance | 1 | premium/yr | $ 33,863 | /site | $ 3.87 | $ 33,863 |
| **Labor** | | | | | | |
| Technician | 1 | Technician | $ 84,114 | /year | $ 40.44 | $ 84,114 |
| Operator | 4 | Operators | $ 56,570 | /year | $ 27.20 | $ 226,279 |
| **Maintenance** | 2.0% | TICI | $ 8,680,126 | /TICI | $ 19.82 | $ 173,603 |
| | | | | | **Total Annual Recurring Operating Costs[1]:** | **$ 899,926** |

[1] An additional catalyst replacement cost (not included in the annual costs above) of $86,146 also occurs every 5 years. Cost is annualized in the economic analysis.

## 5.4 Evaluation

The total life cycle cost of the ALECS is based upon the discounted cash flow of costs in the future (which brings the costs to their present value), and the annualized payments of initial capital costs to account for the time value of money. The costs are summed to produce the total life cycle cost of the ALECS. The interest (discount rate) is assumed to be 4 percent based upon the value used in the Carl Moyer program (CARB, January 6, 2006). The system is designed and projected to have a life of 20 years (the EPA Air Pollution Control Cost Manual uses a 20 year economic lifetime for a SCR system) (EPA, January 2002).

The Initial Capital Investment of $8,593,980 (without the catalyst cost) is annualized with an adjustment for the time value of money (4 percent interest for 20 years) to be $632,360/year. The cumulative 20 year cost is $12,647,202.

The catalyst cost of $86,146 is annualized with an adjustment for time value of money (4 percent interest for 5 years) for the first 5 years. Each subsequent 5 year increment has a catalyst replacement cost reduced to the present value (from the year the catalyst is replaced) before adjusting for the time value of money. This results in a total catalyst cost of $287,727 over the 20 year life of ALECS. The summary of the components used to build up the catalyst costs are presented in Table 19.

**Table 19. Summary of Catalyst Costs for ALECS**

| | Years 1 - 5 | Years 6 – 10 | Years 11 - 15 | Years 16 - 20 | Total |
|---|---|---|---|---|---|
| **Catalyst Cost (2007$)** | 86,146 | 86,146 | 86,146 | 86,146 | 344,585 |
| **Year of Replacement** | | 6 | 11 | 16 | |
| **Present (discounted) Value (2007$)** | 86,146 | 68,083 | 55,959 | 45,994 | 256,182 |
| **Adjusted for Time Value of Money (2007$)** | 96,754 | 76,466 | 62,849 | 51,658 | 287,727 |
| **Annualized Cost/year (2007$)** | 19,351 | 15,293 | 12,570 | 10,332 | |

The net present value (which accounts for the changes in value of money over time) of the operation and maintenance cost ($899,926/year) over the life of ALECS is $12,230,292.

The ALECS total life cycle cost over a 20 year period is $25,165,221. The summary of the annual costs (fully loaded with the burden, markup, and taxes) adjusted for the time value of money is shown in Table 20 and Figure 28.

**Table 20. Summary of Annual Costs (2007$)**

| Year | Initial Capital Cost (w/o catalyst) | Catalyst Cost | Operation and Maintenance Cost | Total Cost |
|---|---|---|---|---|
| **1** | 632,360 | 19,351 | 865,314 | 1,517,025 |
| **2** | 632,360 | 19,351 | 832,032 | 1,483,743 |
| **3** | 632,360 | 19,351 | 800,031 | 1,451,742 |
| **4** | 632,360 | 19,351 | 769,261 | 1,420,972 |
| **5** | 632,360 | 19,351 | 739,674 | 1,391,385 |
| **6** | 632,360 | 15,293 | 711,225 | 1,358,878 |
| **7** | 632,360 | 15,293 | 683,870 | 1,331,523 |
| **8** | 632,360 | 15,293 | 657,567 | 1,305,221 |
| **9** | 632,360 | 15,293 | 632,276 | 1,279,930 |
| **10** | 632,360 | 15,293 | 607,958 | 1,255,611 |
| **11** | 632,360 | 12,570 | 584,575 | 1,229,505 |
| **12** | 632,360 | 12,570 | 562,091 | 1,207,021 |
| **13** | 632,360 | 12,570 | 540,472 | 1,185,402 |
| **14** | 632,360 | 12,570 | 519,685 | 1,164,615 |
| **15** | 632,360 | 12,570 | 499,697 | 1,144,627 |
| **16** | 632,360 | 10,332 | 480,478 | 1,123,170 |
| **17** | 632,360 | 10,332 | 461,998 | 1,104,690 |
| **18** | 632,360 | 10,332 | 444,229 | 1,086,921 |
| **19** | 632,360 | 10,332 | 427,143 | 1,069,835 |
| **20** | 632,360 | 10,332 | 410,715 | 1,053,406 |
| **Total Cost** | 12,647,202 | 287,727 | 12,230,292 | **$ 25,165,221** |

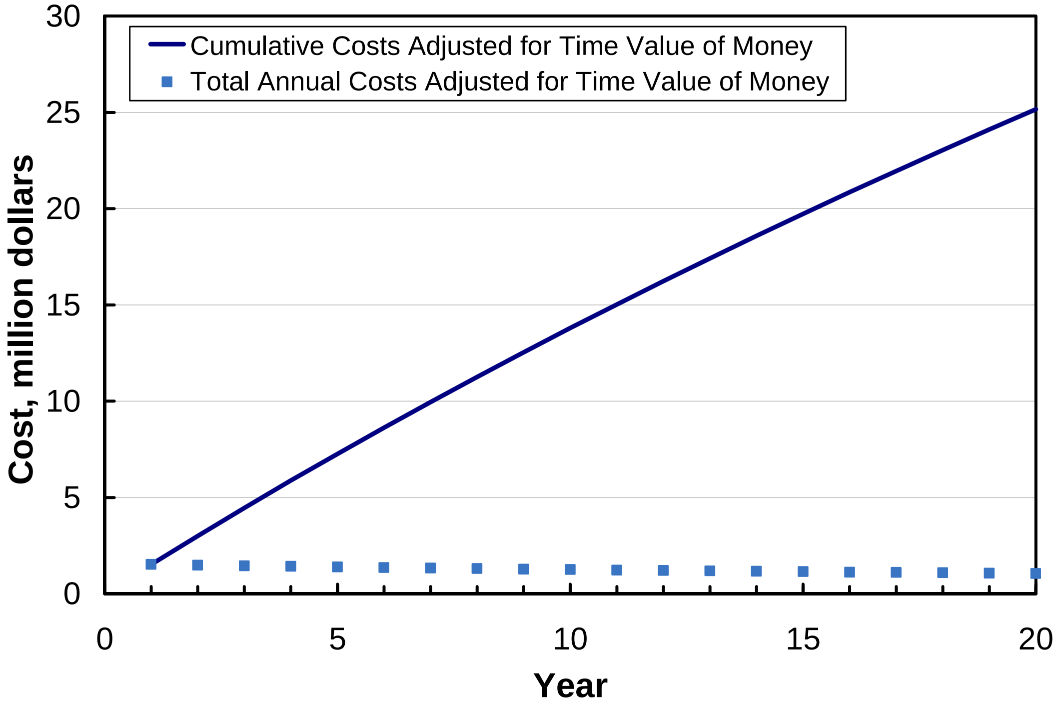


Figure 28.  ALECS Annual Cash Flow and Cumulative Costs (2007$)

# 6. Cost Effectiveness

The cost effectiveness of ALECS is determined by dividing the total ALECS life cycle cost by the total weighted emissions reduced by ALECS over the life of the system. The use of weighted reduced emissions is based upon the Carl Moyer Memorial Air Quality Standards Program (CARB, January 6, 2006). The Carl Moyer program considers $NO_x$, THC and $PM_{10}$ emission reductions in one calculation where weighting factors are applied. For $NO_x$ and THC emission reductions, a weighting factor of one is used. CARB has identified particulate emissions from diesel-fueled engines as toxic air contaminants, and believes emission reductions of $PM_{10}$ should carry additional weight in the calculation because, for an equivalent weight, these emissions are more harmful to human health. CARB uses a PM10 weighting factor of 20. The Carl Moyer method utilizes the Annualized Cash Flow method which multiplies the initial capital cost by a capital recovery factor to obtain an equivalent end of year annual capital cost payment.[1] This report utilizes the annualized capital costs adjusted for the time value of money and the Discount Cash Flow method for future costs which calculates the cost by determining the present value of the costs of buying, operating, and maintaining the equipment over the life of the equipment (see life cycle costs analysis above).

The weighted cost effectiveness formula for ALECS analysis is:

$$\frac{\text{Total Life Cycle Cost (2007\$)}}{(NO_x + THC + 20*PM_{10})\text{ (tons reduced over life of equipment)}}$$

The emissions measurements from this proof-of-concept test are based upon just two locomotives (the Dash-8 and the GP38) and may not be representative of all Dash-8 (line-haul) or all GP38 (switcher) locomotives. The emissions reduced in the rail yard application will be highly dependent on the specific details of each application. In an attempt to bound the possible uses in a rail yard, two examples using only two locomotives are presented. One example case utilizes all idling, Tier 2 locomotives that will produce the lowest emissions for treatment by the ALECS. The other example case, representing high emissions, assumes Tier 0 locomotives operating at various conditions.

Tier 0 Dash-8 emissions data were obtained from CARB (based upon GE certification data for C40-8) as compiled for the Roseville rail yard health risk assessment study (CARB, October 14, 2004)_and should be more representative of the locomotives operating at the rail yard. Tier 2 emissions data were estimated based upon EPA engine certification data for the GE engine family “6getg0958efb” (EPA website, March 2007). These emission factors are presented in Table 21. $SO_x$ emission factors were not used because Tier 0 data were not available

Without further information on the estimated number of locomotives and their throttle settings in a specific area of the rail yard, the following 4 scenarios (the first 3 scenarios apply to the Tier 0 locomotives) in Table 22 were created. All of these scenarios were designed to fully use the

---

[1] The Moyer method does not consider annual operating and maintenance costs.

12,000 scfm capability of ALECS. For example, 6 Tier 2 engines at idle would fully use the systems capability or only 1 Tier 0 locomotive at notch 8.

**Table 21. Locomotive Emission Factors**

| Locomotive | Throttle | Exhaust (scfm)[1] | PM (g/hr) | $NO_x$ (g/hr) | THC (g/hr) |
|---|---|---|---|---|---|
| **Tier 0** | 8 | 12,077 | 615 | 29,527 | 861.21 |
| | 5 | 7,176 | 327.68 | 14,746 | 655.36 |
| | idle | 2,000 | 36.95 | 746.49 | 268.65 |
| **Tier 2** | idle | 2,000 | 25.1 | 747.2 | 71.5 |

[1] Exhaust flow rate for Tier 0 at throttle notch 8 and 5 are from proof-of-concept testing. The idle exhaust flow rates are estimated.

**Table 22. Locomotive Scenarios**

| Scenario # | Locomotive | Number of Locomotives | | | Total Exhaust (scfm) |
|---|---|---|---|---|---|
| | | Notch 8 | Notch 5 | Idle | |
| **1** | Tier 0 | 1 | - | - | 12,077 |
| **2** | Tier 0 | - | 1 | 2 | 11,176 |
| **3** | Tier 0 | - | - | 6 | 12,000 |
| **4** | Tier 2 | - | - | 6 | 12,000 |

Applying the emission factors from Table 21 and this proof-of-concept's overall control efficiencies from Table 12 (the $NO_x$ control efficiency was reduced 1.5 percent, from 97.8 to 96.3 percent, to account for catalyst degradation over time) to the scenarios produced the total emissions controlled in Table 23 if each scenarios were individually running 100 percent of the time.

Table 24 shows the maximum available controlled emissions if ALECS was able to run at full capability (12,000 scfm) 100 percent of the time for each of the bounding cases (Tier 0 and Tier 2). The Tier 0 example case utilizes all GE Dash-8 locomotives with a mix of notch 8 (10 percent), notch 5 (20 percent) and idling (70 percent) operating conditions. The higher notch running of the locomotives represents a situation where the ALECS is situated in a location where there is diagnostic and load testing performed. The testing is supplemented with idling to keep the ALECS fully employed.

No deterioration factors (DF) are used for the Tier 2 locomotives over the 20 year life of the ALECS system.

**Table 23. Maximum Controlled Emissions for Each Scenario**

| Scenario # | PM (g/hr) | $NO_x$ (g/hr) | THC (g/hr) |
|---|---|---|---|
| **1 (Tier 0)** | 566 | 28,440 | 540 |
| **2 (Tier 0)** | 370 | 15,640 | 748 |
| **3 (Tier 0)** | 204 | 4,314 | 1,010 |
| **4 (Tier 2)** | 139 | 4,318 | 269 |

**Table 24. Maximum Annual Controlled Emissions**

| Scenario # | Hours/yr | PM (ton/yr) | $NO_x$ (ton/yr) | THC (ton/yr) |
|---|---|---|---|---|
| 1 (Tier 0) | 876 | 0.55 | 27.46 | 0.52 |
| 2 (Tier 0) | 1,752 | 0.71 | 30.21 | 1.44 |
| 3 (Tier 0) | 6,132 | 1.38 | 29.16 | 68.83 |
| **Total Tier 0** | **8,760** | **2.64** | **86.83** | **8.80** |
| **Total Tier 2** | **8,760** | **1.34** | **41.70** | **2.60** |

Deterioration factors (DFs) were applied to the emission factors for the Tier 0 case. Roseville rail yard is a major service center for Union Pacific where locomotives are brought for diagnostics and repair. Some of these locomotives have been observed to produce visible emissions not common to well-running engines. It is anticipated that some of these abnormally high emission locomotives would be connected to the ALECS during diagnostics.

The Dash-8 locomotive tested in this proof-of-concept project was obtained from the normal operational fleet, but was suspected of having higher than average emissions. When compared to the certification data for this locomotive type (see Table 21), the emissions for PM and $NO_x$ were considerably higher. The DFs used for this Tier 0 example case were set at the average of the certification data and the test results obtained in this project. The project PM data were 229 percent greater than the certification data with the $NO_x$ data 159 percent greater (THC was 44 percent). The DFs applied for PM is 1.64 with 1.29 applied to $NO_x$ (THC factor is not applied).

**Table 25. Tier 0 Deterioration and New Engine Introduction Factor**

|  | PM | $NO_x$ | THC |
|---|---|---|---|
| % Greater than Certification | 229% | 159% | - |
| Deterioration Factor | 1.64 | 1.29 | 1 |
| Reduction due to New Engines | 14% | 14% | 13% |
| **Adjusted Deterioration Factor** | **1.42** | **1.12** | **0.87** |

To recognize that over the next 20 years the fleet of locomotives is expected to trend toward lower emissions as new locomotives are added and the oldest locomotives are retired, a reduction factor was added to represent the upgrading of the fleet. This information was obtained from an EPA projection that lists fleet average emission factors by year going into the future (EPA, December 1997). Looking at the reduction projected from 2008 to 2028 and averaging over the 20 years gives emission factor reductions of 14 percent for PM, 14 percent for $NO_x$, and 13 percent for HC. Combining the DF and fleet average reduction into a single factor gives the following factors used for this analysis:

For the cost effectiveness calculations, the ALECS is assumed to have a 96 percent utilization factor (ACTI estimate) and the emission estimates for the Tier 0 example are shown in Table 26 and 27. The adjusted emissions shown in these tables include the factor of 20 for the $PM_{10}$ adjustment and the adjusted DFs shown in Table 25 for PM10, $NO_x$ and THC.

**Table 26. Annual Tier 0 Controlled Emissions with ALECS at 96 Percent Utilization**

| Scenario # | Hours/yr | PM (ton/yr) | $NO_x$ (ton/yr) | THC (ton/yr) |
|---|---|---|---|---|
| 1 | 841 | 0.52 | 26.36 | 0.50 |
| 2 | 1,682 | 0.69 | 29.00 | 1.39 |
| 3 | 5,887 | 1.32 | 27.99 | 6.56 |
| Sum | 8,410 | 2.53 | 83.35 | 8.44 |
| **Adjusted Emissions** | | 71.87 | 93.23 | 7.34 |

**Table 27. Annual Tier 2 Controlled Emissions with ALECS at 96 Percent Utilization**

| Scenario # | Hours/yr | PM (ton/yr) | $NO_x$ (ton/yr) | THC (ton/yr) |
|---|---|---|---|---|
| 4 | 8,410 | 1.29 | 40.03 | 2.49 |
| **Adjusted Emissions** | | 25.72 | 40.03 | 2.49 |

The total weighted controlled PM, $NO_x$, and THC emission for Tier 0 is 172.4 tons/yr with Tier 2 estimate of 68.2 tons/yr. $SO_x$ emissions reductions are not considered in these estimates. Over the total 20 year life of the ALECS, the total weighted emissions reduced ranges from 1,365 tons to 3,449 tons. The resulting cost effectiveness is estimated to range from $18,437/ton to $7,297/ton of weighted pollutant reduced. Figure 29 shows the cost effectiveness curve over the 20 year projected life of the ALECS. The point to the furthest left of the figure represents Tier 2 locomotives operating only in idle mode (with a 96 percent ALECS uptime factor). The point on the curve to the furthest right of the graph represents Tier 0 Dash-8 locomotives operating 10 percent of the time at notch 8, 20 percent at notch 5, and the remaining 70 percent of the time at idle (also applying a 96 percent ALECS uptime factor and DFs). The single magenta point (square shape) is an estimated midpoint to be used for sensitivity analysis.

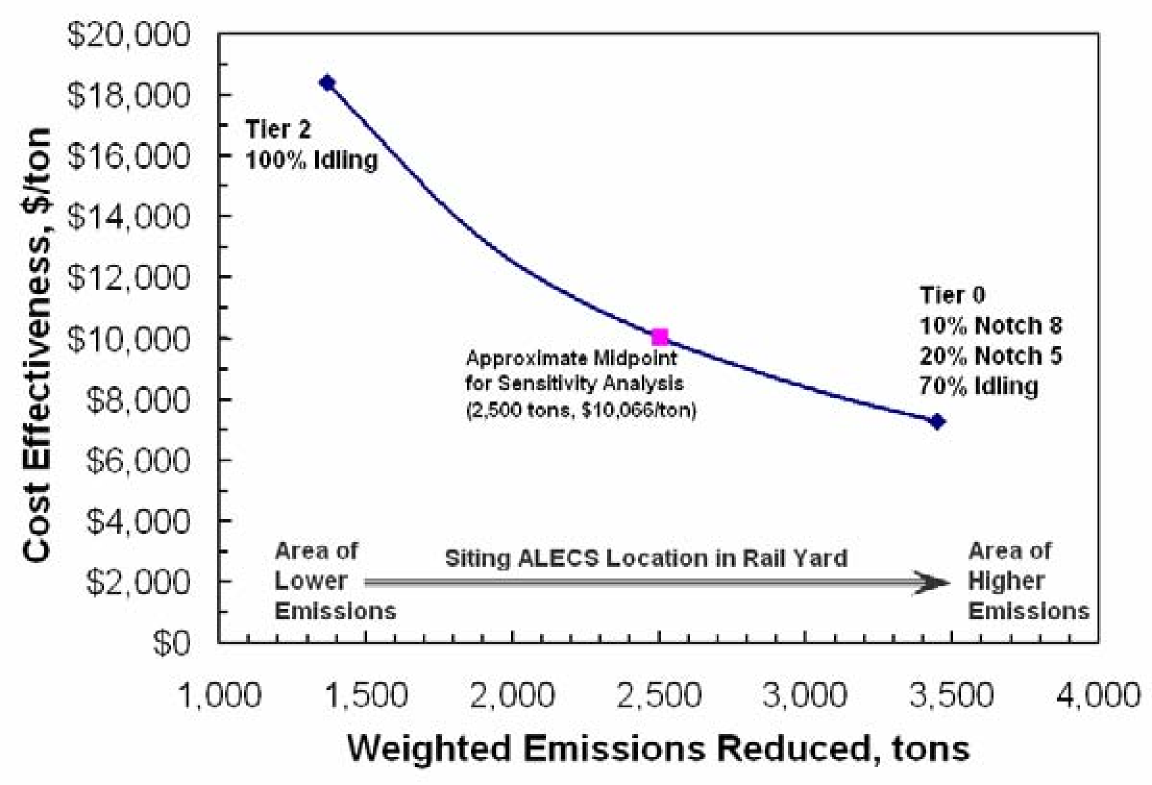


**Figure 29. ALECS Cost Effectiveness**

Figure 29 highlights the importance of installing the ALECS in an area of the rail yard where there are locomotives operating in higher notch settings. Installing the ALECS in an area where emissions reductions fall on the right side of the figure would result in better cost effectiveness than locations with emissions that fall further to the left. Higher emissions would result from higher engine settings than at idle, therefore, it is possible for less engines running at higher notch settings to have higher total emissions than if more engines were running, but were only idling. Careful analysis of the locomotive mix and how many engines are running in specific areas of the rail yard is important, but also knowing what notch setting and for how long each engine is running would also be important in determining where the ALECS should be located to maximize emissions reductions and provide best ALECS cost effectiveness.

Sensitivity analysis on the cost effectiveness was performed on the approximate midpoint according to the hypothetical base case parameters listed in Table 28. The results are graphed in the tornado chart in Figure 30.

**Table 28. Parameters Used for the Cost Effectiveness Sensitivity Analysis**

| | Better Cost Effectiveness | Approximate Midpoint Case | Worse Cost Effectiveness |
|---|---|---|---|
| **Throttle Notch Positions** | 10% N8, 20% N5, 70% Idle | 5% N8, 10% N5, 85% Idle | 100% Idle |
| **Emissions Reduction Rate** | 150 ton/yr | 125 ton/yr | 100 ton/yr |
| **System Utilization Rate** | 100% | 96% | 70% |
| **ALECS Lifetime** | 25 years | 20 Year Life | 15 years |
| **Interest (Discount Rate)** | - | 4% | 6% |

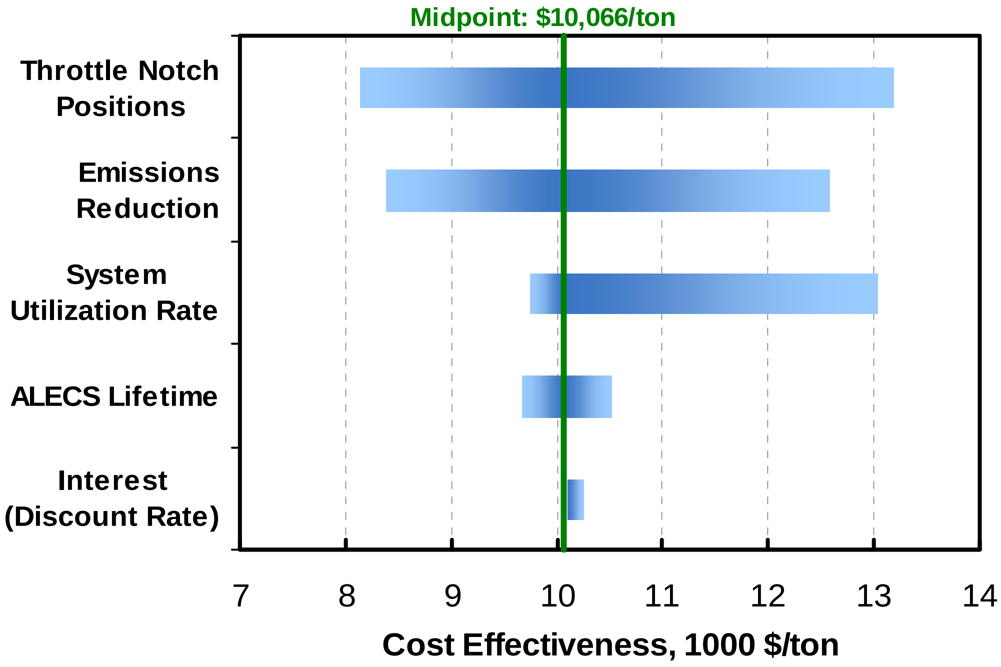


**Figure 30. Cost Effectiveness Sensitivity on Midpoint**

The estimated 96 percent system utilization rate is based upon locomotive emissions being generated 100 percent of the year (based upon the scenarios described above) and the ALECS being available 96 percent of the time. The minimum cost effectiveness value (better) was based on the ALECS being available 100 percent of the time. The maximum cost effectiveness value (worst) is based upon a 70 percent system utilization rate which is not only based upon the ALECS availability (ACTI expects ALECS to be available at least 96 percent of the time), but it also incorporates whether there are emissions being generated. The 70 percent would represent the ALECS being available and exhaust emissions are also being generated at the same time. A 30 percent increase in cost effectiveness would be due to a drop in system utilization rate to 70 percent. This highlights the importance of installing the ALECS in a busy area of the rail yard where there would be a high concentration of locomotives generating emissions.

The locomotive throttle notch positions were examined at 100 percent idling for the maximum cost effectiveness value and 10 percent at notch 8 with 20 percent at notch 5 for the minimum.

The increase in time at higher notch settings (with 70 percent of the remaining time spent idling) resulted in a 19 percent reduction in cost effectiveness.  At 100 percent idling, the cost effectiveness jumps up 31 percent. Understanding the operational modes of the locomotives is important because they have a large impact on the cost effectiveness.  Preference in placement of the ALECS would be in areas where locomotives would run at higher notches than areas where locomotives would only idle.

An increase of 20 percent of the pollutants reduced from the baseline resulted in a 17 percent reduction in cost effectiveness.  A 20 percent reduction in pollutants from the base case increased the cost effectiveness by 25 percent.

Increasing the interest (discount rate) from the baseline of 4 percent (Moyer guideline) to 6 percent, results in a 2 percent higher cost effectiveness value. Analysis of interest rates less than 4 percent were not performed.

The ALECS was designed for a 20 year life, but if the system does not run after 15 years, the cost effectiveness increases 5 percent to $10,521/ton. If the system runs for 25 years, the cost effectiveness drops down 4 percent to $9,663/ton.

# 7. Summary/Next Steps

## 7.1 Summary

This project was a "proof-of-concept" effort designed to demonstrate the possible effectiveness of one set of stationary air pollution control equipment to capture and treat emissions from locomotives that are temporarily idling while sitting on a ready track, being prepared for servicing, being serviced, or undergoing engine load tests. The equipment was to be evaluated for effectiveness in capturing and treating PM, $NO_x$, SOx, and VOC emissions from such locomotives. The specific objectives of this proof-of-concept project and its accomplishments are summarized in Table 29.

**Table 29. Summary of Project Objectives and Accomplishments**

| OBJECTIVE | ACCOMPLISHED? |
|---|---|
| **Objective 1: Demonstrate the Possible Effectiveness of Stationary Control Equipment on Locomotive Exhaust:**<br>This proof-of-concept test of the ALECS equipment should quantify the overall capture and control efficiency of particulate matter (PM), $NO_x$, $SO_x$, and total hydrocarbons (THC) in actual locomotive exhaust in a rail yard environment. Locomotive engines in common use come in two distinct technologies; two-stroke and four-stroke. This proof-of-concept test will test one engine of each technology; a GP38 locomotive operating on ultra-low sulfur (15 ppmw) fuel, and a Dash-8 locomotive operating on a fuel with a sulfur content between 200 ppmw and 500 ppmw. Sound measurements will be taken with and without the control equipment to determine the extent of noise reduction due to the control equipment (sound measurements added during the project).<br>Emissions testing will be conducted according to a test protocol developed for this project. The test protocol should prescribe accepted test methods appropriate to the pollutants being measured. The protocol will be reviewed by the air districts, CARB, and EPA. The testing will be conducted on the locomotive before the control equipment and upon exit from the control equipment and will determine emissions on a concentration and mass basis. | **Overall control efficiency:**<br>☑ **Accomplished**<br>**Overall capture efficiency:**<br>☒ **Partially Accomplished:**<br>Complete capture efficiency determination will require assessment of emission capture system functionality. Proof-of-concept project only tested one locomotive at a time in either motionless or short (50 feet) distance motion.<br>**Testing according to protocol:**<br>☑ **Accomplished**<br>(but note that emissions sampling at the locomotive stack was of questionable value) |
| **Objective 2: Demonstrate the Attachment Scheme Between the Locomotive and the Stationary Control Equipment:**<br>Since a rail yard is a busy place where efficiency of operations is important, the attachment of the emissions control equipment to the locomotive must be quick, simple, and safe to the operating personnel. The operation of the ALECS must absolutely not impede the fluidity of normal railroad operations in any manner. Attachment, detachment, and capture efficiency will be demonstrated on locomotives with one and two emission stacks. During the emissions testing phase of this project, multiple attachments and disconnects shall be performed to demonstrate this capability. Rail yard personnel shall be given a chance to operate the attachment controls. | **Demonstrated on locomotives with one and two emission stacks:**<br>☑ **Accomplished**<br>**Multiple attachments and disconnects:**<br>☑ **Accomplished**<br>**Rail yard personnel given chance to operate the attachment controls:**<br>☒ **Not Accomplished** |

### Table 29. Summary of Project Objectives and Accomplishments (concluded)

| OBJECTIVE | ACCOMPLISHED? |
|---|---|
| **Objective 3: Demonstrate the Capability of Some Locomotive Movement While Connected to the Control Equipment:**<br>One of the design features of the ALECS is to allow movement of the locomotive along the track for a prescribed distance while connected to the emissions control equipment. During the emissions testing, some portion of the testing on each locomotive shall be conducted with the locomotive connected to the stationary control equipment and the locomotive moving to demonstrate this capability while fully capturing the exhaust from the engine in the locomotive. | **Testing while motionless and while moving:**<br>☑ **Accomplished** |
| **Objective 4: Develop Improved Information on Capital Cost, Operating Procedures, and Operating Costs:**<br>The underlying purpose of this proof-of-concept test project is to provide information on performance, operation and cost of using stationary emissions control equipment to treat locomotive exhaust in rail yards that will enable the railroad and equipment suppliers to make business decisions on moving forward in deploying this type of equipment. During the installation and operation of the ALECS, information shall be collected and recorded that will enable capital and life cycle costs to be generated. Rail yard facility requirements for infrastructure and support utilities will be defined. These cost estimates shall be documented in the final report. Railroad personnel shall be instructed on operation and maintenance of the ALECS during the proof-of-concept project, and will provide to the PCAPCD estimates for all costs for impacts to yard or system operations (either capital or operating) are included in the final accounting. These cost estimates will be included in the project final report.<br>The ALECS to be used for this proof-of-concept test is borrowed from another project where the equipment size was optimized for another application. As part of this objective, the cost of equipment appropriately sized and ALECS designed to serve the J. R. Davis Rail Yard will be estimated. | **Information collected to estimate cost.**<br>**Rail yard infrastructure defined:**<br>☑ **Accomplished**<br>**Cost estimates shall be documented:**<br>☑ **Accomplished**<br>**Railroad personnel instructed on operation and maintenance of the ALECS:**<br>☒ **Not Accomplished**<br>**Railroad provides estimates for all costs:**<br>☑ **Accomplished**<br>**Cost estimates for rail yard impacts included in the project final report:**<br>☒ **Not Accomplished**<br>**Cost of appropriately sized equipment:**<br>☑ **Accomplished** |
| **Objective 5: Document Test Results and Project Findings in a Final Report:**<br>Since this proof-of-concept test project has, as one purpose, the generation of information on performance and operation of the ALECS sufficient to allow railroads to make business decisions on use of this stationary control equipment on their rail yards, the project results will be documented in a final report. The final report will include, as a minimum, details of the locomotives tested, configuration of the test setup, test equipment, test conditions, and test methods, logistic and operation issues identified during project implementation, and emission (and noise) test results before and after the control equipment. | **Information sufficient to allow railroads to make business decisions:**<br>☒ **Not Accomplished**<br>**The final report details on test:**<br>☑ **Accomplished** |

Table 30 summarizes the overall average pollutant control efficiencies of ALECS. The range of estimated emission reductions based upon two scenarios are presented in Table 31. ALECS installation in a rail yard is expected to yield emission reductions between the two assumptions, depending on the specific application.

**Table 30. Summary of Pollutant Control Efficiencies**

| | $NO_x$ | THC | PM | $SO_2$ |
|---|---|---|---|---|
| **Overall Average Control Efficiency**[1] | 97.8% | 62.7% | 92.1% | 97.3% |

[1] ALECS proof-of-concept test at Roseville rail yard

**Table 31. Range of Estimated Emission Reductions (tons/yr)**

| | $NO_x$ | HC | PM |
|---|---|---|---|
| **Mixed Loads Tier 0 Emissions** | 83.4 | 8.44 | 2.53 |
| **Idling Only Tier 2 Emissions** | 40.0 | 2.49 | 1.29 |

The fully loaded total initial capital cost of the ALECS (for an estimated 12 bonnet system) is $8,680,126 with an annual operational cost estimate of $899,926 (not including the recurring $86,146 catalyst replacement every 5 years).

The total weighted controlled PM, $NO_x$, and THC emissions reduced over the 20 year life of ALECS is estimated to range from 1,365 tons to 3,449 tons. The resulting cost effectiveness ranged between $18,437/ton in the all idling mode to $7,297/ton of weighted pollutant reduced in the mixed mode of a combination of locomotives at idle and at higher loads.

Noise measurements made with, and without the bonnet attached to the locomotive, yielded noise reductions of 5.3 to 6.8 decibels, representing noise energy reductions of 70 to 79 percent.

## 7.2 Next Steps

While the ALECS proof-of-concept test mostly met the project objectives and yielded valuable information in confirming that the system is capable of capturing and treating locomotive emissions, there remains additional work in selected areas in order to support fielding a system in a rail yard with the anticipation of maximizing the ALECS potential in cost effective emissions reductions. The next steps towards possible implementation of the technology in a working rail yard are depicted in Figure 31, which identifies those areas where additional work is needed. It is envisioned that these steps, which may be viewed as pathways or tracks that should be followed in parallel, will yield more refined information in order to make implementation decisions. These tracks include public policy leadership, identification of a specific rail yard site for the initial system deployment, further technical demonstration, development of financial mechanisms for the funding of systems, and community benefits.

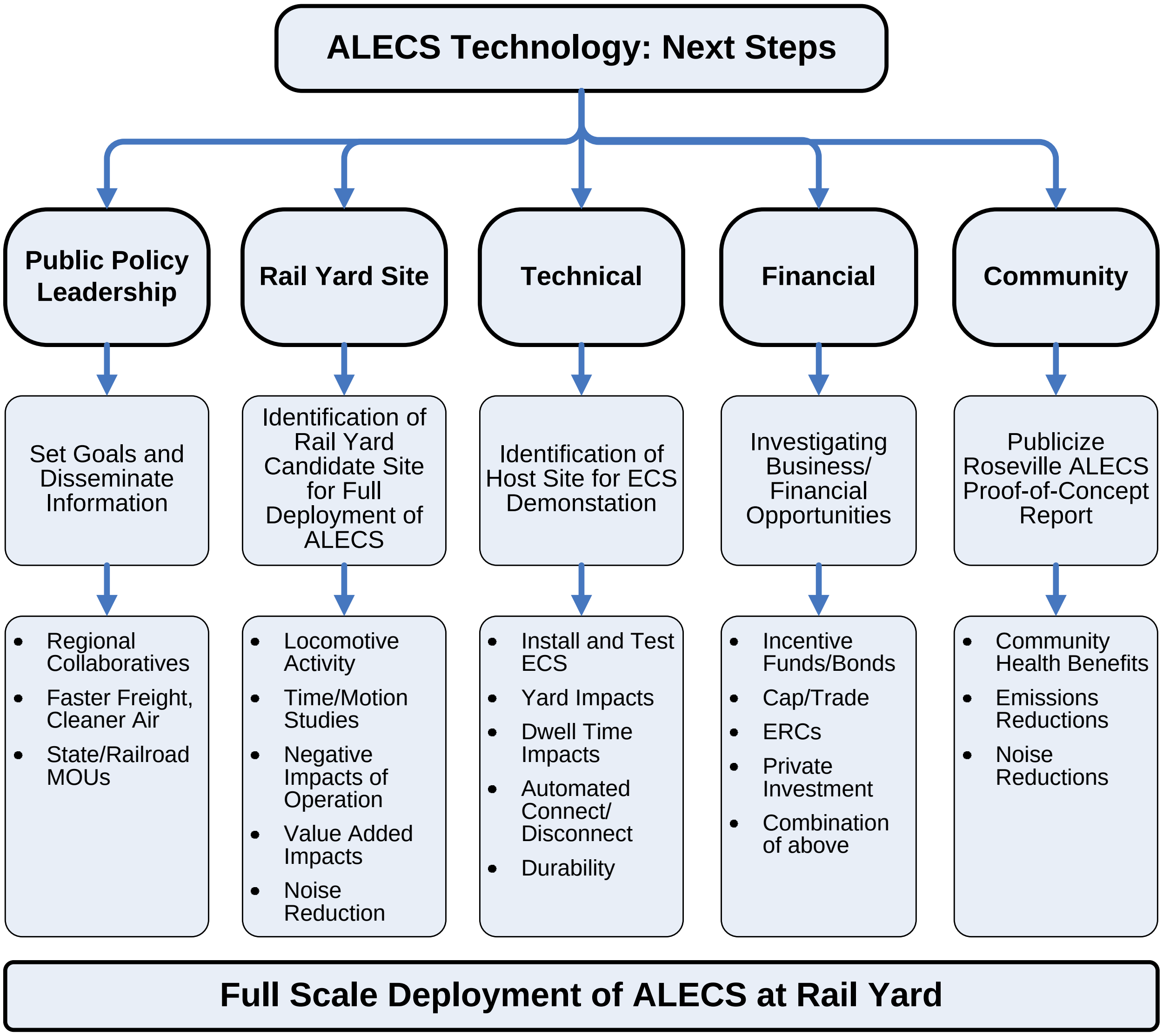


**Figure 31. Next Steps Pathways**

### 7.2.1 Public Policy Leadership

Government encouragement of utilization of this type of control equipment to reduce criteria and hazardous emissions from rail yards can have a positive effect on the railroad companies. Public agencies can encourage use by setting goals through regional diesel collaboratives and disseminating information in conferences like Faster Freight and Cleaner Air. State environmental agencies can encourage proliferation of this technology through agreements with the railroad companies which among other strategies to reduce rail emissions, includes implementation of the ALECS technology. Local air districts that have concerns over rail yard emissions in their territory can develop agreements with the railroad companies to utilize this technology in appropriate locations.

### 7.2.2 Rail Yard Site

Identification of the specific location of the initial full-scale system installation is critical. The operational experience of the first system will greatly influence the possibility of the installation of additional systems. Key considerations in choosing the location of the system in the rail yard are a continuous supply of an adequate number of running locomotives to keep the capacity of the ALECS fully utilized while not requiring additional effort from rail yard workers to route locomotives to this location.

It is recommended that the initial system deployment be at the J. R. Davis Rail Yard in Roseville, California. Some rail yard personnel are somewhat familiar with the ALECS and there are a number of potentially suitable sites for the system. Figure 32 is an aerial view of the rail yard with a number of potential sites labeled. Figure 33, Figure 34, and Figure 35 are photographs of potential ALECS locations in the diagnostics area of the diesel shop, the ready tracks, and the sanding station.

Figure 32. Aerial View of Potential ALECS Locations

Figure 33.  Diagnostics Area of Diesel Shop

Figure 34.  Ready Tracks

**Figure 35. Sanding Stations**

UPRR will need to perform an analysis of candidate locations to determine if current locomotive activity can support a high utilization factor for an ALECS at that location. Parameters to be considered are numbers of operating locomotives at the site over time, quantity of idle, diagnostic, and load testing conducted at that site, and typical mix of locomotive types using the site. For the more promising sites, UPRR should perform an in-depth time/motion study of the activity at the site and identify any operational changes that could improve the efficiency of the site operation using the ALECS. As part of these studies, UPRR should consider opportunities to use the capabilities of the ALECS to improve their rail yard efficiency and operations and reduce locomotive maintenance dwell time. Examples of these capabilities would be to utilize the emissions measurement function of the ALECS to aid in engine diagnostics, use particulate matter measurements to identify engines that have excessive visual emissions and need repair (higher levels of PM may be an indication of leaky fuel injectors), and perform high power load testing and diagnostics under the ALECS bonnets to reduce noise. Noise is a nuisance issue with the residential neighbors in Roseville.

### 7.2.3 Technical

Along a technical track, the proof-of-concept test program identified that additional demonstration is required for a redesigned trolley/bonnet and overhead manifold concept capable of hosting multiple locomotives. While a full-scale ALECS would include 12 trolley/bonnets and about 1,200 feet of overhead structure and collection manifold, it is recommended that approximately a one-half size subsystem should be installed and tested. The test system would not include the emissions control components, just the emissions capture subsystem. Any potential user of this system would require to see this demonstrated to evaluate automated connect/disconnect of multiple locomotives, impacts on the yard workflow and efficiency, and durability of the ECS components. This demonstration is estimated to cost $1.5 million. Funding for this demonstration is an open issue at this time. If possible, this demonstration should be conducted at a rail yard site with high potential to host a permanent ALECS installation.

### 7.2.4 Financial

There may be a number of options for funding the installation of ALECS systems in rail yards. In addition to the obvious option of railroad capital investment, there may be opportunities for incentive funds from state programs, private investment, cap/trade programs, and emission reduction credits. These funding options should be explored in parallel with the other next steps tracks.

Emission reduction credit (ERC) generation is an interesting funding option. Currently, the rules of most, if not all, California air districts are not structured in a way that would allow this type of credit generation. However, the ALECS can likely meet the general criteria for establishing ERCs. Noteworthy are the facts that the emission reductions from an ALECS are real and surplus. Surplus generally means that the emission reductions are not mandated by law, regulation or planned into the SIP; and the historical emissions are included in the state inventory. The California Air Pollution Control Officers Association (CAPCOA) has initiated an effort to develop protocols for non-traditional ERC generation. Currently, three pilot projects are proceeding, including one that includes the ALECS concept. PCAPCD is taking the lead on the rail yard stationary equipment ERC protocol development. EPA, CARB, and the air districts are involved in this effort. The goal of the effort is to produce a model protocol, approved by EPA and CARB, that can be adopted as a rule by the air districts. In the Roseville area, a number of industrial companies have expressed interest in possibly funding installation of an ALECS in order to have a claim on the ERCs generated.

Private investment and ownership of a system is another financial model that has potential to fund the installation of an ALECS. In this model, a third party company would own and maintain the system and lease its use to the railroad.

### 7.2.5 Community

Communities that are adjacent to rail yards are becoming more aware of the potential health impacts of rail yard emissions and more active in complaining of noise from the yard. In California, through the agreement between the major railroads and the California Air Resources Board, health risk assessments will soon be made public for the larger yards in the state. A community track of next steps should publicize the benefits of the ALECS in reducing diesel particulate emissions (and associated reduction in health risk) and the potential noise reduction of using the system on locomotives being tested at high power.

# 8. List of Acronyms

| | |
|---|---|
| **ACTI** | Advanced Cleanup Technologies, Inc. |
| **ALECS** | Advanced Locomotive Emission Control System |
| **CAPCOA** | California Air Pollution Control Officers Association |
| **CARB** | California Air Resources Board |
| **CCS** | Cloud Chamber Scrubber (subsystem of ETS) |
| **CEMS** | Continuous Emission Monitoring System |
| **CO** | Carbon Monoxide |
| **$CO_2$** | Carbon Dioxide |
| **Cp** | Total Equipment Costs |
| **DF** | Deterioration Factor |
| **ECS** | Emissions Capture Subsystem |
| **EF&EE** | Engine, Fuel, and Emissions Engineering, Incorporated |
| **EIB** | Emissions Intake Bonnet |
| **EMD** | General Motors Electro-Motive Division |
| **EPA** | U.S. Environmental Protection Agency |
| **ERC** | Emission reduction credit |
| **ETS** | Emissions Treatment Subsystem |
| **F** | Fahrenheit |
| **ft3** | Cubic Feet |
| **gal** | Gallons |
| **GE** | General Electric |
| **hr** | Hour |
| **ID** | Induced Draft |
| **ISO** | International Standards Organization |
| **kWh** | Kilowatt Hours |
| **lb** | Pounds |
| **mcf** | Thousand Cubic Feet |
| **MMBtu** | Million British Thermal Units |
| **MOU** | Memorandum of Understanding |
| **$N_2O$** | Nitrous Oxide |
| **$NH_3$** | Ammonia |
| **NO** | Nitric Oxide |
| **$NO_x$** | Oxides of Nitrogen |
| **$O_2$** | Oxygen |
| **OCU** | Operational Control Unit of the ETS |
| **PCAPCD** | Placer County Air Pollution Control District |
| **PCC** | Preconditioning Chamber (subsystem of the ETS) |
| **PEC** | Purchased Equipment Cost |
| **PM** | Particulate Matter |
| **$PM_{2.5}$** | Particulate Matter less than or equal to 2.5 microns |
| **$PM_{10}$** | Particulate Matter less than or equal to 10 microns |
| **ppm** | parts per million |
| **RAVEM** | Ride-Along Vehicle Emissions Measurement system |
| **SCAQMD** | South Coast Air Quality Management District |
| **scfm** | Standard Cubic Feet per Minute |

| | |
|---|---|
| **SCR** | Selective Catalytic Reduction |
| **SMAQMD** | Sacramento Metropolitan Air Quality Management District |
| **$SO_2$** | Sulfur Dioxide |
| **$SO_x$** | Oxides of Sulfur |
| **THC** | Total Hydrocarbons |
| **TICI** | Total Initial Capital Investment |
| **UPRR** | Union Pacific Railroad Company |

# 9. References

California Air Resources Board, “Roseville Rail Yard Study,” October 14, 2004

California Air Resources Board, “The Carl Moyer Program Guidelines,” Approved revision 2005, released January 6, 2006

Christofk, T., “Statewide Railyard Agreement: Second Public Meeting,” Presentation at the Second Public Meeting to Discuss Future Locomotive Emission Control Measures in Sacramento, July 13, 2006

Energy Information Administration, Short-Term Energy Outlook, January 2007 website: http://www.eia.doe.gov/emeu/steo/pub/contents.html

Fuller, S., Petersen, S., *Life-Cycle Costing Manual for the Federal Energy Management Program*, 1995 Edition, February 1996

Kay, M., Baez, A., Lange, H., “Best Available Control Technology Guidelines,” South Coast Air Quality Management District, July 14, 2006

Union Pacific Railroad Company website (January 2007): http://www.uprr.com/aboutup/index.shtml

United States Environmental Protection Agency, “Emission Factors for Locomotives,” Technical Highlights Report #EPA420-F-97-051, December 1997

United States Environmental Protection Agency, "EPA Air Pollution Control Cost Manual," 6th Edition, Report #EPA/452/B-02-001, January 2002

United States Environmental Protection Agency’s Office of Transportation and Air Quality website (March 2007): http://www.epa.gov/otaq/certdata.htm

# Appendix A. Test Plan

**J.R. DAVIS RAILYARD**

# ADVANCED LOCOMOTIVE EMISSION CONTROL SYSTEM (ALECS) DEMONSTRATION PROJECT

## EMISSION TESTING PROTOCOL

**VERSION 2.1**
**MAY 25, 2006**

**Prepared by**
**Christopher Weaver, P.E.**
**Engine, Fuel, and Emissions Engineering, Inc.**
**Rancho Cordova, CA**

# 1. INTRODUCTION

The Union Pacific Railroad's J.R. Davis Railyard has been determined to be a significant emissions source for diesel particulate matter (PM) and other toxic air contaminants related to locomotive emissions. An agreement between the Placer County Air Pollution Control District (APCD) and the Union Pacific Railroad Company includes a mitigation plan for reducing diesel particulate emissions from the railyard. This plan includes consideration of stationary air pollution control equipment to capture and treat emissions from stationary locomotives in the railyard while idling or undergoing engine load tests. To carry out this part of the plan, the APCD has initiated a project to demonstrate the Advanced Locomotive Emission Control System (ALECS).

The ALECS demonstration is a public-private collaborative project involving many parties, including the APCD, U.S. Environmental Protection Agency, Sacramento Metropolitan Air Quality Management District, Union Pacific Railroad, Advanced Cleanup Technologies Inc., the South Coast Air Quality Management District (AQMD), the California Air Resources Board, and the City of Roseville. Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) has been tasked with carrying out the emissions measurements under a contract with the South Coast AQMD.

The ALECS is a system designed to control emissions from locomotives by capturing the exhaust stream from their engines and treating it to remove most harmful pollutants. The system includes a set of stationary emissions control equipment connected to an articulated bonnet or hood. The bonnet is designed to capture locomotive exhaust, delivering it to the ground-mounted emission control system by means of a flexible duct. The bonnet or hood remains attached while the locomotive is moving along the track to the extent of the flexible duct.

The emissions control equipment consists of a sodium hydroxide wash to remove sulfur dioxide ($SO_2$), a dual chamber cloud chamber scrubber for particulate matter (PM) removal, followed by a Selective Catalytic Reduction (SCR) reactor using urea as the ammonia source for oxides of nitrogen (NOx) reduction. The demonstration system is designed to treat exhaust flows between 2,000 and 12,000 standard cubic feet per minute (scfm).

## 1.1 OBJECTIVES

The objectives of the test program are:

- To measure and document the effectiveness of the ALECS system in controlling locomotive emissions of diesel particulate matter (PM), oxides of nitrogen (NOx) and other pollutants of concern under typical railyard operating conditions;
- to assure that the emission control process does not generate excessive amounts of other pollutants, such as ammonia; and
- to quantify the water and chemical consumption, operating costs, and waste generated by the ALECS system.

### 1.2 OVERVIEW OF THE TEST PROGRAM

The test program will include emission measurements at three locations: in the locomotive stack(s), at the inlet to the ground-mounted emission control system, and at the outlet from the emission control system**.** The effectiveness of the ALECS emission control system will be determined by comparing the mass emissions measured both at the locomotive stack and at the inlet to the emission control system with those measured at the system outlet to the system. Comparing the emissions measured at the locomotive stack to those at the inlet will make it possible to identify any effects on pollutant mass or characteristics due to the overhead manifold system.

The test program will include two locomotives, each of which will be operated in a defined sequence of test modes. Each of the test sequences will be repeated three times. Testing is scheduled to begin July 31, and will take two weeks (eight testing days, plus setup time) to complete.

Pollutants to be measured include particulate matter PM, NOx, CO, $SO_2$, and total hydrocarbons (THC). The test procedures for these pollutants will follow ISO standard 8178, which is extremely similar to the steady-state diesel testing procedures defined by the U.S. EPA and the California ARB. Ammonia ($NH_3$) and nitrous oxide ($N_2O$) will be measured only at the inlet and outlet of the emission control system, generally following the procedures specified in EPA Method 320.

## 2. LOCOMOTIVES TO BE TESTED

The locomotives to be tested are a Electromotive Division (EMD) GP 38 and a General Electric B39-8 or C39-8. The GP 38 is used primarily for switching and local service. It is equipped with a two-stroke, Roots-blown, EMD 16-645E engine. The engine has 16 cylinders and is rated at 2000 tractive horsepower. It has two exhaust stacks, fed by the front eight and rear eight cylinders, respectively. The maximum exhaust flow rate at full power approximately is 6,000 scfm.

The GE Dash-8 series locomotives are used primarily for line-haul freight service, and are equipped with four-stroke, turbocharged, GE FDL-16 engines. These 16-cylinder engines produce 3900 tractive horsepower, and discharge exhaust through a single rectangular stack connected directly to the turbocharger outlet. The maximum exhaust flow rate at full power is approximately 12,000 scfm.

The Union Pacific Railroad will be responsible for supplying the two locomotives for the test, and for ensuring that they are continuously available during the scheduled test period. Both locomotives will need to be available and have full tanks of fuel on July 21. The GE locomotive will then be needed from July 31 to August 5 for testing, and the GP 38 from August 7 to 11.

# 3. TEST FUEL

The test fuel for the GP 38 will be an ultra-low sulfur diesel fuel meeting ARB regulations for sulfur and aromatic content, as specified in 13 CC 2281 and 2282. The sulfur limit is 15 parts per million w/w, and the limit on aromatic content is 10% v/v unless the fuel is produced according to an approved alternative formulation. The test fuel for the Dash-8 will be a diesel fuel that is actually supplied to Union Pacific line-haul locomotives outside California, and that has a sulfur content between 200 and 500 ppm w/w.

The Union Pacific Railroad will be responsible for ensuring that the locomotives' tanks contain an adequate volume of the appropriate fuel: 3000 gallons for the Dash-8 and 2500 gallons for the GP 38 (this is double the estimated fuel consumption in the test program).

Table 1 shows the analyses to be performed on each fuel sample. EF&EE will collect fuel samples from each locomotive's fuel tank in time for the analyses to take place before the start of emission testing. The fuel tanks will then be sealed and labeled to ensure that fuel is not added to the tanks by mistake.

**Table 1: Fuel analyses**

| ASTM Method | Description |
|---|---|
| D 2622-94 | Sulfur content |
| D 5291 | Carbon-hydrogen-nitrogen elemental content |

# 4. TESTING SCHEDULE

The emission testing calendar is shown in Table 2. Fuel sampling will take place on July 21 to ensure that the results are available before the emission test equipment is installed on July 31. Steady-state emission testing on the Dash 8 will take place August 1 and August 3 to 4, to accommodate the media day scheduled for August 2. These tests will be conducted with the locomotive stationary, and the engine loaded using the "self test" capability of the dynamic brake system.

The test sequence for each day of stationary testing is shown in Table 3. The sequence provides for preconditioning the locomotive engine, and then measuring at idle, Notch 5, and Notch 8. The effects of "souping" (PM buildup in the exhaust system at light loads) will be determined by operating at Notch 3 for half-hour periods following each of the four-hour test periods at idle. The daily test sequence is 10 hours long.

Moving tests, with the locomotive moving back and forth within a restricted section of track, will be conducted on the day following the stationary tests. The schedule for these days is shown in Table 4. Three tests will be conducted, each one-half hour long. The limited length of these tests is based on considerations of operator fatigue, since the engineer will be constantly changing the throttle and reverser positions to move the locomotive back and forth on the 50 foot test section.

### Table 2: Emission testing calendar

| Date | Activity |
|---|---|
| July 21 | Sample fuel on both locomotives |
|  | Weekend |
| July 31 | Set up emission test equipment for Dash-8 |
| August 1 | Stationary test Dash-8 |
| 2 | Media day |
| 3 | Stationary test Dash-8 |
| 4 | Stationary test Dash-8 |
| 5 | Moving test Dash-8, remove emission test equipment |
|  | Sunday |
| August 7 | Set up emission test equipment for GP38 |
| 8 | Stationary test GP38 |
| 9 | Stationary test GP38 |
| 10 | Stationary test GP38 |
| 11 | Moving test GP38, remove emission test equipment |

### Table 3: Sequence of test modes and testing schedule for stationary test days

| Step | Purpose | Throttle | Hours | Cumul. Hours | Test Activity |
|---|---|---|---|---|---|
| 1 | Precondition | 3 | 0.5 | 0.5 | Install filters/check instruments/calibrate |
| 2 | Souping baseline | 3 | 0.5 | 1.0 | Measure emissions |
| 3 | Stabilize | 1 | 0.5 | 1.5 | Change filters/calibrate |
| 4 | Idle Test | 1 | 4.0 | 5.5 | Measure emissions |
| 5 | Filter Change | 1 | 0.5 | 6.0 | Change filters/calibrate |
| 6 | Souping test | 3 | 0.5 | 6.5 | Measure emissions |
| 7 | Stabilize | 5 | 0.5 | 7.0 | Change filters/calibrate |
| 8 | Notch 5 Test | 5 | 1.0 | 8.0 | Measure emissions |
| 9 | Stabilize | 8 | 0.5 | 8.5 | Change filters/calibrate/refill day tank |
| 10 | Notch 8 Test | 8 | 1.0 | 9.5 | Measure emissions and noise |
| 11 | Cool down | Idle | 0.5 | 10.0 | Remove filters/refill day tank |

### Table 4: Sequence of test modes and testing schedule for moving test days

| Step | Purpose | Throttle | Hours | Cumul. Hours | Test Activity |
|---|---|---|---|---|---|
| 1 | Precondition | 3 | 0.5 | 0.5 | Check/warmup instruments |
| 2 | Stabilize | Idle | 0.5 | 1.0 | Install filters/calibrate |
| 3 | Moving Test #1 | Var | 0.5 | 1.5 | Measure emissions |
| 4 | Filter Change | Idle | 0.5 | 2.0 | Change filters/calibrate |
| 5 | Moving Test #2 | Var | 0.5 | 2.5 | Measure emissions |
| 6 | Filter Change | Idle | 0.5 | 3.0 | Change filters/calibrate |
| 7 | Moving Test #3 | Var | 0.5 | 3.5 | Measure emissions |
| 8 | Change locomotive | Off | 2.0 | 5.5 | Remove RAVEM |

Five emission tests will be conducted during each of the three days of stationary testing on each locomotive, and three during the one day of moving tests. Thus, a total of 18 emission tests will be conducted on each locomotive.

# 5. PARTICULATE EMISSION MEASUREMENTS

PM emissions before and after the ALECS system will be measured according to the isokinetic partial flow dilution method specified as one option under ISO 8178. Raw exhaust will be extracted from the exhaust conduit using EF&EE's RAVEM isokinetic sampling system. In the RAVEM system, isokinetic sampling conditions are maintained by adjusting the flow rate of raw exhaust through the sample probe until the static pressures inside and outside the probe are equal. This adjustment is performed continuously in real time by the RAVEM system, allowing it to follow transient changes in exhaust flow rate.

The raw exhaust from the sample probe will pass through a 250 $^{o}$C heated sample line to the RAVEM dilution tunnel. Dilution air will pass through a prefilter and a HEPA filter before entering the tunnel. Dilute exhaust containing PM will be drawn from the dilution tunnel through a PM10 cyclone (URG 2000-30ENB), and then through filters of Teflon film or Teflon coated borosilicate glass in accordance with ISO 8178 and 40 CFR 1065. The rate of exhaust extraction will be controlled to a constant value of 16.7 standard liters per minute by a mass flow controller (Alicat MC 50 slpm) using the laminar flow principle. The dilution flow rate in the CVS will be adjusted to ensure that the gas temperature at the filter face is no more than 52 $^{o}$C. Blank filters exposed only to dilution air will be collected along with each sample. In addition to correcting for any background PM that makes it past the HEPA filter, subtracting the change in weight of the blank filter from the sample weight also automatically corrects for the effects of small differences in weighing chamber temperature, humidity, and atmospheric pressure.

ISO 8178 specifies the use of both primary and backup filters for each sample, while 40 CFR 1065 specifies the use of a single filter mounted in a filter cassette. Up to this point, EF&EE has used the ISO 8178 method, but the 40 CFR 1065 method appears advantageous in reducing the risk of filter damage during handling. During May, 2006, EF&EE will experiment with the Part 1065 method, and will recommend one or the other approach to the testing committee.

Separate RAVEM samplers will be used to sample the exhaust at the locomotive stack, at the inlet to the ALECS system, and in the outlet stack from the ALECS system. A total of 6 PM samples will be collected for each of the 36 emission tests – three PM samples and three blanks. Thus, a total of 216 pre-weighed filter cassettes (or pairs of pre-weighed filters, if the Committee opts to retain primary and backup filters) will be required.

At the request of the ARB Monitoring and Laboratory Division, the RAVEM sampler at the ALECS system inlet will be modified to allow a second PM sampler to be connected. The additional sampler will be provided by ARB, and will be used to collect 47 mm Teflon filters for characterization of the hydrocarbon content of the PM in an effort to identify potential marker chemicals for PM source apportionment.

# 6. GASEOUS EMISSION MEASUREMENTS

Gaseous emission measurements will include oxides of nitrogen (NOx), total hydrocarbons (THC), carbon monoxide (CO), carbon dioxide ($CO_2$), sulfur dioxide ($SO_2$), oxygen ($O_2$), ammonia ($NH_3$), and nitrous oxide ($N_2O$). Table 5 summarizes the gas concentration measurement techniques to be used. Except for the FTIR measurements, all of the analyzers and measurement techniques will comply with ISO 8178 specifications.

The ALECS system itself includes continuous emission monitoring systems for NOx, $SO_2$, and $O_2$ at both the inlet and the outlet, and for THC and $NH_3$ at the outlet only. These analyzers are configured for raw gas sampling, which means that the results must be combined with a measured exhaust gas flow rate to calculate the total mass of emissions. The exhaust flowrate measurement is provided by venturis located in both the inlet and outlet sections.

**Table 5: Gas concentration measurements by sampling location**

| | **Locomotive Stack** | **ALECS Inlet** | **ALECS Outlet** |
|---|---|---|---|
| NOx | Dilute** | Raw+/Bag** | Raw+/Bag** |
| THC | | Raw | Raw+ |
| CO | Dilute** | Raw/Bag** | Raw/Bag** |
| CO2 | Dilute** | Raw/Bag** | Raw/Bag** |
| SO2 | - | Raw+ | Raw+ |
| NH3 | - | FTIR* | FTIR*/CLD+ |
| N2O | - | FTIR* | FTIR* |
| Gas Flow | - | Venturi+ | Venturi+ |

*Time-shared between inlet and outlet
+ALECS system equipment
**RAVEM system equipment

The RAVEM sampling systems perform exhaust gas dilution according to the constant volume sampling (CVS) principle, so that the pollutant concentration in the dilute gas is proportional to the pollutant mass flow rate in the exhaust. The RAVEM system located at the locomotive stack will be configured to measure dilute NOx, CO, and $CO_2$ continuously, as well as collecting integrated bag samples of the dilute gas to be analyzed after the end of each test. The RAVEM samplers at the ALECS inlet and outlet will collect integrated bag samples only, to be analyzed at the end of each test by the analyzers of the first RAVEM system. The results will be used to calculate a carbon balance check for the PM sampling. The dilute NOx results from these bags will also be available as a backup to NOx measurements of the ALECS CEMS systems.

The ALECS system includes an analyzer to measure ammonia emissions by oxidizing the ammonia to NOx, measuring NOx by CLD, and subtracting the NOx already present in the sample gas (determined by another CLD analyzer). The accuracy of this method potentially suffers from the difference-of-large-numbers problem. A more accurate measurement of ammonia emissions, as well as $N_2O$, can be obtained by Fourier Transform Infrared (FTIR) analysis. EF&EE will apply its MIDAC FTIR analyzer system to measure $NH_3$ and $N_2O$ concentrations in the raw gas at both the ALECS inlet and outlet. Heated sample lines will bring gas samples from each source to a heated valve/filter combination next to the FTIR unit. The system will measure emissions primarily from the ALECS outlet, but will be switched to measure inlet emissions several times during each steady-state test.

Prior to beginning the emission testing, 10-point linearity checks will be performed on all gas analyzers using EF&EE's Environics 4000-series precision dilution system. The FTIR system will be checked using the diesel exhaust procedure specified in the Water Transit Authority testing protocol. Zero and span calibrations will be performed on each gas analyzer after each emission test.

# 7. FUEL CONSUMPTION MEASUREMENTS

Fuel consumption will be measured during each emission test as a check on the accuracy of the emission measurements. If these measurements are accurate, the sum of the carbon contained in the $CO_2$, CO, HC, and PM emissions should be equal to the mass of carbon in the fuel consumed.

Fuel consumption by the locomotive engine will be measured using a 250 gallon “tote” positioned on a pallet scale as a day tank. EF&EE staff will install three-way valves in the locomotive’s fuel supply and return lines to allow these to be switched between the locomotive fuel tank and the day tank. Switching both supply and return lines to the day tank will mean that the change in weight of the day tank is equal to the fuel consumed by the engine. The day tank will be filled (and refilled, when necessary) from the locomotive fuel tank by running the electric fuel pump with the supply line connected to the locomotive tank, and the return line connected to the day tank.

Since locomotive fuel systems can contain voids and air pockets that affect the fuel balance during startup, the system will be stabilized while running on the day tank before beginning each emission test. The weight of fuel in the day tank will be recorded at frequent intervals automatically during the test.

Since the returned fuel picks up considerable heat in the engine, it will be necessary to cool it before returning it to the day tank. Otherwise, the relatively small volume of fuel in the day tank could become hot enough to affect the emissions results (hotter fuel is less viscous, atomizes and ignites more readily). Cooling will be achieved by running it through a fuel-to-air heat exchanger.

# 8. NOISE MEASUREMENTS

Locomotive noise measurements will be performed using a hand-held noise meter. Emission measurements will be made using the “slow” response function of the meter, at a point 30 meters away from the locomotive along a line passing through the center of the locomotive perpendicular to the track, and will follow the requirements of 40 CFR 201.20 et seq. as closely as possible, given the conditions of the test site. Notch 8 noise measurements will be made within 15 minutes of the end of the test. Background noise measurements will be made in the same location as soon as possible after the locomotive engine has cooled down from Notch 8 operation and been turned off.

Baseline noise tests at Notch 8 will be made once the locomotive is in place on the test track, but prior to attaching the locomotive exhaust to the ALECS system. The baseline noise test will be repeated at the end of testing, after disconnecting the locomotive from the ALECS system and before moving it from the test track.

# 9. USE OF WATER, ELECTRICITY, AND CONSUMABLES

## 9.1 Solid waste characterization

The solid waste (sludge) is collected in filter bags at two locations in the ALECS system: at the discharge of the Preconditioning Chamber (PCC), and at the discharge of the Cloud Chamber Scrubber (CCS). Total PM mass will be determined by weighing the bags after use. The variation in bag weight is negligible in comparison to the weight of particulate each will collect, so an average bag weight will be used for the "before" weight. The bags will be hung to dry before weighing in order to allow water retained in the bag fabric to evaporate.

Filter bags will be changed between tests for the two locomotives.

Samples of the collected sludge will be taken and sent to an outside lab for the following analyses:

- Oil & grease (Refer to EPA Method 413.1)
- Heat content (Btu content)
- ICP (Inductively Coupled Plasma) tests for metals such as Cu, Ni, Pb, Cr, and Zn (Refer to EPA Method 200.7)
- IC (Ion Chromatography) tests for anions such as Cl, F, NO2, NO3, and SO4 (Refer to EPA Method 300.0)
- TPH (Total Petroleum Hydrocarbons) (Refer to EPA Method 418.1)

## 9.2 Wastewater (blowdown) characterization

Rotometers will be adjusted to set the blowdown for the PCC and the CCS. These rates will be set to maintain the conductivity within specified limits. The blowdown rate will be a function of the sulfur content in the exhaust gas stream, and will be experimentally determined. The total blowdown for any period of time will be determined by measuring the level in the wastewater tank.

Properties of the water in the recirculation loops will be monitored as part of the control system, and will be used in part to determine the blowdown. These properties are:

- pH
- conductivity

Samples of wastewater will be collected for analysis prior to starting the test, at the changeover from the Dash 8 to the GP 38, at the end of the test, and periodically as deemed necessary during the test program. The analysis will include:

- suspended solids (Refer to EPA Method 160.2)
- dissolved solids (Refer to EPA Method 160.1)
- pH (Refer to EPA Method 150.1)
- conductivity (Refer to EPA Method 120.1)
- IC anions (Refer to EPA Method 300.0)
- ICP metals (Refer to EPA Method 200.7)
- Oil & grease (Refer to EPA Method 413.1)

### 9.3 Water usage

The inlet water flow rate will be intermittent. When the need for makeup water is detected by sensors in the system, a solenoid valve will be opened for a fixed, preset length of time to admit water to the system. The flow rate during the time the valve is open will be determined one time by physically measuring the amount of water that flows during one valve-open period. The control system will log the number of valve openings during system operation, and from these two quantities the total inlet water will be determined.

### 9.4 Electricity Use

Electricity use will be the sum of two parts as far as measurement is concerned. There is a base load, which is the usage for basic system functions such as instrumentation and controls, and a variable load, which is the power consumption of the various motors that drive pumps and fans.

The base load will be measured with a clamp-on meter. This will be an essentially constant quantity.

By far the majority of the power used is consumed by the pump and fan motors. These are all driven by variable frequency drives controlled by the control system, and the power consumption of each individual motor is logged by the control system. These are real time, continuous measurements and will form part of the output data. The sum of these motor powers and the base power will give the total power consumption.

### 9.5 Urea Consumption

The urea is introduced into the exhaust gas stream by three separate injection lances. Each lance has its own metering pump and flow transmitter. These flow data will be logged by the control system.

### 9.6 NaOH Consumption

Sodium hydroxide is fed into the system by constant volume pumps that are either on or off, and the feed will be controlled by the pH of the recirculating water. These pumps will initially be adjusted so that they will be running 60% to 80% of the time with the maximum expected sulfur load in the exhaust gas.

Following this initial adjustment, the pumps will either be on or off. The flow rate during the on state will be determined by a physical measurement of volume over a given time. This will give us the flow rate in gallons per minute of on-time.

The control system will log the on-time, both instantaneous and cumulative, and this will be used to determine the total NaOH usage.

# Appendix B. EF&EE Emission Test Report

ENGINE, FUEL, AND EMISSIONS
ENGINEERING, INCORPORATED

3215 Luyung Drive
Rancho Cordova, CA 95742 USA
ph. (916) 368-4770
fax (916) 362-2579

March 27, 2007

Don Duffy
Placer County Air Pollution Control District
3091 County Center Drive, Suite 240
Auburn, CA 95603

Dear Don:

As you requested, this letter responds to two of the comments by the Union Pacific Railroad on our report, Emission Measurements on the Advanced Locomotive Emissions Control System at the J.R. Davis Rail Yard . These were received too late to be addressed in the final report.

One comment concerned the recommendation in the Executive Summary that "… locomotives should first be operated at higher load with the ALECS system in place after a prolonged period of idle or Notch 1 operation." Union Pacific commented that "The comment about the use of the ALECS following prolonged idle should be deleted, as it is not accompanied by an analysis of whether such an operating mode is practical, or what the emissions might be associated with moving a locomotive from another portion of the railyard to the location where the ALECS might be installed. At page 19, this recommendation is framed as continuing to leave the locomotive connected to the ALECS for a few minutes after a prolonged idle, and not as connecting a locomotive to ALECS after a prolonged idle."

We disagree with this comment. The sentence in the Executive Summary simply summarizes the recommendation on Page 19. Nothing in our report should be read as recommending that locomotives be moved from another location to the ALECS system *after* a prolonged idling period. Instead, our understanding of the potential use of the ALECS system is that locomotives would be moved to it and connected prior to *beginning* a prolonged period of idle.

In another comment, Union Pacific requested that we note that no emission tests were performed at idle, and that all references to idle in our report should be changed to Notch 1. This is correct. Although it was originally planned that testing would be carried out at idle, concerns about the minimum design exhaust flow rate for the ALECs system led to the test condition being changed to Notch 1. In several places in the final report, it is stated incorrectly that the test locomotive was operating at idle. All such references should be read as referring to "Notch 1" instead.

I hope that this will clarify any confusion on these issues.

Christopher S. Weaver, P.E.
President

# EMISSION MEASUREMENTS ON THE ADVANCED LOCOMOTIVE EMISSION CONTROL SYSTEM AT THE J.R. DAVIS RAIL YARD

## FINAL REPORT

**February 26, 2007**

**submitted to:**
**Technology Advancement Office**
**South Coast Air Quality Management District**
**and**
**Placer County Air Pollution Control District**

EF & EE
ENGINE, FUEL, AND EMISSIONS
ENGINEERING, INCORPORATED

# EMISSION MEASUREMENTS ON THE ADVANCED LOCOMOTIVE EMISSION CONTROL SYSTEM AT THE J.R. DAVIS RAIL YARD

## Final Report

**February 26, 2007**

**Submitted to**
**Technology Advancement Office**
**South Coast Air Quality Management District**
**21865 East Copley Drive**
**Diamond Bar, CA 91765**
**Contract No. 06184**

**Placer County Air Pollution Control District**
**11464 B Avenue**
**Auburn, CA 95603**

**Submitted by**
**Christopher Weaver, P.E.**
**Engine, Fuel, and Emissions Engineering, Inc.**
**3215 Luyung Drive**
**Rancho Cordova, CA 95742 USA**
**(916) 368-4770**

# EXECUTIVE SUMMARY

The Union Pacific Railroad's J.R. Davis rail yard in Roseville, California, is a major center for locomotive maintenance, as well as for assembling and reassembling trains of freight cars. Locomotive operations at the rail yard have been determined to be a significant source of emissions of diesel particulate matter (PM) and other pollutants. An agreement between the Placer County Air Pollution Control District (APCD) and the Union Pacific Railroad Company includes a mitigation plan for reducing PM emissions from the rail yard. Part of this plan is an assessment of the use of stationary air pollution control equipment to capture and treat emissions from stationary locomotives while idling or undergoing engine load tests.

The Advanced Locomotive Emission Control System (ALECS) comprises a set of stationary emissions control equipment connected to an articulated bonnet or hood. The hood is designed to capture locomotive exhaust, delivering it to the ground-mounted emission control system by means of a flexible duct. The hood remains attached while the locomotive is moving along the track to the extent of the flexible duct. The emission control equipment comprises a sodium hydroxide wash to remove sulfur dioxide ($SO_2$), a triple cloud chamber scrubber for particulate matter (PM) removal, and a Selective Catalytic Reduction (SCR) reactor to reduce oxides of nitrogen (NOx). The demonstration ALECS is designed to treat exhaust flows between 2,000 and 12,000 standard cubic feet per minute (scfm). The former is slightly more than the exhaust flow from a locomotive at idle, while the latter is approximately the exhaust flow from a line-haul locomotive at Notch 8 (full power).

The ALECS demonstration is a public-private collaborative project involving the Placer County APCD, U.S. Environmental Protection Agency, Sacramento Metropolitan Air Quality Management District, Union Pacific Railroad, Advanced Cleanup Technologies Inc., the South Coast Air Quality Management District (SCAQMD), the California Air Resources Board, and the City of Roseville. Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) was contracted by the SCAQMD to carry out emission measurements before and after the ALECS system.

Emission measurements were performed on two locomotives: an EMD GP38 and a General Electric C39-8 (Dash 8). The GP38 has a 2000 horsepower two-stroke diesel engine, and is typically used for switching and local service. The Dash-8 has a 3900 horsepower four-stroke engine, and is normally used for line-haul freight service. Tests were performed with the locomotives stationary at idle, Notch 3, Notch 5, and Notch 8 power settings, and while moving slowly in Notch 1.

Measurements before and after the ALECS system showed NOx removal efficiency of 96 to 100%, with efficiency of 99% or more in most test modes. $SO_2$ emissions were low to begin with, were further reduced by 85 to 100%. PM control efficiency ranged from 89 to 99% over most test modes, but was only 81% in Notch 5 operation on the Dash 8. This mode had a high exhaust flow rate with low PM concentration.

$CO_2$ emissions increased through the ALECS system, as a result of the fuel-fired reheat stage before the SCR reactor. CO emissions were very low to begin with, but increased somewhat

through the system. Emissions due to ammonia slip from the SCR system ranged from zero (in most operating modes) to 1.3 grams per minute in full-power operation on the Dash 8. The latter emission rate was about 1/700th of the mass of NOx emissions destroyed by the ALECS system.

Testing conducted before and after prolonged periods of Notch 1 operation showed that PM buildup or “souping” during Notch 1 accounted for 26 to 37% of the total emissions attributable to Notch 1 operation. Although produced in Notch 1, this material adheres to the exhaust system, and is emitted subsequently, when the locomotive returns to higher-power operation. The ALECS system was virtually 100% effective in controlling the PM spikes due to this buildup. This suggests that the locomotives should first be operated at higher load with the ALECS system in place after a prolonged period of idle or Notch 1 operation.

# CONTENTS

APPENDIX: RAVEM SYSTEM DESCRIPTION

# LIST OF TABLES

# LIST OF FIGURES

# 1. INTRODUCTION

The Union Pacific Railroad's J.R. Davis rail yard in Roseville, California, is a major center for locomotive maintenance, as well as for assembling and reassembling trains of freight cars. Locomotive operations at the rail yard have been determined to be a significant source of emissions of diesel particulate matter (PM) and other pollutants.[1] An agreement between the Placer County Air Pollution Control District (APCD) and the Union Pacific Railroad Company includes a mitigation plan for reducing PM emissions from the rail yard. This plan includes considering the use of stationary air pollution control equipment to capture and treat emissions from stationary locomotives while idling or undergoing engine load tests. To carry out this part of the plan, the APCD initiated a project to demonstrate the Advanced Locomotive Emission Control System (ALECS).

The ALECS demonstration is a public-private collaborative project involving many parties. Participants include the APCD, U.S. Environmental Protection Agency, Sacramento Metropolitan Air Quality Management District, Union Pacific Railroad, Advanced Cleanup Technologies Inc., the South Coast Air Quality Management District (SCAQMD), the California Air Resources Board, and the City of Roseville. Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) was tasked with carrying out the emissions measurements under a contract with the SCAQMD.

## 1.1 OVERVIEW OF THE ALECS

The ALECS is designed to control harmful emissions from locomotives by capturing the exhaust stream from their engines and treating it to remove most pollutants. The system includes a set of stationary emissions control equipment connected to an articulated bonnet or hood. The hood is designed to capture locomotive exhaust, delivering it to the ground-mounted emission control system by means of a flexible duct. The bonnet or hood remains attached while the locomotive is moving along the track to the extent of the flexible duct.

The ALECS's emissions control equipment comprises a sodium hydroxide wash to remove sulfur dioxide ($SO_2$), followed by a triple cloud chamber scrubber for particulate matter (PM) removal. The exhaust is then reheated and passed through a Selective Catalytic Reduction (SCR) reactor to reduce oxides of nitrogen (NOx). The SCR reactor uses urea as the ammonia source. The demonstration ALECS is designed to treat exhaust flows between 2,000 and 12,000 standard cubic feet per minute (scfm).

## 1.2 OBJECTIVES

The objectives of the test program were:

- To measure and document the effectiveness of the ALECS system in controlling locomotive emissions of diesel particulate matter (PM), oxides of nitrogen (NOx) and other pollutants of concern under typical railyard operating conditions;

- To assure that the emission control process does not generate excessive amounts of other pollutants, such as ammonia;

- To quantify the effect of the hood system on locomotive noise emissions at full power; and
- To quantify the water and chemical consumption, operating costs, and waste generated by the ALECS system. (This information was compiled by ACTI during the test program, and is outside the scope of the present report).

# 2. THE TEST PROGRAM

The test program included emission measurements at three locations: at the inlet to the ground-mounted emission control system, at the outlet from the emission control system**,** and in the locomotive stack(s). The effectiveness of the ALECS emission control system was determined by comparing the mass emissions measured at the inlet with those measured at the system outlet. Emission measurements at the locomotive stack were obtained to make it possible to identify any effects on pollutant mass or characteristics due to the overhead manifold system.

The test program included two locomotives, each of which was operated in a defined set of test modes. Each of the test modes was repeated at least three times. Pollutants measured included PM, NOx, CO, $SO_2$, and total hydrocarbons (THC). The test procedures for these pollutants followed ISO standard 8178, which is extremely similar to the steady-state diesel testing procedures defined by the U.S. EPA and the California ARB. Ammonia ($NH_3$) and nitrous oxide ($N_2O$) were measured at the inlet and outlet of the emission control system during some of the tests, generally following the procedures specified in EPA Method 320.

## 2.1 TEST LOCOMOTIVES

The two locomotives tested were made available by the Union Pacific Railroad. They were a General Electric (GE) C39-8 line-haul locomotive (UPRR 9143) and an Electromotive Division (EMD) GP38 road-switcher (UPRR 604). The GE Dash-8 series locomotives are used primarily for line-haul freight service, and are equipped with four-stroke, turbocharged, GE FDL-16 engines. These 16-cylinder engines produce 3900 tractive horsepower, and discharge exhaust through a single rectangular stack connected directly to the turbocharger outlet. The maximum exhaust flow rate at full power is approximately 12,000 scfm.

The GP38 is used primarily for switching and local service. It is equipped with a two-stroke, Roots-blown, EMD 16-645E engine. The engine has 16 cylinders and is rated at 2000 tractive horsepower. It has two exhaust stacks, fed by the front eight and rear eight cylinders, respectively. The maximum exhaust flow rate at full power approximately is 6,000 scfm.

## 2.2 TEST FUEL

The test fuel for the GP38 was ultra-low sulfur diesel fuel meeting ARB regulations for sulfur and aromatic content, as specified in 13 CC 2281 and 2282. The sulfur limit is 15 parts per million w/w, and the limit on aromatic content is 10% v/v unless the fuel is produced according to an approved alternative formulation. The test fuel for the Dash-8 was a diesel fuel that is actually supplied to Union Pacific line-haul locomotives outside California. This fuel was specified with a sulfur content between 200 and 500 ppm w/w.

Table 1 shows the results of analyses performed on each fuel sample. EF&EE collected fuel samples from each locomotive's fuel tank during the test program. The fuel tanks were sealed and labeled to ensure that fuel was not added to the tanks by mistake.

**Table 1: Fuel analyses**

| | Method | Dash 8 | GP38 |
|---|---|---|---|
| Carbon Content | D-5291 | 86.00% | 86.10% |
| Hydrogen Content | D-5291 | 13.33% | 13.73% |
| Nitrogen Content | D-5291 | 0.50% | 0.06% |
| Sulfur Content (ppm) | D-4294 | 500 | <15 |

## 2.3 TESTING SCHEDULE

The test sequence originally planned for each day of stationary testing is shown in Table 2. The sequence was designed to provide for preconditioning the locomotive engine, and then for measuring at Notch 1, Notch 5, and Notch 8. The effects of "souping" (PM buildup in the exhaust system at light loads) were determined by operating at Notch 3 for half-hour periods following each of the test periods at Notch 1, and comparing the results to a baseline measurement made at Notch 3 following a half hour of preconditioning at Notch 3.

Because of equipment problems and other issues, the actual test program diverged considerably from the sequence shown in Table 2. However, each test mode except the "Souping" tests was always preceded by at least 30 minutes of operation at the same mode to stabilize engine temperature. Notch 1 tests were also preceded by at least 30 minutes at Notch 3 to eliminate any "soup" buildup before the start of the test. The "Souping" test always followed a substantial period of operation at idle, generally comprising a Notch 1 test, the preceding stabilization period, and the time required for changing filters and reading sample bags at the end of the test.

The original schedule called for each Notch 1 test to be four hours long, and each test at Notches 5 and 8 to be one hour. This was based on considerations of the minimum detectable PM emission level at the outlet, assuming 99% collection efficiency by the ALECS. Based on the PM buildup observed on the filters during the first few tests, however, it was concluded that the length of the Notch 1 and Notch 8 tests could be cut in half.

Moving tests were conducted with the locomotive moving back and forth within a restricted section of track. The schedule for these days is shown in Table 3. Three tests were conducted, each one-half hour long. The limited length of these tests is based on considerations of operator fatigue, since the engineer will be constantly changing the throttle and reverser positions to move the locomotive back and forth on the 50 foot test section.

**Table 2: Planned sequence of test modes and testing schedule for stationary test days**

| Step | Purpose | Throttle | Hours | Cumul. Hours | Test Activity |
|---|---|---|---|---|---|
| 1 | Precondition | 3 | 0.5 | 0.5 | Install filters/check instruments/calibrate |
| 2 | Souping baseline | 3 | 0.5 | 1.0 | Measure emissions |
| 3 | Stabilize | 1 | 0.5 | 1.5 | Change filters/calibrate |
| 4 | Idle test | 1 | 4.0 | 5.5 | Measure emissions |
| 5 | Filter Change | 1 | 0.5 | 6.0 | Change filters/calibrate |
| 6 | Souping test | 3 | 0.5 | 6.5 | Measure emissions |
| 7 | Stabilize | 5 | 0.5 | 7.0 | Change filters/calibrate |
| 8 | Notch 5 test | 5 | 1.0 | 8.0 | Measure emissions |
| 9 | Stabilize | 8 | 0.5 | 8.5 | Change filters/calibrate/refill day tank |
| 10 | Notch 8 test | 8 | 1.0 | 9.5 | Measure emissions and noise |
| 11 | Notch 8 noise baseline | 8 | .1 | 9.6 | Raise bonnet and re-measure noise |
| 12 | Cool down | Idle | 0.4 | 10.0 | Remove filters/refill day tank |

**Table 3: Planned sequence of test modes and testing schedule for moving test days**

| Step | Purpose | Throttle | Hours | Cumul. Hours | Test Activity |
|---|---|---|---|---|---|
| 1 | Precondition | 3 | 0.5 | 0.5 | Check/warmup instruments |
| 2 | Stabilize | Idle | 0.5 | 1.0 | Install filters/calibrate |
| 3 | Moving Test #1 | Var | 0.5 | 1.5 | Measure emissions |
| 4 | Filter Change | Idle | 0.5 | 2.0 | Change filters/calibrate |
| 5 | Moving Test #2 | Var | 0.5 | 2.5 | Measure emissions |
| 6 | Filter Change | Idle | 0.5 | 3.0 | Change filters/calibrate |
| 7 | Moving Test #3 | Var | 0.5 | 3.5 | Measure emissions |
| 8 | Change locomotive | Off | 2.0 | 5.5 | Remove RAVEM |

## 2.4 PARTICULATE EMISSION MEASUREMENTS

PM emissions before and after the ALECS system were measured using EF&EE’s Ride-Along Vehicle Emissions Measurement (RAVEM) system. The RAVEM uses the isokinetic partial flow dilution method specified as one option under ISO 8178. Raw exhaust is extracted from the exhaust conduit using an isokinetic sampling system. Isokinetic sampling conditions are maintained by adjusting the flow rate of raw exhaust through the sample probe until the static pressures inside and outside the probe are equal. This adjustment is performed continuously in real time by the RAVEM system, allowing it to follow transient changes in exhaust flow rate.

The raw exhaust from the sample probe was passed through an insulated sample line to the RAVEM dilution tunnel. Dilution air passed through a prefilter and a HEPA filter before entering the tunnel. Dilute exhaust containing PM was then drawn from the dilution tunnel through a PM2.5 cyclone (URG 2000-30EH), and then through filters of Teflon film in accordance with ISO 8178 and 40 CFR 1065. The rate of exhaust extraction was controlled to constant values of 16.7 standard liters per minute (SLPM) for the RAVEM systems measuring outlet and stack emissions, and 10 SLPM for the inlet RAVEM. The dilution flow rate in the

CVS was adjusted to ensure that the gas temperature at the filter face was no more than 52 $^{o}$C. Blank filters exposed only to dilution air were collected along with each sample. In addition to correcting for any background PM that makes it past the HEPA filter, subtracting the change in weight of the blank filter from the sample weight also automatically corrects for the effects of small differences in weighing chamber temperature, humidity, and atmospheric pressure.

ISO 8178 specifies the use of both primary and backup filters for each sample, while 40 CFR 1065 specifies the use of a single filter mounted in a filter cassette. For compatibility with the ongoing ambient sampling program at the railyard, EF&EE used the 40 CFR 1065 method during these tests.

Separate RAVEM samplers were used to sample the exhaust at the locomotive stack, at the inlet to the ALECS system, and in the outlet stack from the ALECS system. One Teflon sample filter and one Teflon blank were collected by each RAVEM during each test. In addition, the RAVEM system at the ALECS inlet collected one sample and one dilution air blank on 47 mm quartz filters during each test. These filters are to undergo analysis for elemental vs. organic carbon (EC/OC) content by the South Coast AQMD.

**Figure 1: RAVEM installations at the ALECS inlet and outlet**

At the request of the ARB Monitoring and Laboratory Division, the RAVEM sampler at the ALECS system inlet was also modified to allow a third PM sampler to be connected. The additional sampler was provided by ARB, and was used without a cyclone to collect 47 mm Teflon filters. These will be analyzed by ARB for mass and characterization of the hydrocarbon content of the PM in an effort to identify potential marker chemicals for PM source apportionment.

### 2.5 GASEOUS EMISSION MEASUREMENTS

Gaseous emission measurements included oxides of nitrogen (NOx), total hydrocarbons (THC), carbon monoxide (CO), carbon dioxide ($CO_2$), sulfur dioxide ($SO_2$), oxygen ($O_2$), ammonia ($NH_3$), and nitrous oxide ($N_2O$). Table 4 summarizes the gas concentration measurement techniques used. Except for the FTIR measurements, all of the analyzers and measurement techniques complied with ISO 8178 specifications.

The ALECS system itself includes continuous emission monitoring systems (CEMS) for NOx, $SO_2$, and $O_2$ at both the inlet and the outlet, and for THC and $NH_3$ at the outlet only. For these tests, EF&EE provided another THC analyzer for the inlet. The CEMS analyzers are configured for raw gas sampling, which means that the results must be combined with a measured exhaust gas flow rate to calculate the total mass of emissions. The exhaust flowrate measurement is provided by venturis located in both the inlet and outlet sections.

THC emissions in the CEMS are measured “hot” and “wet” – directly from a heated line maintained at 190 +/- 10 C. The other pollutants are measured “dry” -- after moisture is removed by a sample conditioning system. The $NH_3$ measurement method used by the ALECS is that specified in ISO 8178 – conversion of $NH_3$ to NO, followed by quantification using a chemilumenescent analyzer. Since $NH_3$ is highly soluble in water, it was converted to NO prior to the sample conditioning step.

**Table 4: Gas concentration measurements by sampling location**

| | **Locomotive Stack** | **ALECS Inlet** | **ALECS Outlet** |
|---|---|---|---|
| NOx | Dilute** | Raw+/Bag** | Raw+/Bag** |
| THC | | Raw | Raw+ |
| CO | Dilute** | Raw/Bag** | Raw/Bag** |
| $CO_2$ | Dilute** | Raw/Bag** | Raw/Bag** |
| $SO_2$ | - | Raw+ | Raw+ |
| $NH_3$ | - | FTIR* | FTIR*/CLD++ |
| $N_2O$ | - | FTIR* | FTIR* |
| Gas Flow | - | Venturi+ | Venturi+ |

*Fourier Transform Infrared of raw gas, time-shared between inlet and outlet
+ALECS system equipment **RAVEM system equipment
++ALECS system ammonia-to-NO with chemilumenescent detector

The effect of removing water vapor on pollutant concentrations in the remaining gas is substantial, especially in the outlet from the ALECS system. The water vapor concentration in the inlet gas was calculated from the absolute humidity of the ambient air and the chemical composition of the fuel. For the outlet gas, the water vapor concentration is determined by the exit conditions from the cloud chambers. According to the supplier, Tri-Met Corporation, these conditions were 140 to 150 $^{o}$F and 95% relative humidity. For the emission calculations, we assumed 24.7% by volume of water vapor in the outlet gas, corresponding to conditions of 145 $^{o}$F and 95% humidity.

The RAVEM sampling systems perform exhaust gas dilution according to the constant volume sampling (CVS) principle, so that the pollutant concentration in the dilute gas is proportional to the pollutant mass flow rate in the exhaust. The RAVEM system located at the ALECS inlet was configured to measure dilute NOx, CO, and $CO_2$ continuously, as well as collecting integrated bag samples of the dilute gas to be analyzed after the end of each test. The RAVEM samplers at the outlet and at the locomotive stack collected integrated bag samples only. These were analyzed at the end of each test by the analyzers of the first RAVEM system.

The results of the $CO_2$ measurements were used to calculate a carbon balance check for the PM sampling. The dilute NOx results from these bags were also compared to the NOx measurements of the ALECS CEMS systems.

The ALECS system ammonia analyzer works by oxidizing the ammonia to NO, measuring NO by CLD, and subtracting the NO already present in the sample gas (determined by another CLD analyzer). The accuracy of this method potentially suffers from the difference-of-large-numbers problem. A more accurate measurement of ammonia emissions, as well as $N_2O$, can be obtained by Fourier Transform Infrared (FTIR) analysis. During several emission tests, EF&EE applied a MIDAC FTIR analyzer system to measure $NH_3$ and $N_2O$ concentrations in the raw gas at both the ALECS inlet and outlet. A heated sample line was used to bring gas samples from each source to a heated filter next to the FTIR unit.

## 2.6 FUEL CONSUMPTION MEASUREMENTS

Fuel consumption was measured during each stationary emission test as a check on the accuracy of the results. If the measurements are accurate, the sum of the carbon contained in the $CO_2$, CO, HC, and PM emissions should be equal to the mass of carbon in the fuel consumed.

Fuel consumption by the locomotive engine was measured using a 250 gallon intermediate bulk container positioned on a pallet scale as a day tank, as shown in Figure 2. Three-way valves were installed in the locomotive's fuel supply and return lines to allow these to be switched between the locomotive fuel tank and the day tank. Switching both supply and return lines to the day tank meant that the change in weight of the day tank was equal to the fuel consumed by the engine. The day tank was filled (and refilled, when necessary) from the locomotive fuel tank by running the electric fuel pump with the supply line connected to the locomotive tank, and the return line connected to the day tank.

Since locomotive fuel systems can contain voids and air pockets that affect the fuel balance during startup, the system was stabilized while running on the day tank before beginning each emission test. The weight of fuel in the day tank was recorded at 1-second intervals automatically during the test.

Although the returned fuel can pick up considerable heat in the engine, the relatively large volume of fuel in the day tank and the length of the supply and return hoses made it unnecessary to cool the fuel during these tests.

**Figure 2: Dash 8 locomotive under emission testing, showing the fuel day tank**

# 3. EMISSION RESULTS

This program employed three different approaches to emission measurements: the RAVEM partial-flow dilution systems, the ALECS's own CEMS systems using conventional analyzers, and FTIR analysis of the raw exhaust for ammonia and $N_2O$. The RAVEM results are presented and discussed in Section 3.1, the CEMS results in Section 3.2, and the FTIR results in Section 3.3. The effects of "souping" – the buldup of PM in the exhaust system at light loads, to be emitted later when the exhaust temperature increases – are quantified in Section 3.4. Section 3.5, finally, compares the limited RAVEM measurements conducted in the locomotive exhaust stacks with those at the inlet to the ALECS system.

## 3.1 RAVEM RESULTS: PM, NOX, CO, AND $CO_2$

RAVEM system measurements from the stationary testing of the Dash 8 locomotive are shown in Table 5. Emissions were measured separately at the inlet and outlet the ALECS system, using two separate RAVEM units. Results (in grams of pollutant per minute) are shown for each test, as well as for the mean and coefficient of variation (standard deviation divided by the mean) in each test mode. Except for the Test 959 (the final souping test), the coefficients of variation are relatively low, and within expectations for test-to-test variability.

The emission control effectiveness of the ALECS system can be calculated from the ratio of the pollutant mass flow at the outlet to that at the inlet. For NOx, the control efficiencies ranged from 96.8% to 100%. For PM, the control efficiency ranged from 97% at low loads to 81% at Notch 5; increasing to 88.8% at Notch 8. CO emissions were extremely low at the inlet, and increased slightly in passing through the system. $CO_2$ emissions also increased through the ALECS system, due to the use of fuel to reheat the exhaust before the SCR system.

Table 5 also compares the fuel consumption measured by the change in weight of the day tank to that calculated from the emission results by carbon balance. Only the inlet fuel data are shown, as the outlet $CO_2$ emissions include the fuel used by the exhaust reheater in the ALECS system, and are thus not directly comparable to the measured fuel use. Except at Notch 1, the measured and calculated fuel consumption agree within a few percent, showing that the RAVEM was accurately collecting a proportional sample of the exhaust. The results for Notch 1, however, show that the RAVEM was oversampling by about 50%. The exhaust velocities and flow rates in this condition are extremely low, and the differential pressure signal used by the RAVEM system is proportional to the square of the exhaust velocity. Thus, at very low velocities, any inaccuracy in the sampling system can have a substantial effect. Thus, assuming that the measured fuel consumption data are accurate, the RAVEM results at idle should be multiplied by a factor 0.67 to get the true emissions.

## Table 5: ALECS inlet vs. outlet emissions - RAVEM data for the Dash 8

| Test | Start | Inlet Emissions (g/min) | | | | Outlet Emissions (g/min) | | | | Inlet Fuel (g/min) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Date/Time | $CO_2$ | CO | NOx | PM | $CO_2$ | CO | NOx | PM | Calc. | Meas. | Ratio |
| **DASH 8 - NOTCH 8** | | | | | | | | | | | | |
| T0946 | 9/8/2006 18:29 | 30,424 | 122 | 689 | 24.6 | 11,658 | 40 | 0.0 | 1.5 | 9,642 | 10,058 | 96% |
| T0951 | 9/10/2006 10:44 | 31,281 | 110 | 647 | 28.3 | 36,274 | 162 | 22.4 | 2.9 | 9,975 | 10,043 | 99% |
| T0952 | 9/10/2006 12:23 | 29,197 | 113 | 631 | 26.5 | 32,697 | 134 | 18.4 | 2.9 | 9,316 | 8,543 | 109% |
| T0953 | 9/11/2006 11:23 | 30,059 | 120 | 651 | 23.0 | 33,564 | 143 | 26.6 | 2.6 | 9,592 | 10,021 | 96% |
| T0955 | 9/11/2006 13:33 | 30,073 | 130 | 624 | 25.0 | 32,697 | 143 | 14.3 | 3.0 | 9,602 | 9,850 | 97% |
| Average | | 30,207 | 119 | 648 | 25.5 | 33,808 | 146 | 20.4 | 2.9 | 9,703 | 9,993 | 97% |
| Coeff. Of Deviation | | 2.5% | 6.5% | 3.9% | 7.9% | 5.0% | 8.0% | 25.9% | 6.2% | 1.9% | 1.0% | |
| **Control Efficiency** | | | | | | **-11.9%** | **-22.0%** | **96.8%** | **88.8%** | | | |
| **DASH 8 - NOTCH 8 - 2 CLOUD CHAMBERS** | | | | | | | | | | | | |
| T0954 | 9/11/2006 12:25 | 29,798 | 121 | 629 | 25.0 | 32,818 | 141 | 13.7 | 3.4 | 9,510 | 9,913 | 96% |
| **Control Efficiency** | | | | | | **-10.1%** | **-15.9%** | **97.8%** | **86.5%** | | | |
| **DASH 8 - NOTCH 5** | | | | | | | | | | | | |
| T0941 | 9/6/2006 18:06 | 18,058 | 131 | 428 | 3.2 | 23,600 | 188 | 5.3 | 1.4 | 5,792 | 6,152 | 94% |
| T0945 | 9/7/2006 19:32 | 17,348 | 122 | 411 | 6.5 | 20,639 | 151 | 1.6 | 1.0 | 5,562 | 6,111 | 91% |
| T0950 | 9/9/2006 18:41 | 18,065 | 113 | 438 | 7.0 | 20,355 | 123 | 13.2 | 1.2 | 5,745 | 6,079 | 95% |
| T0956 | 9/11/2006 15:28 | 18,971 | 145 | 433 | 5.8 | 19,697 | 142 | 6.8 | 1.4 | 6,088 | 6,218 | 98% |
| Average | | 18,111 | 128 | 427 | 6.4 | 21,073 | 151 | 6.7 | 1.2 | 5,797 | 6,140 | 94% |
| Coeff. Of Deviation | | 3.7% | 10.8% | 2.7% | 8.9% | 8.2% | 18.0% | 71.9% | 12.9% | 3.8% | 1.0% | |
| **Control Efficiency** | | | | | | **-16.4%** | **-18.1%** | **98.4%** | **80.9%** | | | |
| **DASH 8 - NOTCH 1** | | | | | | | | | | | | |
| T0943 | 9/7/2006 13:01 | 3,961 | 26 | 90 | 4.3 | 3,539 | 18 | 1.4 | 0.1 | 1,261 | 783 | 161% |
| T0948 | 9/9/2006 11:02 | 3,528 | 13 | 106 | 4.9 | 3,550 | 17 | 0.1 | 0.1 | 1,105 | 799 | 138% |
| T0958 | 9/12/2006 15:25 | 3,865 | 13 | 94 | 4.7 | 3,781 | 19 | 4.0 | 0.1 | 1,232 | 808 | 152% |
| Average | | 3,785 | 17 | 97 | 4.6 | 3,623 | 18 | 1.9 | 0.1 | 1,199 | 797 | 150% |
| Coeff. Of Deviation | | 6.0% | 45.6% | 8.4% | 6.5% | 3.8% | 6.0% | 107% | 2.9% | 6.9% | 1.6% | |
| **Control Efficiency** | | | | | | **4.3%** | **-3.0%** | **98.1%** | **98.6%** | | | |
| **DASH 8 SOUPING BASELINE** | | | | | | | | | | | | |
| T0947 | 9/9/2006 9:54 | 11,148 | 32 | 271 | 4.5 | 11,044 | 38 | 0.0 | 0.3 | 3,552 | 3,558 | 100% |
| T0957 | 9/12/2006 14:00 | 10,825 | 38 | 263 | 3.1 | #N/A | #N/A | #N/A | 0.4 | 3,428 | #N/A | #N/A |
| T0960 | 9/13/2006 13:28 | 11,087 | 41 | 268 | 3.9 | 13,094 | 58 | 0.0 | 0.3 | 3,536 | 3,510 | 101% |
| Average | | 11,020 | 37 | 267 | 3.8 | 12,069 | 48 | 0.0 | 0.4 | 3,505 | 3,534 | 99% |
| Coeff. Of Deviation | | 1.6% | 11.6% | 1.6% | 18% | 12.0% | 29.5% | 141% | 22.0% | 1.9% | 1.0% | |
| **Control Efficiency** | | | | | | **-9.5%** | **-28.5%** | **100%** | **90.7%** | | | |
| **DASH 8 SOUPING TEST** | | | | | | | | | | | | |
| T0944 | 9/7/2006 18:24 | 9,926 | 40 | 242 | 10.9 | 12,864 | 61 | 7.5 | 0.4 | 3,168 | #N/A | #N/A |
| T0949 | 9/9/2006 16:30 | 11,654 | 33 | 265 | 12.1 | 11,517 | 53 | 15.5 | 0.3 | 3,687 | 3,437 | 107% |
| T0959 | 9/12/2006 18:17 | 10,943 | 50 | 265 | 31.6 | 13,146 | 62 | 0.0 | 1.0 | 3,495 | 3,321 | 105% |
| Average | | 10,841 | 41 | 257 | 18.2 | 12,509 | 58 | 7.7 | 0.5 | 3,450 | 3,379 | 102% |
| Coeff. Of Deviation | | 8.0% | 19.8% | 5.3% | 64% | 7.0% | 8.7% | 101% | 65.4% | 7.6% | 2.4% | |
| **Control Efficiency** | | | | | | **-15.4%** | **-42.6%** | **97.0%** | **97.0%** | | | |

The shaded cells in Table 5 indicate results that were excluded from the averages due to technical problems with the measurements. In Test 941, the PM results were affected by a leak into the PM filter suction when the suction line to the aethelometer became disconnected. Test 946 was the first test conducted at Notch 8, and the resulting exhaust flow was so high that the RAVEM was unable to maintain isokinetic sampling. The outlet RAVEM was originally equipped with a one-inch diameter isokinetic probe to maximize the amount of pollutant collected at low loads. A one-half inch probe was used for subsequent testing at Notch 5 and Notch 8, while the one inch probe continued to be used at lower power settings.

In Test 952, the locomotive engine shut down due to low lube oil pressure at 22 minutes into the test. While this did not affect the validity of the emission results, fuel in the locomotive engine circuit drained back into the day tank after the shutdown, affecting the mass fuel consumption measurement.

RAVEM system results from the stationary testing on the GP38 locomotive are summarized in Table 6. Exhaust mass flow and pollutant flow rates were significantly lower from this 2000 horsepower locomotive than from the 3900 horsepower Dash 8, and both the emission testing crew and the ALECS operations had gained experience during the earlier testing. Fewer technical problems were experienced, therefore, and the carbon balance results show close agreement between the measured and calculated fuel consumption.

The NOx control efficiency of the ALECs system in these tests ranged from 95 to 99%, while the PM control efficiency was 90% or better across all of the test modes. Except at Notch 8, CO emissions were too low to measure accurately, so that the high percentage increases shown for this pollutant are of little actual significance.

RAVEM system results from the moving tests on both locomotives are presented in Table 7. Because of the motion, the day tank had to be disconnected, so that mass fuel consumption measurements were not possible. Since the locomotives were only able to move very slowly, and over a restricted distance, the power required, calculated fuel consumption, and emissions were very low. The mass emission rates and calculated fuel consumption rates are even lower than those for continuous Notch 1 operation. PM and NOx control efficiencies under these conditions were well above 90%.

## Table 6: ALECS inlet vs. outlet emissions - RAVEM data for the GP38

| **Test No.** | **Start Date/Time** | **Inlet Emissions (g/min)** | | | | **Outlet Emissions (g/min)** | | | | **Inlet Fuel (g/min)** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **$CO_2$** | **CO** | **NOx** | **PM** | **$CO_2$** | **CO** | **NOx** | **PM** | **Calc.** | **Meas.** | **Ratio** |
| **GP 38 - NOTCH 8** | | | | | | | | | | | | |
| T0967 | 9/16/2006 16:09 | 18,189 | 34 | 462 | 7.7 | 20,679 | 42 | 16.8 | 0.5 | 5,778 | 6,175 | 94% |
| T0968 | 9/16/2006 17:19 | 19,535 | 32 | 469 | 6.3 | 22,153 | 46 | 2.1 | 0.5 | 6,204 | 6,167 | 101% |
| T0969 | 9/16/2006 18:18 | 20,509 | 44 | 468 | 5.7 | 21,567 | 48 | 1.3 | 0.8 | 6,518 | 6,150 | 106% |
| Average | | 19,411 | 37 | 466 | 6.6 | 21,466 | 45 | 6.8 | 0.6 | 6,167 | 6,164 | 100% |
| Coeff. Of Deviation | | 6.0% | 18.2% | 0.8% | 16% | 3.5% | 6.5% | 129% | 27.8% | 6.0% | 0.2% | |
| **Control Efficiency** | | | | | | **-10.6%** | **-24.0%** | **98.6%** | **90.7%** | | | |
| **GP 38 - NOTCH 5** | | | | | | | | | | | | |
| T0964 | 9/16/2006 10:50 | 9,754 | 3 | 201 | 5.5 | 10,811 | 10 | 0.0 | 0.4 | 3,091 | 3,208 | 96% |
| T0965 | 9/16/2006 12:33 | 10,036 | 6 | 209 | 4.5 | 11,281 | 12 | 1.4 | 0.4 | 3,182 | 3,178 | 100% |
| T0966 | 9/16/2006 14:18 | 9,816 | 1 | 204 | 4.0 | 11,356 | 18 | 2.9 | 0.5 | 3,110 | 3,168 | 98% |
| Average | | 9,869 | 3 | 205 | 4.7 | 11,150 | 14 | 1.4 | 0.4 | 3,128 | 3,185 | 98% |
| Coeff. Of Deviation | | 1.5% | 77.3% | 2.0% | 16% | 2.6% | 32.3% | 101% | 6.2% | 1.5% | 0.7% | |
| **Control Efficiency** | | | | | | **-13.0%** | **-324%** | **99.3%** | **90.7%** | | | |
| **GP 38 - NOTCH 1** | | | | | | | | | | | | |
| T0962 | 9/15/2006 16:30 | 1,600 | 3 | 27 | 0.40 | 2,292 | 3 | -0.4 | 0.03 | 505 | 438 | 115% |
| T0971 | 9/17/2006 11:43 | 1,326 | 2 | 28 | 0.20 | 2,223 | 3 | 2.6 | 0.03 | 421 | 430 | 98% |
| T0973 | 9/17/2006 15:27 | 1,628 | (7) | 27 | 0.36 | 2,256 | 5 | 0.3 | 0.04 | 509 | 426 | 119% |
| Average | | 1,518 | (1) | 27 | 0.32 | 2,257 | 4 | 0.8 | 0.03 | 478 | 431 | 111% |
| Coeff. Of Deviation | | 11.0% | 638% | 2.6% | 34% | 1.5% | 31.7% | 194% | 9.4% | 10.4% | 1.4% | |
| **Control Efficiency** | | | | | | **-48.7%** | **#N/A** | **97.0%** | **89.6%** | | | |
| **GP 38 SOUPING BASELINE** | | | | | | | | | | | | |
| T0961 | 9/15/2006 15:15 | 6,085 | (1) | 114 | 1.9 | 6,777 | 9 | 2.5 | 0.2 | 1,916 | 1,759 | 109% |
| T0970 | 9/17/2006 10:30 | 5,316 | 2 | 100 | 1.7 | 5,971 | 6 | 2.3 | 0.1 | 1,685 | 1,765 | 95% |
| T0975 | 9/17/2006 19:10 | 5,489 | 3 | 102 | 1.4 | 6,294 | 8 | 0.1 | 0.2 | 1,740 | 1,732 | 100% |
| Average | | 5,630 | 1 | 106 | 1.7 | 6,347 | 8 | 1.6 | 0.2 | 1,780 | 1,752 | 102% |
| Coeff. Of Deviation | | 7.2% | 159% | 7.1% | 14% | 6.4% | 18.9% | 79.8% | 6.4% | 6.8% | 1.0% | |
| **Control Efficiency** | | | | | | **-12.7%** | **-474%** | **98.4%** | **90.8%** | | | |
| **GP 38 SOUPING TEST** | | | | | | | | | | | | |
| T0963 | 9/15/2006 19:17 | 6,222 | (2) | 109 | 3.5 | 6,192 | 9 | 12.1 | 0.1 | 1,970 | 1,698 | 116% |
| T0972 | 9/17/2006 14:16 | 5,065 | (1) | 96 | 2.6 | 6,213 | 7 | 2.0 | 0.2 | 1,604 | 1,692 | 95% |
| T0974 | 9/17/2006 18:08 | 4,694 | (2) | 93 | 2.7 | 5,045 | 7 | 0.3 | 0.1 | 1,477 | 1,459 | 101% |
| Average | | 5,327 | (2) | 99 | 2.9 | 5,817 | 8 | 4.8 | 0.1 | 1,684 | 1,617 | 104% |
| Coeff. Of Deviation | | 15.0% | 55.5% | 8.4% | 17% | 11.5% | 13.7% | 133% | 14.0% | 15.2% | 8.4% | |
| **Control Efficiency** | | | | | | **-9.2%** | **#N/A** | **95.2%** | **94.9%** | | | |

**Table 7: ALECS inlet vs. outlet emissions - RAVEM data for moving tests**

| Test No. | Start Date/Time | Inlet Emissions (g/min) $CO_2$ | CO | NOx | PM | Outlet Emissions (g/min) $CO_2$ | CO | NOx | PM | Inlet Fuel (g/min) Calc. | Meas. | Ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **DASH 8 MOVING TEST** | | | | | | | | | | | | |
| T0980 | 9/20/2006 14:11 | 2,116 | 9 | 51 | 5.6 | 2,398 | 15 | 1.4 | 0.0 | 675 | #N/A | #N/A |
| T0981 | 9/20/2006 15:28 | 2,306 | 10 | 53 | 3.1 | 2,563 | 14 | 0.0 | 0.1 | 736 | #N/A | #N/A |
| T0982 | 9/20/2006 16:24 | 969 | (1) | 26 | 1.0 | 1,947 | 7 | 0.3 | 0.0 | 307 | #N/A | #N/A |
| Average | | 1,797 | 6 | 43 | 3.2 | 2,303 | 12 | 0.6 | 0.0 | 573 | #N/A | #N/A |
| Coeff. Of Deviation | | 40.3% | 97.6% | 35.4% | 71% | 13.9% | 38.9% | 129% | 16.8% | 40.6% | #N/A | |
| **Control Efficiency** | | | | | | **-28.2%** | **-99.4%** | **98.7%** | **98.5%** | | | |
| **GP 38 MOVING TEST** | | | | | | | | | | | | |
| T0976 | 9/19/2006 15:00 | 1,072 | 4 | 22 | 0.2 | 1,508 | 2 | 2.3 | 0.0 | 342 | #N/A | #N/A |
| T0978 | 9/20/2006 9:41 | 884 | 1 | 23 | 0.0 | 1,705 | 3 | 0.0 | 0.0 | 281 | #N/A | #N/A |
| T0979 | 9/20/2006 10:52 | 739 | 1 | 21 | 0.5 | 1,769 | 4 | 0.2 | 0.0 | 235 | #N/A | #N/A |
| Average | | 898 | 2 | 22 | 0.2 | 1,661 | 3 | 0.8 | 0.0 | 286 | #N/A | #N/A |
| Coeff. Of Deviation | | 18.6% | 70.9% | 6.5% | 116% | 8.2% | 20.1% | 158% | 66.8% | 18.8% | #N/A | |
| **Control Efficiency** | | | | | | **-84.9%** | **-47.7%** | **96.3%** | **93.5%** | | | |

## 3.2 CEMS RESULTS: NOX, SO$_2$, THC, AND NH$_3$

CEMS results for the stationary emission tests on the Dash 8 locomotive are shown in Table 8, while those for the GP38 are shown in Table 9. Results of the moving tests on both locomotives are shown in Table 10. The CEMS data recording was not fully functional during the first few tests in this program, so that these data are shown as #NA in the tables.

The CEMS data, like the RAVEM data, show extremely high control efficiency for NOx. Although $SO_2$ emissions in these tests were already low, the ALECS system reduced these to barely-detectable levels. Ammonia emissions were also below or close to the limits of detectability over most of the test period. Control of THC emissions was considerably less effective, ranging from about 31% to 85% effective. THC control was least efficient in the test conditions with the highest THC emissions.

Since NOx emissions were measured using both the CEMS and the RAVEM systems, a comparison between these two methods provides insight into the accuracy of the measurements. Figure 3 is a cross-plot of the NOx emission rate at the ALECS inlet as measured by the CEMS vs. that measured by the RAVEM. As this figure shows, the relationship is nearly 1:1, except at the highest NOx flow rates (measured at Notch 8 on the Dash 8 locomotive), where the CEMS results are about 12% higher. Since the carbon balance data for the RAVEM agree closely with the mass fuel consumption measurements, it is likely that the error lies in the CEMS data. This discrepancy may be due to excess water vapor from water injected into the exhaust duct to protect it from overheating. This would have had the effect of increasing apparent exhaust flow through the venturi. According to ACTI personnel, water injection was done only at high load, and the amount of water injected was not measured.

## Table 8: ALECS inlet vs. outlet emissions - CEMS data for the Dash 8

| Test No. | Start Date/Time | Inlet (g/min) | | | Outlet (g/min) | | | | Flow SCFM | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | NOx | $SO_2$ | THC | NOx | $SO_2$ | THC | NH3 | Inlet | Outlet |
| **DASH 8 - NOTCH 8** | | | | | | | | | | |
| T0946 | 9/8/2006 18:29 | 732.9 | 31.06 | #N/A | 31.5 | 0.00 | 7.11 | 1.1 | 12,829 | 14,011 |
| T0951 | 9/10/2006 10:44 | 737.4 | 29.12 | 13.26 | 26.2 | 0.30 | 6.76 | 1.2 | 12,365 | 14,010 |
| T0952 | 9/10/2006 12:23 | 725.9 | 26.18 | 9.87 | 16.5 | 0.00 | 7.39 | 1.6 | 12,028 | 13,941 |
| T0953 | 9/11/2006 11:23 | 727.3 | 26.68 | 8.11 | 24.8 | 0.00 | 6.41 | 1.1 | 12,115 | 13,992 |
| T0955 | 9/11/2006 13:33 | 710.9 | 23.68 | 8.36 | 14.6 | 0.00 | 6.02 | 1.2 | 11,801 | 13,812 |
| Average | | 726.9 | 27.34 | 9.90 | 22.7 | 0.07 | 6.64 | 1.3 | 12,077 | 13,939 |
| Coeff. Of Deviation | | 1.4% | 10.4% | 24.0% | 31.0% | 198.7% | 8.7% | 17.8% | 1.9% | 0.6% |
| **Control Efficiency** | | | | | **96.9%** | **99.7%** | **32.9%** | | | |
| **DASH 8 - NOTCH 8 - 2 CLOUD CHAMBERS** | | | | | | | | | | |
| T0954 | 9/11/2006 12:25 | 718.8 | 25.19 | 8.05 | 15.9 | 0.00 | 6.16 | 1.8 | 11,983 | 13,898 |
| **Control Efficiency** | | | | | **97.8%** | **100.0%** | **23.5%** | | | |
| **DASH 8 - NOTCH 5** | | | | | | | | | | |
| T0941 | 9/6/2006 18:06 | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A |
| T0945 | 9/7/2006 19:32 | #N/A | 19.23 | #N/A | 1.1 | 0.00 | 1.58 | 1.7 | 7,515 | 8,040 |
| T0950 | 9/9/2006 18:41 | 462.7 | 18.82 | 4.02 | 9.4 | 0.00 | 3.46 | 0.8 | 7,015 | 8,140 |
| T0956 | 9/11/2006 15:28 | 469.6 | 16.43 | 4.10 | 6.1 | 0.00 | 3.33 | 0.0 | 6,998 | 8,173 |
| Average | | 466.1 | #N/A | 4.06 | 5.5 | 0.00 | 2.79 | 0.8 | 7,176 | 8,117 |
| Coeff. Of Deviation | | 1.0% | #N/A | 1.3% | 75.2% | 173.2% | 37.7% | 103.9% | 4.1% | 0.9% |
| **Control Efficiency** | | | | | **98.8%** | **#N/A** | **31.4%** | | | |
| **DASH 8 - NOTCH 1** | | | | | | | | | | |
| T0943 | 9/7/2006 13:01 | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A | #N/A |
| T0948 | 9/9/2006 11:02 | 52.8 | 1.48 | 1.08 | 1.3 | 0.02 | 0.73 | 0.0 | 2,257 | 2,948 |
| T0958 | 9/12/2006 15:25 | 57.1 | 1.39 | 1.70 | 2.5 | 0.00 | 0.45 | 0.6 | 2,326 | 2,936 |
| Average | | 55.0 | 1.44 | 1.39 | 1.9 | 0.01 | 0.59 | 0.3 | 2,291 | 2,942 |
| Coeff. Of Deviation | | 5.5% | 4.3% | 31.5% | 47.5% | 97.4% | 33.4% | 136.0% | 2.1% | 0.3% |
| **Control Efficiency** | | | | | **96.5%** | **99.1%** | **57.6%** | | | |
| **DASH 8 SOUPING BASELINE** | | | | | | | | | | |
| T0947 | 9/9/2006 9:54 | 277.2 | 12.68 | #N/A | 0.1 | 0.00 | 2.27 | 0.0 | 4,417 | 4,699 |
| T0957 | 9/12/2006 14:00 | 278.6 | 9.97 | 3.84 | 3.0 | 0.00 | 2.77 | 0.0 | 4,169 | 4,540 |
| T0960 | 9/13/2006 13:28 | 277.2 | 9.95 | 3.95 | 0.2 | 0.00 | 2.94 | 0.0 | 4,221 | 4,516 |
| Average | | 277.7 | 10.87 | 3.90 | 1.1 | 0.00 | 2.60 | 0.0 | 4,319 | 4,607 |
| Coeff. Of Deviation | | 0.3% | 14.4% | 2.1% | 152.6% | 0.0% | 13.5% | 115.2% | 3.0% | 2.2% |
| **Control Efficiency** | | | | | **99.6%** | **100.0%** | **33.2%** | | | |
| **DASH 8 SOUPING TEST** | | | | | | | | | | |
| T0944 | 9/7/2006 18:24 | #N/A | 9.75 | #N/A | 3.1 | 0.04 | 1.43 | 0.2 | 4,333 | 4,378 |
| T0949 | 9/9/2006 16:30 | 255.5 | 9.80 | 4.89 | 7.1 | 0.16 | 3.09 | 0.1 | 4,095 | 4,437 |
| T0959 | 9/12/2006 18:17 | 244.9 | 8.71 | 4.33 | 6.5 | 0.02 | 2.20 | 0.0 | 3,980 | 4,354 |
| Average | | 250.2 | 9.42 | 4.61 | 5.6 | 0.07 | 2.24 | 0.1 | 4,136 | 4,390 |
| Coeff. Of Deviation | | 3.0% | 6.6% | 8.7% | 39.3% | 104.9% | 37.0% | 75.5% | 4.4% | 1.0% |
| **Control Efficiency** | | | | | **97.8%** | **99.2%** | **51.4%** | | | |

## Table 9: ALECS inlet vs. outlet emissions - CEMS data for the GP 38

| **Test** | **Start** | **Inlet (g/min)** | | | **Outlet (g/min)** | | | | **Flow SCFM** | |
|---|---|---|---|---|---|---|---|---|---|---|
| **No.** | **Date/Time** | **NOx** | **$SO_2$** | **THC** | **NOx** | **$SO_2$** | **THC** | **NH3** | **Inlet** | **Outlet** |
| **GP 38 - NOTCH 8** | | | | | | | | | | |
| T0967 | 9/16/2006 16:09 | 490.3 | 16.26 | 3.74 | 14.4 | 0.00 | 0.92 | 0.0 | 8,376 | 9,413 |
| T0968 | 9/16/2006 17:19 | 486.6 | 16.19 | 3.23 | 1.5 | 0.00 | 0.89 | 0.0 | 8,288 | 9,369 |
| T0969 | 9/16/2006 18:18 | 480.9 | 16.25 | 3.17 | 0.9 | 0.00 | 0.91 | 0.4 | 8,270 | 9,355 |
| Average | | 485.9 | 16.23 | 3.38 | 5.6 | 0.00 | 0.90 | 0.1 | 8,311 | 9,379 |
| Coeff. Of Deviation | | 1.0% | 0.2% | 9.3% | 136.0% | 0.00 | 1.7% | 173.1% | 0.7% | 0.3% |
| **Control Efficiency** | | | | | **98.8%** | **100.0%** | **73.2%** | | | |
| **GP 38 - NOTCH 5** | | | | | | | | | | |
| T0964 | 9/16/2006 10:50 | 196.9 | 4.73 | 1.47 | 0.3 | 0.00 | 0.22 | 0.0 | 6,522 | 7,023 |
| T0965 | 9/16/2006 12:33 | 202.0 | 4.75 | 1.66 | 1.0 | 0.00 | 0.23 | 0.0 | 6,320 | 6,924 |
| T0966 | 9/16/2006 14:18 | 204.8 | 4.63 | 1.71 | 2.2 | 0.00 | 0.24 | 0.0 | 6,270 | 6,889 |
| Average | | 201.2 | 4.70 | 1.62 | 1.2 | 0.00 | 0.23 | 0.0 | 6,371 | 6,945 |
| Coeff. Of Deviation | | 2.0% | 1.4% | 7.8% | 79.9% | 0.00 | 2.4% | 99.0% | 2.1% | 1.0% |
| **Control Efficiency** | | | | | **99.4%** | **100.0%** | **85.7%** | | | |
| **GP 38 - NOTCH 1** | | | | | | | | | | |
| T0962 | 9/15/2006 16:30 | 21.0 | 0.27 | 0.46 | 0.07 | 0.06 | 0.08 | 0.0 | 3,286 | 3,827 |
| T0971 | 9/17/2006 11:43 | 21.6 | 0.12 | 0.50 | 1.73 | 0.00 | 0.10 | 1.9 | 3,735 | 4,245 |
| T0973 | 9/17/2006 15:27 | 21.8 | 0.11 | 0.60 | 0.08 | 0.00 | 0.09 | 0.0 | 3,677 | 4,193 |
| Average | | 21.5 | 0.17 | 0.52 | 0.63 | 0.02 | 0.09 | 0.6 | 3,566 | 4,088 |
| Coeff. Of Deviation | | 1.9% | 52.4% | 13.9% | 152.6% | 173.2% | 11.2% | 169.1% | 6.8% | 5.6% |
| **Control Efficiency** | | | | | **97.1%** | **88.4%** | **83.1%** | | | |
| **GP 38 SOUPING BASELINE** | | | | | | | | | | |
| T0961 | 9/15/2006 15:15 | 98.6 | 1.66 | 0.99 | 2.5 | 0.00 | 0.13 | 0.0 | 4,802 | 5,197 |
| T0970 | 9/17/2006 10:30 | 97.5 | 1.24 | 0.84 | 2.3 | 0.00 | 0.14 | 0.1 | 5,872 | 6,355 |
| T0975 | 9/17/2006 19:10 | 97.9 | 1.13 | 1.01 | 0.1 | 0.00 | 0.16 | 0.0 | 5,493 | 6,037 |
| Average | | 98.0 | 1.35 | 0.95 | 1.6 | 0.00 | 0.14 | 0.0 | 5,389 | 5,863 |
| Coeff. Of Deviation | | 0.6% | 20.9% | 9.7% | 80.6% | 0.0% | 10.6% | 157.3% | 10.1% | 10.2% |
| **Control Efficiency** | | | | | **98.3%** | **100.0%** | **84.9%** | | | |
| **GP 38 SOUPING TEST** | | | | | | | | | | |
| T0963 | 9/15/2006 19:17 | 86.5 | 1.44 | 0.92 | 9.4 | 0.14 | 0.14 | 0.3 | 4,962 | 5,399 |
| T0972 | 9/17/2006 14:16 | 92.0 | 0.99 | 1.02 | 1.3 | 0.00 | 0.15 | 0.0 | 5,620 | 6,135 |
| T0974 | 9/17/2006 18:08 | 92.5 | 1.00 | 0.98 | 0.2 | 0.00 | 0.17 | 0.3 | 5,486 | 5,987 |
| Average | | 90.3 | 1.14 | 0.97 | 3.6 | 0.05 | 0.15 | 0.2 | 5,356 | 5,840 |
| Coeff. Of Deviation | | 3.7% | 22.2% | 5.3% | 137.2% | 173.2% | 7.4% | 87.6% | 6.5% | 6.7% |
| **Control Efficiency** | | | | | **96.0%** | **96.0%** | **84.2%** | | | |

A cross-plot of the outlet NOx concentrations measured by the CEMS vs. the RAVEM shows a similar 1:1 relationship, but with much greater variability, due to the low NOx concentrations involved.

## Table 10: ALECS inlet vs. outlet emissions - CEMS data for the moving tests

| Test No. | Start Date/Time | Inlet (g/min) | | | Outlet (g/min) | | | | Flow SCFM | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | NOx | $SO_2$ | THC | NOx | $SO_2$ | THC | NH3 | Inlet | Outlet |
| **DASH 8 MOVING TEST** | | | | | | | | | | |
| T0980 | 9/20/2006 14:11 | 36.4 | 0.94 | 1.67 | 1.1 | 0.00 | 0.91 | 0.000 | 2,645 | 3,154 |
| T0981 | 9/20/2006 15:28 | 35.4 | 0.88 | 1.36 | 0.1 | 0.00 | 0.53 | 0.000 | 2,458 | 2,946 |
| T0982 | 9/20/2006 16:24 | 19.5 | 0.44 | 0.78 | 0.2 | 0.00 | 0.23 | 0.000 | 2,196 | 2,838 |
| Average | | 30.4 | 0.75 | 1.27 | 0.4 | 0.00 | 0.56 | 0.000 | 2,433 | 2,979 |
| Coeff. Of Deviation | | 31.2% | 36.6% | 35.3% | 131.5% | 0.0% | 60.9% | 100.2% | 9.3% | 5.4% |
| **Control Efficiency** | | | | | **98.5%** | **100.0%** | **56.0%** | | | |
| **GP 38 MOVING TEST** | | | | | | | | | | |
| T0976 | 9/19/2006 15:00 | 17.1 | 0.22 | 0.47 | 2.1 | 0.00 | 0.11 | 0.001 | 3,636 | 4,177 |
| T0978 | 9/20/2006 9:41 | 17.2 | 0.27 | 0.46 | 0.1 | 0.11 | 0.10 | 0.000 | 3,905 | 4,401 |
| T0979 | 9/20/2006 10:52 | 16.0 | 0.25 | 0.46 | 0.1 | 0.00 | 0.09 | 0.000 | 3,843 | 4,331 |
| Average | | 16.8 | 0.24 | 0.46 | 0.8 | 0.04 | 0.10 | 0.000 | 3,795 | 4,303 |
| Coeff. Of Deviation | | 4.1% | 9.1% | 1.1% | 154.8% | 173.2% | 9.6% | 139.2% | 3.7% | 2.7% |
| **Control Efficiency** | | | | | **95.4%** | **84.9%** | **78.6%** | | | |

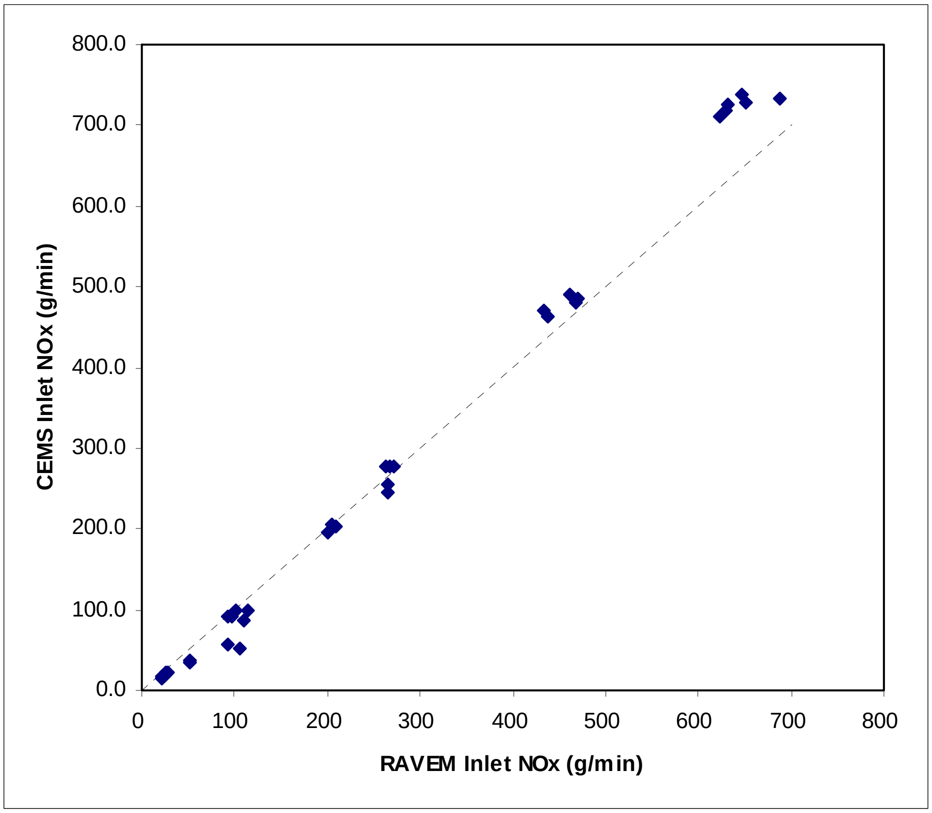


Figure 3: CEMS vs. RAVEM NOx measurements

### 3.3 FTIR RESULTS: $NH_3$ AND $N_2O$

FTIR measurements of ammonia and $N_2O$ concentrations were carried out alternately on the outlet and inlet gas streams in parallel with tests 964 through 979. The ammonia concentrations measured by the FTIR system were extremely low (generally in the range of zero to 2 ppm), and consistent with the results of the chemilumenescent ammonia analyzer incorporated in the CEMS system. The $N_2O$ concentrations reported by the FTIR system were also generally in the range of zero to 2 ppm, and less than the estimated error calculated by the FTIR software. $N_2O$ concentrations measured at the ALECS inlet were similar to those measured at the outlet, suggesting that the reported values were likely due to the presence of interfering species rather than $N_2O$ as such.

### 3.4 SOUPING EMISSIONS: PM BUILDUP DURING NOTCH 1

During prolonged periods of low-load operation, particulate matter (mostly semi-volatile hydrocarbons) tends to build up on the walls of the exhaust system, forming a liquid deposit, colloquially known as “soup”. Since locomotives are often left idling for long periods, substantial amounts of material can build up. Once the locomotive returns to higher-load operation, the accumulated material comes back off of the walls and into the exhaust. If soup deposits are heavy, some of this material is blown out of the exhaust system as large liquid droplets. Much of it, however, is emitted as fine particulate matter, forming a transient cloud of visible white or gray smoke during the first seconds after the engine load increases.

The transient PM spike due to re-mobilization of the soup deposits is not captured by the present Federal test procedure for locomotives, since it measures emissions only under stabilized conditions. Previous testing by EF&EE[2] showed that these soup emissions can be significant: accounting for 0.10 and 0.19 grams per minute (15% and 49% of idling PM emissions, respectively) from two turbocharged EMD locomotives.

To determine the PM emissions in this test program due to soup buildup, we compared the PM results at Notch 3 in the souping baseline tests with those measured in the souping tests, going from Notch 1 to Notch 3 after a prolonged period of Notch 1 operation. This calculation is shown in Table 11. Average PM emissions during the baseline tests on each locomotive were subtracted from the measured PM emissions during the souping test to calculate the excess PM emission due to soup buildup. This excess was then divided by the length of the preceding buildup period to calculate the rate of soup PM buildup for per minute of Notch 1 operation.

As Table 11 shows, the PM emissions attributable to souping in the GP38 are comparable to those measured in our earlier study, averaging 0.38 g/min or 38% of total Notch 1 PM emissions attributable to Notch 1 operation. Souping emissions from the Dash 8 locomotive were much higher, but the Notch 1 PM emissions were higher still, so that souping accounted for only 26% of the Notch 1 PM emissions attributable to this locomotive (see Table 12). The souping emissions from the Dash 8 also exhibited great variability, with one test producing seven times higher emissions than the other two. Such a large discrepancy normally suggests a measurement error, such as an error in PM filter handling or weighing. That is not a likely explanation in this case, however, since the higher PM emissions were also observed in the RAVEM measurements on the ALECS outlet.

**Table 11: Calculation of "soup" PM buildup during Notch 1 operation**

| Test No | Buildup (minutes) | ALECS Inlet PM (g) | | | Souping g/min | ALECS Outlet PM (g) | | | Souping g/min |
|---|---|---|---|---|---|---|---|---|---|
| | | Total | Baseline | Excess | | Total | Baseline | Excess | |
| **Dash 8** | | | | | | | | | |
| 944 | 435.6 | 326.5 | 115.1 | 211.4 | 0.49 | 11.0 | 10.7 | 0.3 | 0.001 |
| 949 | 366.3 | 362.5 | 115.1 | 247.5 | 0.68 | 9.4 | 10.7 | -1.3 | -0.004 |
| 959 | 227.3 | 950.9 | 115.1 | 835.7 | 3.68 | 28.6 | 10.7 | 17.9 | 0.079 |
| **GP 38** | | | | | | | | | |
| 963 | 211.5 | 105.2 | 50.4 | 54.8 | 0.26 | 4.2 | 4.6 | -0.5 | -0.002 |
| 972 | 195.5 | 76.7 | 50.4 | 26.3 | 0.13 | 5.2 | 4.6 | 0.6 | 0.003 |
| 974 | 202.2 | 81.7 | 50.4 | 31.3 | 0.15 | 4.1 | 4.6 | -0.5 | -0.003 |

**Table 12: Souping PM as percentage of total PM emissions during Notch 1**

| Locomotive | Notch 1 PM Emissions (g/min) | | | Soup as Pct of Total |
|---|---|---|---|---|
| | Direct | Soup | Total | |
| **ALECS Inlet** | | | | |
| Dash 8 | 4.64 | 1.61 | 6.25 | 26% |
| GP 38 | 0.32 | 0.18 | 0.50 | 37% |
| **ALECS Outlet** | | | | |
| Dash 8 | 0.07 | 0.025 | 0.09 | 27% |
| GP 38 | 0.03 | -0.001 | 0.03 | -2% |

As Tables 11 and 12 show, the ALECS system was nearly 100% effective in controlling the incremental emissions due to soup buildup and re-entrainment. This suggests that it would be good policy, after a prolonged idle period, to run locomotives at Notch 3 for a few minutes before disconnecting them from the ALECS system.

### 3.5 RAVEM MEASUREMENTS IN THE LOCOMOTIVE STACK VS. ALECS INLET

To determine whether the emission measurements at the ALECS inlet had been affected by the passage of exhaust through the exhaust duct, RAVEM emission measurements were also conducted at the locomotive exhaust stack. In the case of the Dash 8, these measurements faced a number of complications. First, the exhaust composition is not homogeneous in the exhaust stack. As can be seen in Figure 4, the venturi effect of the exhaust velocity provides suction for the crankcase vent tube (right) and three tubes coming from the air cleaner. The function of these latter tubes is unknown, but they appear to carry a significant flow of air into the exhaust. The RAVEM probe was located on the centerline between the left and right sides, but could still have been affected by special variation in the velocity and chemical composition of the exhaust.

Installation of the RAVEM probe on the GP 38 was also complicated, since the GP38 has two round exhaust stacks. This required the use of two probes, with the raw exhaust lines connected together in a T configuration. Two of the four delta-pressure lines from the isokinetic sampler were connected to each probe to maintain approximately isokinetic sampling, but this arrangement would not have been able to compensate for any substantial difference in exhaust velocity between the two stacks.

**Figure 4: View into the Dash 8 exhaust stack, showing the crankcase vent and air filter suction tubes**

Another complicating factor was the interaction between the ALECS hoods and the sample lines and delta-pressure lines of the RAVEM system. The magnets on the hood hold it to the locomotive with considerable force, and this resulted in the crushing of the sample or delta-pressure lines on several occasions. In retrospect, a preferable approach would have been to install the probes in the hood of the ALECS system instead of directly in the stack.

Table 13 compares the NO, PM, and $CO_2$ emissions measured at the locomotive stack and at the inlet to the ALECS system. Because of the uncertainties involved in sampling directly from the stacks, it is more useful to compare the pollutant-to-$CO_2$ ratios measured in these two locations rather than the mass emissions as such. As Table 13 shows, the NOx to $CO_2$ ratios measured in the two locations generally agree well. However, the PM-to-$CO_2$ ratio measured in the stack is generally lower than that in measured at the ALECS inlet.

## Table 13: RAVEM measurements at the locomotive stack vs. inlet emissions

| Test No. | Inlet (g/min) | | | Stack (g/min) | | | $PM/CO_2$ | | $NOx/CO_2$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $CO_2$ | NOx | PM | $CO_2$ | NOx | PM | Inlet | Stack | Inlet | Stack |
| **DASH 8 - NOTCH 1** | | | | | | | | | | |
| T0958 | 3865 | 93.7 | 4.72 | 662 | 17.8 | 0.60 | 1.22 | 0.91 | 24.24 | 26.81 |
| **DASH 8 SOUPING TEST** | | | | | | | | | | |
| T0959 | 10943 | 264.9 | 31.64 | 4465 | 110.2 | 1.16 | 2.89 | 0.26 | 24.21 | 24.68 |
| **DASH 8 MOVING TEST** | | | | | | | | | | |
| T0980 | 2116 | 51.0 | 5.62 | 2980 | 72.8 | 6.59 | 2.66 | 2.21 | 24.12 | 24.43 |
| T0981 | 2306 | 52.8 | 3.09 | 3617 | 88.9 | 4.11 | 1.34 | 1.14 | 22.90 | 24.57 |
| T0982 | 969 | 25.5 | 1.02 | 2906 | 65.3 | 2.06 | 1.06 | 0.71 | 26.37 | 22.45 |
| **GP 38 - NOTCH 5** | | | | | | | | | | |
| T0964 | 9754 | 200.6 | 5.46 | #N/A | #N/A | 5.16 | 0.56 | #N/A | 20.56 | #N/A |
| T0965 | 10036 | 208.6 | 4.52 | 9412 | 162.1 | 3.70 | 0.45 | 0.39 | 20.79 | 17.22 |
| T0966 | 9816 | 204.5 | 4.01 | 4249 | 80.2 | 2.41 | 0.41 | 0.57 | 20.83 | 18.87 |
| **GP 38 - NOTCH 1** | | | | | | | | | | |
| T0962 | 1600 | 26.7 | 0.40 | 1162 | 18.8 | 0.21 | 0.25 | 0.18 | 16.70 | 16.22 |
| **GP 38 SOUPING BASELINE** | | | | | | | | | | |
| T0961 | 6085 | 114.1 | 1.92 | 4778 | 81.1 | 1.43 | 0.32 | 0.30 | 18.76 | 16.97 |
| **GP 38 SOUPING TEST** | | | | | | | | | | |
| T0963 | 6222 | 108.9 | 3.50 | 3594 | 60.1 | 2.56 | 0.56 | 0.71 | 17.50 | 16.72 |
| **GP 38 MOVING TEST** | | | | | | | | | | |
| T0976 | 1072 | 21.6 | 0.17 | 620 | 11.9 | 0.22 | 0.16 | 0.36 | 20.11 | 19.16 |
| T0978 | 884 | 23.4 | 0.00 | 750 | 14.9 | 0.23 | 0.00 | 0.30 | 26.46 | 19.80 |
| T0979 | 739 | 20.6 | 0.52 | 759 | 14.7 | 0.25 | 0.71 | 0.33 | 27.89 | 19.41 |

# 4. NOISE MEASUREMENTS

Locomotive noise emissions were measured using a Larson-Davis model 720 sound level meter. The meter was calibrated before use. The time-weighted average equivalent sound level (Leq) was measured over a three minute period, using the "A" frequency weighting filter. Emission measurements were made at a point 30 meters away from the locomotive, and along a line passing through the center of the locomotive perpendicular to the track, as specified in 40 CFR 201.20 et seq. To minimize the effects of background noise, measurements were taken only when no trains were operating nearby. However, it was not possible to eliminate the noise from other locomotives idling in the vicinity.

The purpose of the noise measurements was to assess the noise reduction due to the exhaust hood, especially the noise experienced during power tests at Notch 8. Noise was measured both with the hood in place, and with the hood raised approximately two feet above the exhaust stack. The results are summarized in Table 14. Due to the silencing effect of its turbocharger, the Dash 8 had noticeably less exhaust noise than the GP38. For the GP38 at full power, and the Dash 8 at part-load, the exhaust hood reduced the average sound level by 6.8 dB(A). Since the dB measurement is logarithmic, this is equivalent to an actual 79% reduction in sound power level. For the Dash 8 at full load, non-exhaust sources such as cooling fans contributed significantly to the overall noise level, so that the percentage reduction was less.

**Table 14: Noise measurements with and without the hood in place**

| | **Leq dB(a)** | | | **Pct Red. In** |
|---|---|---|---|---|
| | **w/o Hood** | **w Hood** | **Reduction** | **Sound Energy** |
| **Dash 8** | | | | |
| Notch 8 | 87.0 | 81.7 | 5.3 | 70% |
| Notch 5 | 84.5 | 77.7 | 6.8 | 79% |
| **GP 38** | | | | |
| Notch 8 | 91.6 | 84.8 | 6.8 | 79% |

# 5. REFERENCES

[1] California Air Resources Board, Roseville Railyard Study, October, 2004.

[2] C.S. Weaver and L.E. Petty, Start-Up and Idling Emissions from Two Locomotives, report under South Coast Air Quality Management District contract No. 00112, Engine, Fuel, and Emissions Engineering, Inc. January 16, 2006.

# Appendix C. Laboratory Report of Fuel Analysis

**Saybolt**
A CORE LABORATORIES COMPANY

SAYBOLT LP
21730 S. Wilmington Avenue
Suite 201
Carson, CA 90810
310-518-4400 Telephone
310-518-4455 Facsimile

**Fast To The Point**

**Saybolt LP**

# Certificate of Analysis

ENGING, FUEL & EMISSIONS ENGINEERING, INC.
LARRY PETTY
3215 LUYUNG DRIVE
RANCHO CORDOVA, CA 95742

**ORIGINAL**

| | | | |
|---|---|---|---|
| Report Date: | 9/30/2006 | Date Sampled: | |
| Job No: | 13091-00002913 | Product: | Diesel Fuel |
| Sample Number: | 601719-01 | Location: | Rancho Cordova, CA |
| Client Ref: | | Sample ID: | Desl- 8 # 1 |
| | | Vessel: | |

| Test | Method | Result | Units |
|---|---|---|---|
| **Carbon/Hydrogen /Nitrogen Content** | | | |
| Carbon Content | ASTM D-5291M | 86.00 | wt% |
| Hydrogen Content | ASTM D-5291M | 13.33 | wt% |
| Nitrogen Content | ASTM D-5291M | 0.05 | wt% |
| Total Sulfur | ASTM D-4294 | 0.060 | wt% |

*Analysis results for D5291M are submitted by a third party laboratory. Saybolt was not present whilst the analysis was carried out, and has signed for receipt only with no liability accepted.

**Approved By:** Signature On File
Ken Nabl
Laboratory Manager

**Saybolt**
A CORE LABORATORIES COMPANY

SAYBOLT LP
21730 S. Wilmington Avenue
Suite 201
Carson, CA 90810
310-518-4400 Telephone
310-518-4455 Facsimile

**Fast To The Point**

**Saybolt LP**

# Certificate of Analysis

ENGING, FUEL & EMISSIONS ENGINEERING, INC.
LARRY PETTY
3215 LUYUNG DRIVE
RANCHO CORDOVA, CA 95742

| | | | |
|---|---|---|---|
| | | Date Sampled: | |
| Report Date: | 9/30/2006 | Product: | Diesel Fuel |
| Job No: | 13091-00002913 | Location: | Rancho Cordova, CA |
| Sample Number: | 601719-02 | Sample ID: | TP38 |
| Client Ref: | | Vessel: | |

| Test | Method | Result | Units |
|---|---|---|---|
| **Carbon/Hydrogen /Nitrogen Content** | | | |
| Carbon Content | ASTM D-5291M | 86.10 | wt% |
| Hydrogen Content | ASTM D-5291M | 13.73 | wt% |
| Nitrogen Content | ASTM D-5291M | 0.06 | wt% |
| Total Sulfur | ASTM D-4294 | <0.0150 | wt% |

*Analysis results for D5291M are submitted by a third party laboratory. Saybolt was not present whilst the analysis was carried out, and has signed for receipt only with no liability accepted.

**Approved By:** Signature On File
Ken Nabl
Laboratory Manager

# Appendix D. Laboratory Reports on Solid and Wastewater Analyses

**CAL TECH Environmental Laboratories**
6814 Rosecrans Avenue, Paramount, CA 90723-3146
Telephone: (562) 272-2700 Fax: (562) 272-2789

# ANALYTICAL RESULTS*

**CTEL Project No:** CT-0701092
**Client Name:** ACTI
18414 S. Santa Fe Ave.
Rancho Dominguez, CA 90221
**Phone:(310) 763-1423**
**Fax: (310) 763-9076**
**Attention:** Mr. John Powel

**Project ID:**
**Project Name:** UPRP

**Date Sampled:** 01/05/07 @ 13:00 p.m.
**Date Received:** 01/12/07 @ 17:00 p.m.
**Date Analyzed** 01/12/07 – 01/18/07
**Matrix: Solid**

| **Laboratory ID:** | 0701-092-1 | 0701-092-2 | **Method** | **Units:** | **Detection Limit** |
|---|---|---|---|---|---|
| **Client Sample ID:** | ROC #89 | R21 #7 | | | |
| **Dilution** | 100 | 100 | | | |
| Dichlorodifluoromethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Chloromethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Vinyl Chloride | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Bromomethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Chloroethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Trichlorofluoromethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Iodomethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Acetone | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,1-Dichloroethene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| t-Butyl Alcohol (TBA) | ND | ND | EPA 8260B | mg/Kg | 0.020 |
| Methylene Chloride | ND | ND | EPA 8260B | mg/Kg | 0.02 |
| Freon 113 | ND | ND | EPA 8260B | mg/Kg | 0.01 |
| Carbon disulfide | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Trans,1,2-Dichloroethene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Methyl-tert-butyl-ether(MtBE) | ND | ND | EPA 8260B | mg/Kg | 0.002 |
| 1,1-Dichloroethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Vinyl acetate | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Diisopropyl Ether (DIPE) | ND | ND | EPA 8260B | mg/Kg | 0.002 |
| Methyl Ethyl Ketone | ND | ND | EPA 8260B | mg/Kg | 0.01 |
| Cis,1,2-Dichloroethene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Bromochloromethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Chloroform | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 2,2-Dichloropropane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Ethyl-t-butyl ether (ETBE) | ND | ND | EPA 8260B | mg/Kg | 0.002 |
| 1,1,1-Trichloroethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,2-Dichloroethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,1-Dichloropropene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Carbon Tetrachloride | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Benzene | ND | ND | EPA 8260B | mg/Kg | 0.001 |
| t-Amyl Methyl Ether (TAME) | ND | ND | EPA 8260B | mg/Kg | 0.002 |
| 1,2-Dichloropropane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Trichloroethene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Dibromomethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Bromodichloromethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 2-Chloroethylvinylether | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Cis, 1,3-Dichloropropene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 4-Methyl-2-pentanone(MI) | ND | ND | EPA 8260B | mg/Kg | 0.01 |
| Trans,1,3-Dichloropropene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Toluene | ND | ND | EPA 8260B | mg/Kg | 0.001 |
| 1,1,2-Trichloroethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |

**CTEL Project No:** CT-0701092

**Project ID:**
**Project Name:** UPRP

| **Laboratory ID:**<br>**Client Sample ID:** | 0701-092-1<br>ROC #89 | 0701-092-2<br>R21 #7 | **Method** | **Units** | **Detection Limit** |
|---|---|---|---|---|---|
| 1,2-Dibromoethane(EDB) | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,3-Dichloropropane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Dibromochloromethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 2-Hexanone | ND | ND | EPA 8260B | mg/Kg | 0.01 |
| Tetrachloroethene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Chlorobenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,1,1,2-Tetrachloroethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Ethylbenzene | ND | ND | EPA 8260B | mg/Kg | 0.001 |
| m.p-Xylene | ND | ND | EPA 8260B | mg/Kg | 0.001 |
| Bromoform | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Styrene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| o-Xylene | ND | ND | EPA 8260B | mg/Kg | 0.001 |
| 1,1,2,2-Tetrachloroethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,2,3-Trichloropropane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Isopropylbenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Bromobenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 2-Chlorotoluene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| n-Propylbenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 4-Chlorotoluene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,3,5-Trimethylbenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Tert-Butylbenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,2,4-Trimethylbenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Sec-Butylbenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,3-Dichlorobenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,4-Dichlorobenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| p-Isopropyltoluene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,2-Dichlorobenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| n-Butylbenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,2 Dibromo-3-Chloropropane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,2,4-Trichlorobenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Naphthalene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,2,3-Trichlorobenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Hexachlorobutadiene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Oil & Grease | 85000 | 78000 | EPA 413.2 | mg/Kg | 10 |
| TRPH | 88000 | 80000 | EPA 418.1 | mg/Kg | 10 |

ND = Not Detected at the indicated Detection Limit

| *SURROGATE SPIKE* | % SURROGATE RECOVERY | | Control Limit |
|---|---|---|---|
| Dibromofluoromethane | 97 | 96 | 70-130 |
| 1,2 Dichloromethaned4 | 119 | 120 | 70-130 |
| Toluene-d8 | 101 | 102 | 70-130 |
| Bromofluorobenzene | 113 | 115 | 70-130 |

**CTEL Project No:** CT-0701092

**Project ID:**
**Project Name:** UPRP

| **Laboratory ID:** | 0701-092-1 | 0701-092-2 | **Method** | **Units** | **Detection Limit** |
|---|---|---|---|---|---|
| **Client Sample ID:** | ROC #89 | R21 #7 | | | |
| 1,2-Dibromoethane(EDB) | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,3-Dichloropropane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Dibromochloromethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 2-Hexanone | ND | ND | EPA 8260B | mg/Kg | 0.01 |
| Tetrachloroethene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Chlorobenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,1,1,2-Tetrachloroethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Ethylbenzene | ND | ND | EPA 8260B | mg/Kg | 0.001 |
| m.p-Xylene | ND | ND | EPA 8260B | mg/Kg | 0.001 |
| Bromoform | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Styrene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| o-Xylene | ND | ND | EPA 8260B | mg/Kg | 0.001 |
| 1,1,2,2-Tetrachloroethane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,2,3-Trichloropropane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Isopropylbenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Bromobenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 2-Chlorotoluene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| n-Propylbenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 4-Chlorotoluene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,3,5-Trimethylbenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Tert-Butylbenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,2,4-Trimethylbenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Sec-Butylbenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,3-Dichlorobenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,4-Dichlorobenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| p-Isopropyltoluene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,2-Dichlorobenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| n-Butylbenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,2 Dibromo-3-Chloropropane | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,2,4-Trichlorobenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Naphthalene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| 1,2,3-Trichlorobenzene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Hexachlorobutadiene | ND | ND | EPA 8260B | mg/Kg | 0.005 |
| Oil & Grease | 85000 | 78000 | EPA 413.2 | mg/Kg | 10 |
| TRPH | 88000 | 80000 | EPA 418.1 | mg/Kg | 10 |

ND = Not Detected at the indicated Detection Limit

| *SURROGATE SPIKE* | % SURROGATE RECOVERY | | Control Limit |
|---|---|---|---|
| Dibromofluoromethane | 97 | 96 | 70-130 |
| 1,2 Dichloromethaned4 | 119 | 120 | 70-130 |
| Toluene-d8 | 101 | 102 | 70-130 |
| Bromofluorobenzene | 113 | 115 | 70-130 |

CALIFORNIA LABORATORY SERVICES
3249 Fitzgerald Road Rancho Cordova, CA 95742

January 09, 2007

**CLS Work Order #: CPJ0336**
**COC #: 76759**

Robert Puga
ACTI
18414 So. Santa Fe Avenue
Rancho Dominguez, CA 90221

**Project Name: Alecs**

Enclosed are the results of analyses for samples received by the laboratory on 10/09/06 17:35. Samples were analyzed pursuant to client request utilizing EPA or other ELAP approved methodologies. I certify that the results are in compliance both technically and for completeness.

Analytical results are attached to this letter. Please call if we can provide additional assistance.

Sincerely,

James Liang, Ph.D.
Laboratory Director

CA DOHS ELAP Accreditation/Registration number 1233

ACTI
18414 So. Santa Fe Avenue
Rancho Dominguez, CA 90221

Project: Alecs
Project Number: [none]
Project Manager: Robert Puga

**CLS Work Order #: CPJ0336**
COC #: 76759

## Conventional Chemistry Parameters by APHA/EPA Methods

**East Side Tank (CPJ0336-01) Water Sampled: 10/09/06 16:35 Received: 10/09/06 17:35**

| Analyte | Result | Reporting Limit | Units | Dilution | Batch | Prepared | Analyzed | Method | Notes |
|---|---|---|---|---|---|---|---|---|---|
| **Specific Conductance (EC)** | **2300** | 1.0 | µmhos/cm | 1 | CP07821 | 10/10/06 | 10/10/06 | EPA 120.1 | |
| **Fluoride** | **2.5** | 2.0 | mg/L | 20 | CP07801 | 10/10/06 | 10/10/06 | EPA 300.0 | |
| **Chloride** | **17** | 10 | " | " | " | " | " | " | |
| **Nitrite as NO2** | **500** | 50 | " | 100 | " | " | " | " | |
| **Bromide** | **0.59** | 0.10 | " | 1 | " | " | " | " | |
| **Nitrate as NO3** | **1.5** | 0.50 | " | " | " | " | " | " | |
| **Sulfate as SO4** | **260** | 10 | " | 20 | " | " | " | " | |
| **Hexane Extractable Material (HEM)** | **33** | 5.0 | " | 1 | CP07807 | 10/10/06 | 10/10/06 | EPA 1664 | |
| **pH** | **8.58** | 0.001 | pH Units | " | CP07805 | 10/10/06 | 10/10/06 | EPA 150.1 | |
| Orthophosphate as PO4 | ND | 0.15 | mg/L | " | CP07829 | 10/10/06 | 10/10/06 | EPA 365.2 | |
| **Total Dissolved Solids** | **1800** | 10 | " | " | CP07817 | 10/10/06 | 10/11/06 | EPA 160.1 | |
| **Total Suspended Solids** | **34** | 5.0 | " | " | CP07816 | 10/10/06 | 10/11/06 | EPA 160.2 | |

**West Side Tank (CPJ0336-02) Water Sampled: 10/09/06 16:40 Received: 10/09/06 17:35**

| Analyte | Result | Reporting Limit | Units | Dilution | Batch | Prepared | Analyzed | Method | Notes |
|---|---|---|---|---|---|---|---|---|---|
| **Specific Conductance (EC)** | **2200** | 1.0 | µmhos/cm | 1 | CP07821 | 10/10/06 | 10/10/06 | EPA 120.1 | |
| **Fluoride** | **2.0** | 1.0 | mg/L | 10 | CP07801 | 10/10/06 | 10/10/06 | EPA 300.0 | |
| **Chloride** | **12** | 5.0 | " | " | " | " | " | " | |
| **Nitrite as NO2** | **570** | 50 | " | 100 | " | " | " | " | |
| **Bromide** | **0.38** | 0.10 | " | 1 | " | " | " | " | |
| **Nitrate as NO3** | **1.9** | 0.50 | " | " | " | " | " | " | |
| **Sulfate as SO4** | **210** | 5.0 | " | 10 | " | " | " | " | |
| **Hexane Extractable Material (HEM)** | **73** | 7.6 | " | 1 | CP07807 | 10/10/06 | 10/10/06 | EPA 1664 | |
| **pH** | **8.56** | 0.001 | pH Units | " | CP07805 | 10/10/06 | 10/10/06 | EPA 150.1 | |
| Orthophosphate as PO4 | ND | 0.15 | mg/L | " | CP07829 | 10/10/06 | 10/10/06 | EPA 365.2 | |
| **Total Dissolved Solids** | **1600** | 10 | " | " | CP07817 | 10/10/06 | 10/11/06 | EPA 160.1 | |
| **Total Suspended Solids** | **34** | 5.0 | " | " | CP07816 | 10/10/06 | 10/11/06 | EPA 160.2 | |

| | | |
|---|---|---|
| ACTI<br>18414 So. Santa Fe Avenue<br>Rancho Dominguez, CA 90221 | Project: Alecs<br>Project Number: [none]<br>Project Manager: Robert Puga | **CLS Work Order #: CPJ0336**<br>COC #: 76759 |

## Metals by EPA 200 Series Methods

| Analyte | Result | Reporting Limit | Units | Dilution | Batch | Prepared | Analyzed | Method | Notes |
|---|---|---|---|---|---|---|---|---|---|
| **East Side Tank (CPJ0336-01) Water Sampled: 10/09/06 16:35 Received: 10/09/06 17:35** | | | | | | | | | |
| **Aluminum** | **110** | 50 | µg/L | 1 | CP07833 | 10/10/06 | 10/11/06 | EPA 200.7 | |
| Antimony | ND | 50 | " | " | " | " | " | " | |
| Arsenic | ND | 100 | " | " | " | " | " | " | |
| **Barium** | **35** | 20 | " | " | " | " | " | " | |
| Beryllium | ND | 5.0 | " | " | " | " | " | " | |
| Cadmium | ND | 10 | " | " | " | " | " | " | |
| **Calcium** | **45000** | 1000 | " | " | " | " | " | " | |
| **Chromium** | **11** | 10 | " | " | " | " | " | " | |
| Cobalt | ND | 20 | " | " | " | " | " | " | |
| Copper | ND | 10 | " | " | " | " | " | " | |
| **Iron** | **100** | 100 | " | " | " | " | " | " | |
| Lead | ND | 50 | " | " | " | " | " | " | |
| **Magnesium** | **3100** | 1000 | " | " | " | " | " | " | |
| Manganese | ND | 20 | " | " | " | " | " | " | |
| **Molybdenum** | **300** | 20 | " | " | " | " | " | " | |
| Nickel | ND | 20 | " | " | " | " | " | " | |
| **Potassium** | **2400** | 1000 | " | " | " | " | " | " | |
| Selenium | ND | 100 | " | " | " | " | " | " | |
| Silver | ND | 10 | " | " | " | " | " | " | |
| **Sodium** | **510000** | 1000 | " | " | " | " | " | " | |
| **Strontium** | **130** | 20 | " | " | " | " | " | " | |
| Thallium | ND | 200 | " | " | " | " | " | " | |
| Vanadium | ND | 20 | " | " | " | " | " | " | |
| **Zinc** | **75** | 20 | " | " | " | " | " | " | |
| **Boron** | **250** | 50 | " | " | " | " | " | " | |
| Tin | ND | 100 | " | " | " | " | " | " | |
| Titanium | ND | 50 | " | " | " | " | " | " | |

ACTI
18414 So. Santa Fe Avenue
Rancho Dominguez, CA 90221

Project: Alecs
Project Number: [none]
Project Manager: Robert Puga

**CLS Work Order #: CPJ0336**
COC #: 76759

## Conventional Chemistry Parameters by APHA/EPA Methods

| Analyte | Result | Reporting Limit | Units | Dilution | Batch | Prepared | Analyzed | Method | Notes |
|---|---|---|---|---|---|---|---|---|---|
| **East Side Tank (CPJ0336-01) Water** | **Sampled: 10/09/06 16:35** | **Received: 10/09/06 17:35** | | | | | | | |
| **Specific Conductance (EC)** | **2300** | 1.0 | µmhos/cm | 1 | CP07821 | 10/10/06 | 10/10/06 | EPA 120.1 | |
| **Fluoride** | **2.5** | 2.0 | mg/L | 20 | CP07801 | 10/10/06 | 10/10/06 | EPA 300.0 | |
| **Chloride** | **17** | 10 | " | " | " | " | " | " | |
| **Nitrite as NO2** | **500** | 50 | " | 100 | " | " | " | " | |
| **Bromide** | **0.59** | 0.10 | " | 1 | " | " | " | " | |
| **Nitrate as NO3** | **1.5** | 0.50 | " | " | " | " | " | " | |
| **Sulfate as SO4** | **260** | 10 | " | 20 | " | " | " | " | |
| **Hexane Extractable Material (HEM)** | **33** | 5.0 | " | 1 | CP07807 | 10/10/06 | 10/10/06 | EPA 1664 | |
| **pH** | **8.58** | 0.001 | pH Units | " | CP07805 | 10/10/06 | 10/10/06 | EPA 150.1 | |
| Orthophosphate as PO4 | ND | 0.15 | mg/L | " | CP07829 | 10/10/06 | 10/10/06 | EPA 365.2 | |
| **Total Dissolved Solids** | **1800** | 10 | " | " | CP07817 | 10/10/06 | 10/11/06 | EPA 160.1 | |
| **Total Suspended Solids** | **34** | 5.0 | " | " | CP07816 | 10/10/06 | 10/11/06 | EPA 160.2 | |
| **West Side Tank (CPJ0336-02) Water** | **Sampled: 10/09/06 16:40** | **Received: 10/09/06 17:35** | | | | | | | |
| **Specific Conductance (EC)** | **2200** | 1.0 | µmhos/cm | 1 | CP07821 | 10/10/06 | 10/10/06 | EPA 120.1 | |
| **Fluoride** | **2.0** | 1.0 | mg/L | 10 | CP07801 | 10/10/06 | 10/10/06 | EPA 300.0 | |
| **Chloride** | **12** | 5.0 | " | " | " | " | " | " | |
| **Nitrite as NO2** | **570** | 50 | " | 100 | " | " | " | " | |
| **Bromide** | **0.38** | 0.10 | " | 1 | " | " | " | " | |
| **Nitrate as NO3** | **1.9** | 0.50 | " | " | " | " | " | " | |
| **Sulfate as SO4** | **210** | 5.0 | " | 10 | " | " | " | " | |
| **Hexane Extractable Material (HEM)** | **73** | 7.6 | " | 1 | CP07807 | 10/10/06 | 10/10/06 | EPA 1664 | |
| **pH** | **8.56** | 0.001 | pH Units | " | CP07805 | 10/10/06 | 10/10/06 | EPA 150.1 | |
| Orthophosphate as PO4 | ND | 0.15 | mg/L | " | CP07829 | 10/10/06 | 10/10/06 | EPA 365.2 | |
| **Total Dissolved Solids** | **1600** | 10 | " | " | CP07817 | 10/10/06 | 10/11/06 | EPA 160.1 | |
| **Total Suspended Solids** | **34** | 5.0 | " | " | CP07816 | 10/10/06 | 10/11/06 | EPA 160.2 | |

CALIFORNIA LABORATORY SERVICES
3249 Fitzgerald Road Rancho Cordova, CA 95742

January 09, 2007

**CLS Work Order #: CPJ0336**
**COC #: 76759**

Robert Puga
ACTI
18414 So. Santa Fe Avenue
Rancho Dominguez, CA 90221

**Project Name: Alecs**

Enclosed are the results of analyses for samples received by the laboratory on 10/09/06 17:35. Samples were analyzed pursuant to client request utilizing EPA or other ELAP approved methodologies. I certify that the results are in compliance both technically and for completeness.

Analytical results are attached to this letter. Please call if we can provide additional assistance.

Sincerely,

James Liang, Ph.D.
Laboratory Director

CA DOHS ELAP Accreditation/Registration number 1233

| | | |
|---|---|---|
| ACTI<br>18414 So. Santa Fe Avenue<br>Rancho Dominguez, CA 90221 | Project: Alecs<br>Project Number: [none]<br>Project Manager: Robert Puga | **CLS Work Order #: CPJ0336**<br>COC #: 76759 |

## Conventional Chemistry Parameters by APHA/EPA Methods - Quality Control

| Analyte | Result | Reporting Limit | Units | Spike Level | Source Result | %REC | %REC Limits | RPD | RPD Limit | Notes |
|---|---|---|---|---|---|---|---|---|---|---|
| **Batch CP07801 - General Prep** | | | | | | | | | | |
| **Matrix Spike Dup (CP07801-MSD1)** | | **Source: CPJ0343-01** | | Prepared & Analyzed: 10/10/06 | | | | | | |
| Fluoride | 2.34 | 0.10 | mg/L | 2.00 | 0.19 | 108 | 75-125 | 4.37 | 25 | |
| Chloride | 9.24 | 0.50 | " | 2.00 | 7.3 | 97.0 | 75-125 | 2.08 | 25 | |
| Nitrite as NO2 | 2.02 | 0.50 | " | 2.00 | ND | 101 | 75-125 | 4.04 | 25 | |
| Bromide | 2.11 | 0.10 | " | 2.00 | ND | 106 | 75-125 | 3.37 | 25 | |
| Nitrate as NO3 | 2.14 | 0.50 | " | 2.00 | ND | 107 | 75-125 | 3.33 | 25 | |
| Sulfate as SO4 | 17.2 | 0.50 | " | 5.00 | 12 | 104 | 75-125 | 2.35 | 25 | |
| **Batch CP07807 - Solvent Extract** | | | | | | | | | | |
| **Blank (CP07807-BLK1)** | | | | Prepared & Analyzed: 10/10/06 | | | | | | |
| Hexane Extractable Material (HEM) | ND | 5.0 | mg/L | | | | | | | |
| **LCS (CP07807-BS1)** | | | | Prepared & Analyzed: 10/10/06 | | | | | | |
| Hexane Extractable Material (HEM) | 41.1 | 5.0 | mg/L | 40.0 | | 103 | 80-120 | | 20 | |
| **LCS Dup (CP07807-BSD1)** | | | | Prepared & Analyzed: 10/10/06 | | | | | | |
| Hexane Extractable Material (HEM) | 41.3 | 5.0 | mg/L | 40.0 | | 103 | 80-120 | 0.485 | 20 | |
| **Batch CP07816 - General Preparation** | | | | | | | | | | |
| **Blank (CP07816-BLK1)** | | | | Prepared: 10/10/06 Analyzed: 10/11/06 | | | | | | |
| Total Suspended Solids | ND | 5.0 | mg/L | | | | | | | |
| **Batch CP07817 - General Preparation** | | | | | | | | | | |
| **Blank (CP07817-BLK1)** | | | | Prepared: 10/10/06 Analyzed: 10/11/06 | | | | | | |
| Total Dissolved Solids | ND | 10 | mg/L | | | | | | | |

ACTI
18414 So. Santa Fe Avenue
Rancho Dominguez, CA 90221

Project: Alecs
Project Number: [none]
Project Manager: Robert Puga

**CLS Work Order #: CPJ0336**
COC #: 76759

## Conventional Chemistry Parameters by APHA/EPA Methods - Quality Control

| Analyte | Result | Reporting Limit | Units | Spike Level | Source Result | %REC | %REC Limits | RPD | RPD Limit | Notes |
|---|---|---|---|---|---|---|---|---|---|---|
| **Batch CP07821 - General Preparation** | | | | | | | | | | |
| **Blank (CP07821-BLK1)** | | | | Prepared & Analyzed: 10/10/06 | | | | | | |
| Specific Conductance (EC) | ND | 1.0 | µmhos/cm | | | | | | | |
| **Batch CP07829 - General Preparation** | | | | | | | | | | |
| **Blank (CP07829-BLK1)** | | | | Prepared & Analyzed: 10/10/06 | | | | | | |
| Orthophosphate as PO4 | ND | 0.15 | mg/L | | | | | | | |
| **LCS (CP07829-BS1)** | | | | Prepared & Analyzed: 10/10/06 | | | | | | |
| Orthophosphate as PO4 | 0.947 | 0.15 | mg/L | 0.918 | | 103 | 80-120 | | 20 | |
| **LCS Dup (CP07829-BSD1)** | | | | Prepared & Analyzed: 10/10/06 | | | | | | |
| Orthophosphate as PO4 | 0.907 | 0.15 | mg/L | 0.918 | | 98.8 | 80-120 | 4.31 | 20 | |
| **Matrix Spike (CP07829-MS1)** | **Source: CPJ0342-01** | | | Prepared & Analyzed: 10/10/06 | | | | | | |
| Orthophosphate as PO4 | 0.947 | 0.15 | mg/L | 0.918 | 0.013 | 102 | 75-125 | | 25 | |
| **Matrix Spike Dup (CP07829-MSD1)** | **Source: CPJ0342-01** | | | Prepared & Analyzed: 10/10/06 | | | | | | |
| Orthophosphate as PO4 | 0.943 | 0.15 | mg/L | 0.918 | 0.013 | 101 | 75-125 | 0.423 | 25 | |

ACTI
18414 So. Santa Fe Avenue
Rancho Dominguez, CA 90221

Project: Alecs
Project Number: [none]
Project Manager: Robert Puga

**CLS Work Order #: CPJ0336**
COC #: 76759

## Metals by EPA 200 Series Methods - Quality Control

| Analyte | Result | Reporting Limit | Units | Spike Level | Source Result | %REC | %REC Limits | RPD | RPD Limit | Notes |
|---|---|---|---|---|---|---|---|---|---|---|
| **Batch CP07833 - EPA 3010A** | | | | | | | | | | |
| **Blank (CP07833-BLK1)** | | | | Prepared & Analyzed: 10/10/06 | | | | | | |
| Aluminum | ND | 50 | µg/L | | | | | | | |
| Antimony | ND | 50 | " | | | | | | | |
| Arsenic | ND | 100 | " | | | | | | | |
| Barium | ND | 20 | " | | | | | | | |
| Beryllium | ND | 5.0 | " | | | | | | | |
| Cadmium | ND | 10 | " | | | | | | | |
| Calcium | ND | 1000 | " | | | | | | | |
| Chromium | ND | 10 | " | | | | | | | |
| Cobalt | ND | 20 | " | | | | | | | |
| Copper | ND | 10 | " | | | | | | | |
| Iron | ND | 100 | " | | | | | | | |
| Lead | ND | 50 | " | | | | | | | |
| Magnesium | ND | 1000 | " | | | | | | | |
| Manganese | ND | 20 | " | | | | | | | |
| Molybdenum | ND | 20 | " | | | | | | | |
| Nickel | ND | 20 | " | | | | | | | |
| Potassium | ND | 1000 | " | | | | | | | |
| Selenium | ND | 100 | " | | | | | | | |
| Silver | ND | 10 | " | | | | | | | |
| Sodium | ND | 1000 | " | | | | | | | |
| Strontium | ND | 20 | " | | | | | | | |
| Thallium | ND | 200 | " | | | | | | | |
| Vanadium | ND | 20 | " | | | | | | | |
| Zinc | ND | 20 | " | | | | | | | |
| Boron | ND | 50 | " | | | | | | | |
| Tin | ND | 100 | " | | | | | | | |
| Titanium | ND | 50 | " | | | | | | | |

ACTI
18414 So. Santa Fe Avenue
Rancho Dominguez, CA 90221

Project: Alecs
Project Number: [none]
Project Manager: Robert Puga

**CLS Work Order #: CPJ0336**
COC #: 76759

## Metals by EPA 200 Series Methods - Quality Control

| Analyte | Result | Reporting Limit | Units | Spike Level | Source Result | %REC | %REC Limits | RPD | RPD Limit | Notes |
|---|---|---|---|---|---|---|---|---|---|---|
| **Batch CP07833 - EPA 3010A** | | | | | | | | | | |
| **LCS (CP07833-BS1)** | | | | Prepared & Analyzed: 10/10/06 | | | | | | |
| Aluminum | 1720 | 50 | µg/L | 2000 | | 86.0 | 80-120 | | 20 | |
| Antimony | 418 | 50 | " | 500 | | 83.6 | 80-120 | | 20 | |
| Arsenic | 2260 | 100 | " | 2000 | | 113 | 80-120 | | 20 | |
| Barium | 1840 | 20 | " | 2000 | | 92.0 | 80-120 | | 20 | |
| Beryllium | 44.3 | 5.0 | " | 50.0 | | 88.6 | 80-120 | | 20 | |
| Cadmium | 43.9 | 10 | " | 50.0 | | 87.8 | 80-120 | | 20 | |
| Calcium | 8690 | 1000 | " | 10000 | | 86.9 | 80-120 | | 20 | |
| Chromium | 190 | 10 | " | 200 | | 95.0 | 80-120 | | 20 | |
| Cobalt | 455 | 20 | " | 500 | | 91.0 | 80-120 | | 20 | |
| Copper | 235 | 10 | " | 250 | | 94.0 | 80-120 | | 20 | |
| Iron | 890 | 100 | " | 1000 | | 89.0 | 80-120 | | 20 | |
| Lead | 463 | 50 | " | 500 | | 92.6 | 80-120 | | 20 | |
| Magnesium | 8970 | 1000 | " | 10000 | | 89.7 | 80-120 | | 20 | |
| Manganese | 452 | 20 | " | 500 | | 90.4 | 80-120 | | 20 | |
| Molybdenum | 455 | 20 | " | 500 | | 91.0 | 80-120 | | 20 | |
| Nickel | 440 | 20 | " | 500 | | 88.0 | 80-120 | | 20 | |
| Potassium | 9120 | 1000 | " | 10000 | | 91.2 | 80-120 | | 20 | |
| Selenium | 1790 | 100 | " | 2000 | | 89.5 | 80-120 | | 20 | |
| Silver | 46.5 | 10 | " | 50.0 | | 93.0 | 80-120 | | 20 | |
| Sodium | 9120 | 1000 | " | 10000 | | 91.2 | 80-120 | | 20 | |
| Strontium | 464 | 20 | " | 500 | | 92.8 | 80-120 | | 20 | |
| Thallium | 1720 | 200 | " | 2000 | | 86.0 | 80-120 | | 20 | |
| Vanadium | 457 | 20 | " | 500 | | 91.4 | 80-120 | | 20 | |
| Zinc | 473 | 20 | " | 500 | | 94.6 | 80-120 | | 20 | |
| Boron | 2240 | 50 | " | 2500 | | 89.6 | 80-120 | | 20 | |
| Tin | 1970 | 100 | " | 2000 | | 98.5 | 80-120 | | 20 | |
| Titanium | 1820 | 50 | " | 2000 | | 91.0 | 80-120 | | 20 | |

| | | |
|---|---|---|
| ACTI<br>18414 So. Santa Fe Avenue<br>Rancho Dominguez, CA 90221 | Project: Alecs<br>Project Number: [none]<br>Project Manager: Robert Puga | **CLS Work Order #: CPJ0336**<br>COC #: 76759 |

## Metals by EPA 200 Series Methods - Quality Control

| Analyte | Result | Reporting Limit | Units | Spike Level | Source Result | %REC | %REC Limits | RPD | RPD Limit | Notes |
|---|---|---|---|---|---|---|---|---|---|---|
| **Batch CP07833 - EPA 3010A** | | | | | | | | | | |
| **LCS Dup (CP07833-BSD1)** | | | | Prepared & Analyzed: 10/10/06 | | | | | | |
| Aluminum | 1710 | 50 | µg/L | 2000 | | 85.5 | 80-120 | 0.583 | 20 | |
| Antimony | 431 | 50 | " | 500 | | 86.2 | 80-120 | 3.06 | 20 | |
| Arsenic | 2250 | 100 | " | 2000 | | 112 | 80-120 | 0.443 | 20 | |
| Barium | 1830 | 20 | " | 2000 | | 91.5 | 80-120 | 0.545 | 20 | |
| Beryllium | 43.3 | 5.0 | " | 50.0 | | 86.6 | 80-120 | 2.28 | 20 | |
| Cadmium | 41.0 | 10 | " | 50.0 | | 82.0 | 80-120 | 6.83 | 20 | |
| Calcium | 8580 | 1000 | " | 10000 | | 85.8 | 80-120 | 1.27 | 20 | |
| Chromium | 189 | 10 | " | 200 | | 94.5 | 80-120 | 0.528 | 20 | |
| Cobalt | 451 | 20 | " | 500 | | 90.2 | 80-120 | 0.883 | 20 | |
| Copper | 233 | 10 | " | 250 | | 93.2 | 80-120 | 0.855 | 20 | |
| Iron | 883 | 100 | " | 1000 | | 88.3 | 80-120 | 0.790 | 20 | |
| Lead | 458 | 50 | " | 500 | | 91.6 | 80-120 | 1.09 | 20 | |
| Magnesium | 8900 | 1000 | " | 10000 | | 89.0 | 80-120 | 0.783 | 20 | |
| Manganese | 447 | 20 | " | 500 | | 89.4 | 80-120 | 1.11 | 20 | |
| Molybdenum | 457 | 20 | " | 500 | | 91.4 | 80-120 | 0.439 | 20 | |
| Nickel | 440 | 20 | " | 500 | | 88.0 | 80-120 | 0.00 | 20 | |
| Potassium | 9110 | 1000 | " | 10000 | | 91.1 | 80-120 | 0.110 | 20 | |
| Selenium | 1780 | 100 | " | 2000 | | 89.0 | 80-120 | 0.560 | 20 | |
| Silver | 46.0 | 10 | " | 50.0 | | 92.0 | 80-120 | 1.08 | 20 | |
| Sodium | 9030 | 1000 | " | 10000 | | 90.3 | 80-120 | 0.992 | 20 | |
| Strontium | 459 | 20 | " | 500 | | 91.8 | 80-120 | 1.08 | 20 | |
| Thallium | 1750 | 200 | " | 2000 | | 87.5 | 80-120 | 1.73 | 20 | |
| Vanadium | 452 | 20 | " | 500 | | 90.4 | 80-120 | 1.10 | 20 | |
| Zinc | 466 | 20 | " | 500 | | 93.2 | 80-120 | 1.49 | 20 | |
| Boron | 2220 | 50 | " | 2500 | | 88.8 | 80-120 | 0.897 | 20 | |
| Tin | 1940 | 100 | " | 2000 | | 97.0 | 80-120 | 1.53 | 20 | |
| Titanium | 1810 | 50 | " | 2000 | | 90.5 | 80-120 | 0.551 | 20 | |

## Metals by EPA 200 Series Methods - Quality Control

**Batch CP07833 - EPA 3010A**

**Matrix Spike (CP07833-MS1)** **Source: CPJ0343-01** Prepared & Analyzed: 10/10/06

| Analyte | Result | Reporting Limit | Units | Spike Level | Source Result | %REC | %REC Limits | RPD | RPD Limit | Notes |
|---|---|---|---|---|---|---|---|---|---|---|
| Aluminum | 1660 | 50 | µg/L | 2000 | ND | 83.0 | 75-125 | | 25 | |
| Antimony | 433 | 50 | " | 500 | ND | 86.6 | 75-125 | | 25 | |
| Arsenic | 2100 | 100 | " | 2000 | ND | 105 | 75-125 | | 25 | |
| Barium | 1880 | 20 | " | 2000 | 130 | 87.5 | 75-125 | | 25 | |
| Beryllium | 42.0 | 5.0 | " | 50.0 | ND | 84.0 | 75-125 | | 25 | |
| Cadmium | 35.8 | 10 | " | 50.0 | ND | 71.6 | 75-125 | | 25 | QM-7 |
| Calcium | 14800 | 1000 | " | 10000 | 7600 | 72.0 | 75-125 | | 25 | QM-7 |
| Chromium | 176 | 10 | " | 200 | ND | 88.0 | 75-125 | | 25 | |
| Cobalt | 424 | 20 | " | 500 | ND | 84.8 | 75-125 | | 25 | |
| Copper | 225 | 10 | " | 250 | ND | 90.0 | 75-125 | | 25 | |
| Iron | 2450 | 100 | " | 1000 | 1800 | 65.0 | 75-125 | | 25 | QM-7 |
| Lead | 439 | 50 | " | 500 | ND | 87.8 | 75-125 | | 25 | |
| Magnesium | 12200 | 1000 | " | 10000 | 3700 | 85.0 | 75-125 | | 25 | |
| Manganese | 889 | 20 | " | 500 | 510 | 75.8 | 75-125 | | 25 | |
| Molybdenum | 433 | 20 | " | 500 | ND | 86.6 | 75-125 | | 25 | |
| Nickel | 410 | 20 | " | 500 | ND | 82.0 | 75-125 | | 25 | |
| Potassium | 14100 | 1000 | " | 10000 | 5400 | 87.0 | 75-125 | | 25 | |
| Selenium | 1680 | 100 | " | 2000 | ND | 84.0 | 75-125 | | 25 | |
| Silver | 26.2 | 10 | " | 50.0 | 3.0 | 46.4 | 75-125 | | 25 | QM-7 |
| Sodium | 25800 | 1000 | " | 10000 | 17000 | 88.0 | 75-125 | | 25 | |
| Strontium | 546 | 20 | " | 500 | 110 | 87.2 | 75-125 | | 25 | |
| Thallium | 1700 | 200 | " | 2000 | ND | 85.0 | 75-125 | | 25 | |
| Vanadium | 427 | 20 | " | 500 | ND | 85.4 | 75-125 | | 25 | |
| Zinc | 494 | 20 | " | 500 | 60 | 86.8 | 75-125 | | 25 | |
| Boron | 2140 | 50 | " | 2500 | 32 | 84.3 | 75-125 | | 25 | |
| Tin | 1860 | 100 | " | 2000 | ND | 93.0 | 75-125 | | 25 | |
| Titanium | 1730 | 50 | " | 2000 | ND | 86.5 | 75-125 | | 25 | |

## Metals by EPA 200 Series Methods - Quality Control

| Analyte | Result | Reporting Limit | Units | Spike Level | Source Result | %REC | %REC Limits | RPD | RPD Limit | Notes |
|---|---|---|---|---|---|---|---|---|---|---|
| **Batch CP07833 - EPA 3010A** | | | | | | | | | | |
| **Matrix Spike Dup (CP07833-MSD1)** | | **Source: CPJ0343-01** | | Prepared & Analyzed: 10/10/06 | | | | | | |
| Aluminum | 1640 | 50 | µg/L | 2000 | ND | 82.0 | 75-125 | 1.21 | 25 | |
| Antimony | 430 | 50 | " | 500 | ND | 86.0 | 75-125 | 0.695 | 25 | |
| Arsenic | 2080 | 100 | " | 2000 | ND | 104 | 75-125 | 0.957 | 25 | |
| Barium | 1870 | 20 | " | 2000 | 130 | 87.0 | 75-125 | 0.533 | 25 | |
| Beryllium | 41.9 | 5.0 | " | 50.0 | ND | 83.8 | 75-125 | 0.238 | 25 | |
| Cadmium | 38.0 | 10 | " | 50.0 | ND | 76.0 | 75-125 | 5.96 | 25 | |
| Calcium | 14800 | 1000 | " | 10000 | 7600 | 72.0 | 75-125 | 0.00 | 25 | QM-7 |
| Chromium | 173 | 10 | " | 200 | ND | 86.5 | 75-125 | 1.72 | 25 | |
| Cobalt | 422 | 20 | " | 500 | ND | 84.4 | 75-125 | 0.473 | 25 | |
| Copper | 219 | 10 | " | 250 | ND | 87.6 | 75-125 | 2.70 | 25 | |
| Iron | 2440 | 100 | " | 1000 | 1800 | 64.0 | 75-125 | 0.409 | 25 | QM-7 |
| Lead | 424 | 50 | " | 500 | ND | 84.8 | 75-125 | 3.48 | 25 | |
| Magnesium | 12100 | 1000 | " | 10000 | 3700 | 84.0 | 75-125 | 0.823 | 25 | |
| Manganese | 885 | 20 | " | 500 | 510 | 75.0 | 75-125 | 0.451 | 25 | |
| Molybdenum | 429 | 20 | " | 500 | ND | 85.8 | 75-125 | 0.928 | 25 | |
| Nickel | 409 | 20 | " | 500 | ND | 81.8 | 75-125 | 0.244 | 25 | |
| Potassium | 13900 | 1000 | " | 10000 | 5400 | 85.0 | 75-125 | 1.43 | 25 | |
| Selenium | 1680 | 100 | " | 2000 | ND | 84.0 | 75-125 | 0.00 | 25 | |
| Silver | 31.2 | 10 | " | 50.0 | 3.0 | 56.4 | 75-125 | 17.4 | 25 | QM-7 |
| Sodium | 25600 | 1000 | " | 10000 | 17000 | 86.0 | 75-125 | 0.778 | 25 | |
| Strontium | 544 | 20 | " | 500 | 110 | 86.8 | 75-125 | 0.367 | 25 | |
| Thallium | 1710 | 200 | " | 2000 | ND | 85.5 | 75-125 | 0.587 | 25 | |
| Vanadium | 424 | 20 | " | 500 | ND | 84.8 | 75-125 | 0.705 | 25 | |
| Zinc | 495 | 20 | " | 500 | 60 | 87.0 | 75-125 | 0.202 | 25 | |
| Boron | 2130 | 50 | " | 2500 | 32 | 83.9 | 75-125 | 0.468 | 25 | |
| Tin | 1860 | 100 | " | 2000 | ND | 93.0 | 75-125 | 0.00 | 25 | |
| Titanium | 1720 | 50 | " | 2000 | ND | 86.0 | 75-125 | 0.580 | 25 | |

## Notes and Definitions

| | |
|---|---|
| QM-7 | The spike recovery was outside acceptance limits for the MS and/or MSD. The batch was accepted based on acceptable LCS/LCSD recovery. |
| DET | Analyte DETECTED |
| ND | Analyte NOT DETECTED at or above the reporting limit |
| NR | Not Reported |
| dry | Sample results reported on a dry weight basis |
| RPD | Relative Percent Difference |

Innovation since 1886

# Evaluation of the Advanced Maritime Emissions Control System (AMECS)

## AMECS Demonstration at the Port of Long Beach, California

**Report to**

**South Coast Air Quality Management District (SCAQMD)**
**Technology Advancement Office**
**21865 Copley Drive**
**Diamond Bar, CA 91765-4182**

**Date: 11/19/08**

**Prepared by**
**Michael Chan**
**Michael D. Jackson**
**TIAX LLC**
**20813 Stevens Creek Blvd., Suite 250**
**Cupertino, California 95014-2107**

TIAX Case D5593

## Table of Contents

## List of Tables

## List of Figures

## Executive Summary

The Port of Long Beach (the port or POLB) is a major international gateway for commerce entering California (and the United States) and one of the world's busiest seaports. The demand for goods moving through the San Pedro Bay region is expected to double before the year 2020. The POLB's ability to accommodate the growth in trade will depend upon their ability to address adverse environmental impacts on air quality. In the South Coast Air Basin, 11% of particulate matter (PM) emissions, 5% oxides of nitrogen (NOx) emissions, and 32% oxides of sulfur (SOx) emissions are attributed to port-related emission from the POLB (Starcrest, June 2008).

The POLB's shipping terminals import and export more than $100 billion worth of goods and products every year to the region and nation.[1]

One of the major contributors to port-related emissions is ocean-going vessels. While docked at the port, the ocean-going vessels shut off their propulsion engines, but use auxiliary diesel engines to power refrigeration, lights, pumps and other functions (activities commonly called 'hotelling'). Auxiliary boilers, also a significant source of particulate matter, heat the very viscous heavy fuel oil (often referred to as residual fuel or bunker fuel) that can be used for propulsion and/or auxiliary engines, heating of water for crew/passengers, and/or space heating of cabins while docked.

Diesel engines release harmful air pollutants, comprised of gaseous and solid material. The solid material in diesel exhaust is known as particulate matter. In 1998, the California Air Resources Board (CARB) identified diesel PM as a toxic air contaminant based on its potential to cause cancer, premature death, and other health problems.

Advanced Cleanup Technologies, Incorporated (ACTI) Advanced Maritime Emissions Control System (AMECS) is designed to significantly reduce harmful exhaust pollutants from the auxiliary engines and auxiliary boilers of ocean-going vessels while at berth or anchored within the port before they are exhausted into the surrounding environment.

Testing of ACTI's AMECS was performed at the Metropolitan Stevedore, Incorporated terminal Pier G, Berth 214 in the Port of Long Beach.

Metropolitan Stevedore, Incorporated is a leading petroleum coke terminal operator and handles stevedore operations in the Port of Long Beach, Berths 212 through 214, exporting cargoes such as petroleum coke, coal, potash, borax and soda ash.

AMECS consists of two major components: a) the Exhaust Capture System (ECS), which is the interface with the ship; and b) the Emissions Treatment System (ETS). The ECS captures the exhaust from the vessel and directs it through a duct into an emissions treatment system. An induced draft fan is used to draw the exhaust from the bonnet (which is attached to the vessel's stack) through the duct and into the ETS, where sulfur dioxide ($SO_2$), particulate matter (PM), nitrogen oxides (NOx) and volatile organic compounds (VOC) are removed.

---

[1] Downloaded 10/24/08: http://www.polb.com/economics/stats/default.asp

In 2007, preliminary testing of AMECS was conducted on the Western Seattle, a Handymax class, 45,630 dwt Bulk Cargo Vessel, using an Octagonal Capture Bonnet. The successful test led to the testing of AMECS on two bulk cargo vessels, the Queen Lily (see Figure 1) and the Angela, on May 26 and July 19, 2008 respectively for this report.

**Figure 1. AMECS Attached to the Queen Lily**

Table 1 summarizes the overall average control efficiencies resulting from the demonstration testing by an independent South Coast Air Quality Management District (SCAQMD) approved testing company of AMECS at the POLB. The emission source test reports were reviewed by the South Coast Air Quality Management District and the control efficiencies represent the performance of AMECS. For the cost effectiveness analysis, the NOx control efficiency was reduced to 97.6% to conservatively account for the estimated selective catalytic reduction reactor catalyst degradation over the estimated six year catalyst life.

**Table 1. Summary of AMECS Pollutant Control Efficiencies**

| | NOx | PM | VOC | $SO_2$ | CO |
|---|---|---|---|---|---|
| **Overall Average Control Efficiency** | >99.1% | 95.0% | 96.3% | 99.8% | 43.8% |

The number of vessels serviced by each ETS is calculated based upon the peak flow rates of the auxiliary engine and auxiliary boiler. The pollutant emission rates for the auxiliary engine and auxiliary boiler for each vessel type were calculated from the average California hotelling loads and their respective emission factors. The average California hotelling times for each vessel call are given in Table 2 (CARB, June 2008). It is expected that AMECS will be installed in a location with a high berth occupancy rate to fully utilize AMECS' capacity. Conservatively, for this analysis, the dock (and hence AMECS) utilization is estimated at 65%. Both the Barge-Based and the Dock-Based ECS design utilize the same ETS. It is possible that the Barge-Based ECS would have a higher utilization rate than the Dock-Based ECS due to the Dock-Based ECS being limited to only treating vessels moored next to the dock and adjacent docks. The Barge-Based ECS was not demonstrated at the POLB. Therefore, the cost effectiveness analysis only examined the Dock-Based ECS. Table 3 presents the resulting estimated total annual auxiliary engine and auxiliary boiler emissions for each vessel type.

**Table 2. Hotelling Time and Utilization**

| Vessel Type | Average Hotelling Time hours/call | Dock Utilization % | Dock Usage calls/year |
|---|---|---|---|
| Auto Carrier | 18.4 | 65% | 310 |
| Bulk | 64.5 | 65% | 88 |
| Container Ship | 34.9 | 65% | 163 |
| General Cargo | 46.1 | 65% | 123 |
| Passenger | 11.7 | 20% | 150 |
| Reefer | 41.9 | 65% | 136 |
| Roll-on/Roll-off | 28.4 | 65% | 200 |
| Tanker | 33.5 | 65% | 170 |

**Table 3. Annual Auxiliary Engine & Boiler Emissions per Vessel Type**

| Vessel Type | PM ton/yr | NOx ton/yr | SOx ton/yr | VOC ton/yr | CO ton/yr |
|---|---|---|---|---|---|
| Auto Carrier | 7.1 | 74.5 | 70.3 | 2.5 | 5.7 |
| Bulk | 2.2 | 23.4 | 21.6 | 0.8 | 1.8 |
| Container Ship | 12.7 | 138.3 | 117.6 | 4.7 | 10.6 |
| General Cargo | 1.8 | 17.6 | 19.8 | 0.6 | 1.4 |
| Passenger | 20.4 | 202.2 | 165.2 | 6.5 | 15.3 |
| Reefer | 10.3 | 109.3 | 97.5 | 3.7 | 8.4 |
| Roll-on/Roll-off | 5.4 | 62.6 | 44.6 | 2.1 | 4.8 |
| Tanker | 12.5 | 76.2 | 197.4 | 2.9 | 6.2 |

The cost effectiveness methodology is based upon the Carl Moyer Program (CARB, April 2008) which only considers PM, NOx, and VOC. Weighting factors of 1 are used for NOx and VOC, but a weighting factor of 20 is used for PM to account for the increased risk to human health. The Moyer method utilizes the Annualized Cash Flow method for initial capital costs but does not account for future recurring annual operation and maintenance costs. This analysis employs Moyer's method for initial capital costs, and applies the Discounted Cash Flow method for recurring annual operation and maintenance costs.

Table 4 summarizes the weighted emissions reduced (weighting factor of 20 applied to PM) based upon the AMECS control efficiencies (with 1.5% reduction in NOx control efficiency to account for the SCR degradation over time). The total pollutants reduced do not include the SOx and CO emissions (Moyer methodology).

**Table 4. Emissions Reduction per Vessel Type**

| Vessel Type | PM[1] ton/yr | NOx ton/yr | VOC ton/yr | TOTAL ton/yr |
|---|---|---|---|---|
| Auto Carrier | 135.8 | 72.7 | 2.4 | 210.9 |
| Bulk | 42.3 | 22.9 | 0.8 | 65.9 |
| Container Ship | 242.0 | 135.0 | 4.5 | 381.5 |
| General Cargo | 34.7 | 17.2 | 0.6 | 52.5 |
| Passenger | 386.7 | 197.4 | 6.2 | 590.3 |
| Reefer | 194.8 | 106.8 | 3.6 | 305.2 |
| Roll-on/Roll-off | 102.7 | 61.1 | 2.0 | 165.8 |
| Tanker | 237.2 | 74.4 | 2.8 | 314.4 |

[1] Moyer weighting factor of 20 was applied to the PM emissions.

Table 5 presents the total 20 year AMECS life cost effectiveness and the number of vessels that can be serviced by AMECS simultaneously. Figure 2 graphs the cost effectiveness for each vessel type (assumes each AMECS is dedicated to a specific vessel type). The costs are fully loaded with burden and markup. Sensitivity analysis showed that placement of the AMECS in berths with high vessel occupancy is important in increasing the AMECS utilization rate and consequently improve the cost effectiveness.

**Table 5. Cost Effectiveness Over 20 Year AMECS Life**

| Vessel Type | Maximum Number of Vessels Treated by AMECS Simultaneously | Total Life Cost 2008$ | Weighted Emissions Reduced tons | Cost Effectiveness 2008$/ton |
|---|---|---|---|---|
| Auto Carrier | 2 | 61,101,546 | 8,437 | 7,242 |
| Bulk | 3 | 54,920,407 | 3,954 | 13,890 |
| Container Ship | 1 | 50,337,176 | 7,630 | 6,597 |
| General Cargo | 4 | 65,586,036 | 4,197 | 15,627 |
| Passenger | 1 | 135,358,120 | 11,807 | 11,465 |
| Reefer | 2 | 65,263,489 | 12,206 | 5,347 |
| Roll-on/Roll-off | 3 | 66,742,301 | 9,951 | 6,707 |
| Tanker | 1 | 51,464,390 | 6,288 | 8,184 |

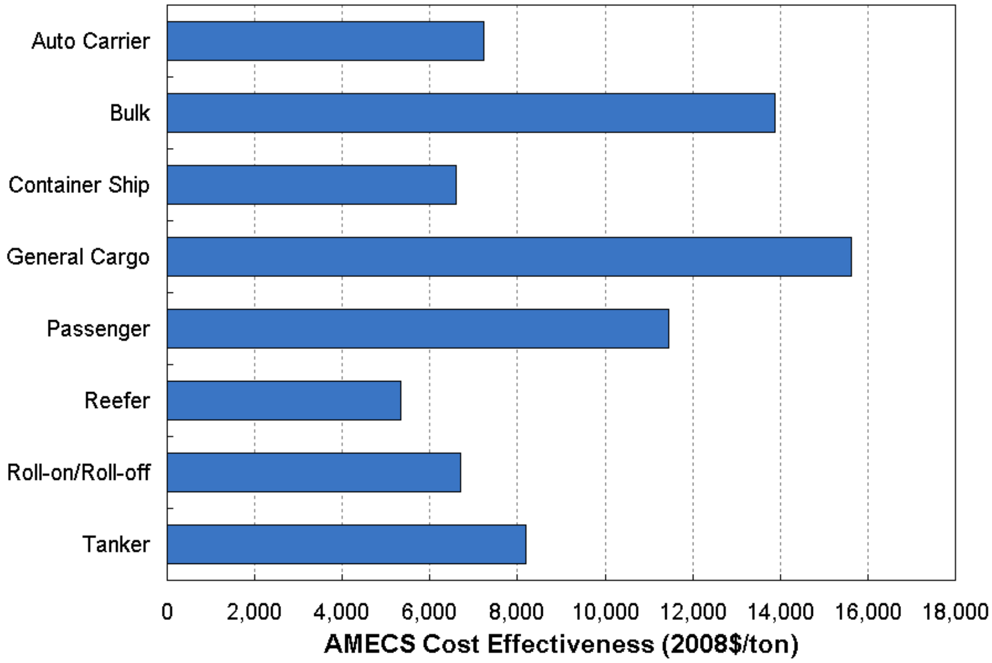


**Figure 2. AMECS Cost Effectiveness**

Additional benefits of AMECS that are not captured by the cost effectiveness analysis are the 99.8% reduction in SOx emissions and 43.8% reduction in CO emissions. An advantage of AMECS is the ability to treat vessel exhaust emissions without requiring any vessel modification.

The AMECS demonstration accomplished the the objective of achieving at least 95% average pollutant removal efficiencies for PM, NOx, VOC, and SOx.

The second objective of AMECS having no adverse affects to Metropolitan Stevedore’s normal operations and no adverse effects on the vessels, auxiliary engines, and auxiliary boilers was also accomplished. Robert Waterman, Assistant Vice-President of Bulk Operations for Metropolitan Stevedore, confirmed that AMECS did not delay nor affect their operation. ACTI’s personnel were present in the ship’s engine control room throughout all the tests and confirmed with the ship’s engineer that there were no observable effects on the ship’s operation due to AMECS’ attachment, operation, and detachment from the ships.

The successful capture efficiencies demonstrated by AMECS at the Port of Long Beach resulted in Barry Wallerstein, Executive Officer of the SCAQMD, stating that the implementation of AMECS (and ALECS for locomotives) could “provide large benefits to the South Coast Air Basin and, in particular, the communities adjacent to these sources.”

# 1. Introduction

## 1.1 Project Background and Overview

The Port of Long Beach (POLB) is one of the world's busiest seaport and a major international gateway for commerce entering California and the United States. The demand for goods moving through the San Pedro Bay region is expected to more than double by the year 2020. The POLB's ability to accommodate the projected growth in trade will depend upon their ability to address adverse environmental impacts and, in particular, air quality impacts that result from such trade. In the South Coast Air Basin, 11% of particulate matter emissions, 5% oxides of nitrogen emissions, and 32% oxides of sulfur emissions are attributed to port-related emission from the POLB (Starcrest, June 2008).

The POLB's shipping terminals import and export more than $100 billion worth of goods and products every year bringing products to the region and nation.[2]

Ports are a major source of air pollution with one of the major contributors being ocean-going vessels. While docked at the port, the ocean-going vessels (OGV) shut off their propulsion engines, but use auxiliary diesel engines (usually coupled to generators) to power refrigeration, lights, pumps and other functions (activities commonly called 'hotelling'). Auxiliary boilers, also a significant source of particulate matter, burn fuel to heat heavy fuel oil, heat water for crew/passengers, drive steam turbine pumps to offload petroleum products carried by tankers, distillation of seawater to generate fresh water, or space heating of cabins while docked.

Diesel engines create a complex mixture of harmful air pollutants, comprised of gaseous and solid material. The visible emissions in diesel exhaust, as well as a considerable quantity of tiny particles that are not generally visible, are known as particulate matter (PM). In 1998, the California Air Resources Board (CARB) identified diesel PM as a toxic air contaminant based on its potential to cause cancer, premature death, and other health problems. The resultant air emissions have an adverse affect on air quality and pose a significant health risk to the surrounding environment. Diesel engine emissions are responsible for the majority of California's potential airborne cancer risk from combustion sources.[3]

Metropolitan Stevedore, Incorporated is a leading petroleum coke terminal operator and handles stevedore operations in the Port of Long Beach for cargoes such as petroleum coke, coal, potash, borax and soda ash, concentrates, and prilled sulfur.

In 2005, Metropolitan Stevedore began working with Advanced Cleanup Technologies, Inc. (ACTI) on its emissions control technology for use on bulk freighters hotelling at POLB's pier G. The goal was to capture and significantly reduce the harmful pollutants emitted by the vessels while loading petroleum coke and other products.

---

[2] Downloaded 10/24/08: http://www.polb.com/economics/stats/default.asp

[3] Downloaded 11/10/08: http://www.arb.ca.gov/diesel/factsheets/dieselpmfs.pdf

In 2007, preliminary testing was conducted on the Western Seattle, a Handymax class, 45,630 dwt bulk cargo vessel, using an octagonal capture bonnet. The tests were performed to demonstrate the ability to attach the bonnet to a ship's exhaust stack, and to measure the exhaust capture effectiveness. Figure 3 shows testing with the bonnet attached to the Western Seattle.

**Figure 3. Western Seattle with Octagonal Capture Bonnet**

Based upon the successful testing using the Western Seattle, an Emission Testing Protocol (see Appendix A) was developed and reviewed by the Ports of Long Beach and Los Angeles, South Coast Air Quality Management District, and the California Air Resources Board. This report documents the demonstration testing of ACTI's Advanced Maritime Emissions Control System (AMECS) in the Port of Long Beach at Metropolitan Stevedore, Pier G, Berth 214 on May 26 and July 19, 2008. A major advantage of the AMECS technology is that no vessel modifications are required for AMECS to treat the exhaust emissions.

The test program consisted of testing the emissions of two vessels, the Queen Lily and the Angela, at the POLB. Both are bulk cargo vessels that frequent the Metropolitan Stevedore berths. Duplicate emissions tests were conducted at AMECS' Emission Treatment System inlet and outlet for pollutants such as particulate matter, oxides of nitrogen, volatile organic compounds and sulfur dioxide.

## 1.2 Project Objectives

The objectives of the test program are:

a. To document the effectiveness of the AMECS system in reducing ocean-going vessel emissions of particulate matter (PM), oxides of nitrogen (NOx), volatile organic compounds (VOC) and other pollutants under typical at-berth operating conditions. The criterion for a successful demonstration will be no less than 90% reduction in PM, NOx, and VOC.

b. To assure that the emission control equipment, process, and procedures do not interfere with normal Metropolitan Stevedore operations. This would include not affecting the loading/offloading operations of Metropolitan Stevedore as well as the auxiliary engine/boiler operation of the vessel.

# 2. Description of Technology

## 2.1 Overall Description

ACTI's AMECS is designed to capture exhaust emissions from the auxiliary engines and auxiliary boilers of ocean-going vessels (OGV) in hotelling mode (at berth or anchored within the port) and direct them to an emissions treatment system for removal of harmful pollutants before being exhausted into the surrounding environment.

AMECS is comprised of two major components: a) the Exhaust Capture System (ECS) and b) the Emissions Treatment System (ETS). The ECS can be Dock-Based or Barge-Based. The Dock-Based ECS is stationary and can only service vessels moored next to the berth or adjacent berths, whereas the Barge-Based ECS is mobile which can treat exhaust emissions of vessels anchored and waiting to come into an available berth. The POLB testing demonstrated the Dock-Based design, which is the main focus of this report.

## 2.2 Emissions Capture System

The ECS, which attaches to the ship's exhaust stack, captures the exhaust from the vessel and directs it through a duct into an emissions treatment system. An induced draft fan is used to draw the exhaust from the bonnet through the duct and into the ETS, where sulfur dioxide ($SO_2$), PM, NOx and VOC (hydrocarbons that are not classified as VOC by the Environmental Protection Agency, such as methane and ethane) may also be removed. Multiple ECS may be used to capture the exhaust emissions (up to the exhaust volume capacity of the ETS) from multiple vessels simultaneously utilizing an interconnecting ducting system.

The ECS consists of a Capture System Placement Device, an Octagonal Capture Bonnet, and a Duct Management system (see Figure 4). The bonnet, which is designed to fit over a wide variety of unique geometries of vessel exhaust stacks, collects the exhausted emissions. The bottom of the bonnet contains a self-adjusting 10-inch thick Pneumatic Interface Collar (Figure 5) that closes around the vessel's stack, limiting the amount of tramp air entering the bonnet as well as preventing exhaust emissions from escaping (see Figure 6). The Pneumatic Interface Collar can be adjusted (offset) to accommodate exhaust stacks that are located in close proximity to the vessel's house and/or antenna farm.

The Capture System Placement Device is the instrument that lifts the Octagonal Capture Bonnet onto the vessel's exhaust stack, and is the attachment interface for the ECS intake ducting. Figure 7 shows a picture of Dock-Based Capture System Placement Device deployed on the Ginga Merlin (Handysize class 19,999 dwt chemical tanker) on June 19, 2008. The purpose of this test was to demonstrate the repeated attachment and detachment of the Exhaust Capture System.

Figure 4. Octagonal Capture Bonnet (furled)

Figure 5. Octagonal Capture Bonnet's Pneumatic Interface Collar

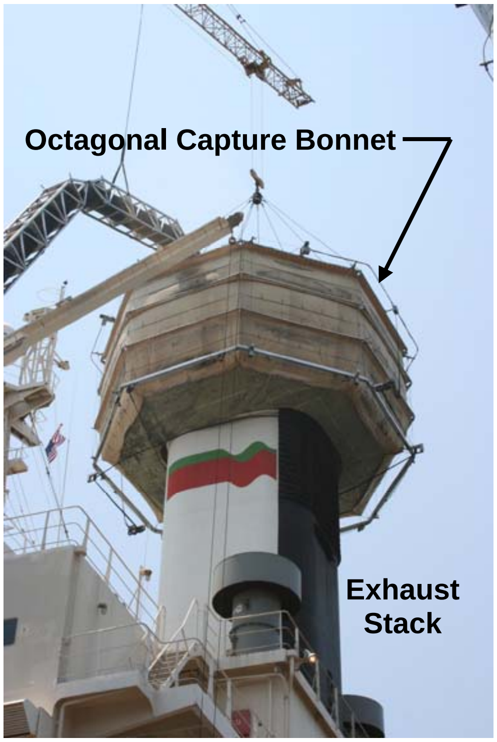


Figure 6. Octagonal Capture Bonnet (attached to the Angela)

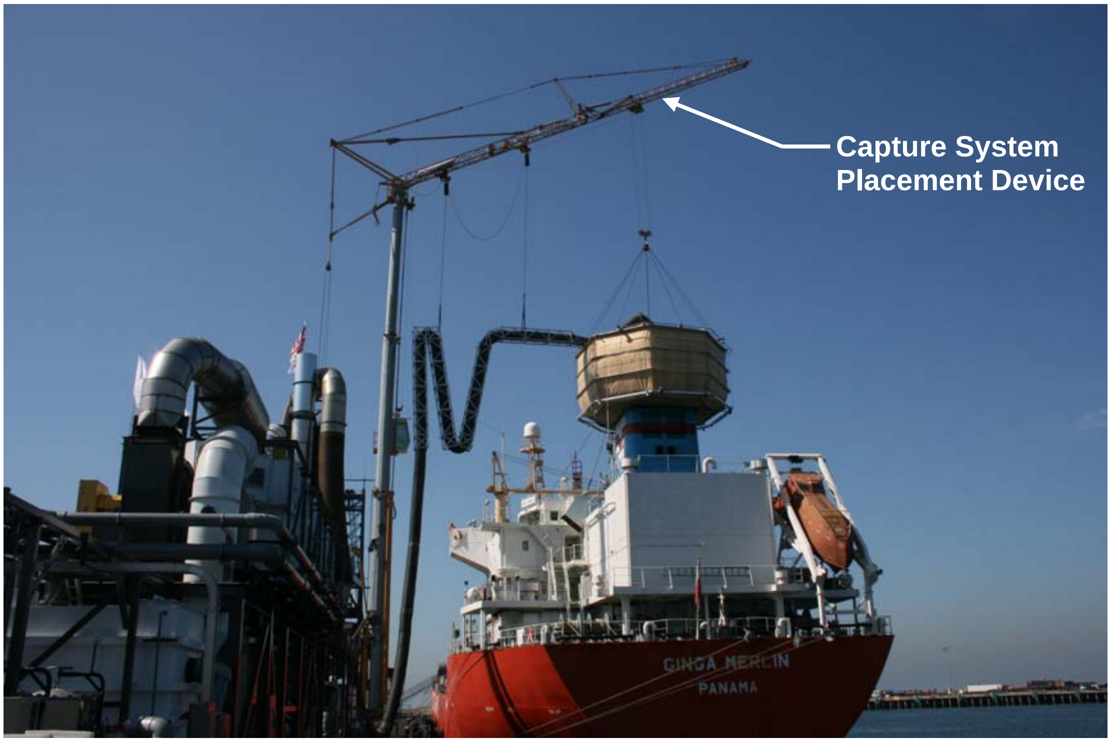


Figure 7. Capture System Placement Device (attached to the Ginga Merlin)

System backpressure will be controlled by a pressure sensor located within the bonnet, which in turn controls a damper located at the top of the bonnet. Backpressure is controlled between atmospheric and minus 0.25 inch of water gauge pressure, which puts the exhaust system under a slight vacuum. This vacuum essentially captures all of the vessel's exhaust and may also add some dilution air from the surrounding atmosphere into the capture system.

This POLB demonstration tests used a single ECS, but the full scale deployment of AMECS is expected to have multiple ECS depending upon the port design, and the expected types of vessels being treated. Vessels with lower exhaust volumes may be treated simultaneously (with multiple ECS) by a single ETS.

### 2.3 Emissions Treatment System

The three major components of the ETS consist of a Preconditioning Chamber (PCC), three patented Cloud Chamber Scrubbers (CCS) and a Selective Catalytic Reduction (SCR) Reactor to remove the harmful exhaust emissions. Figure 8 shows the relative location of the components on the ETS.

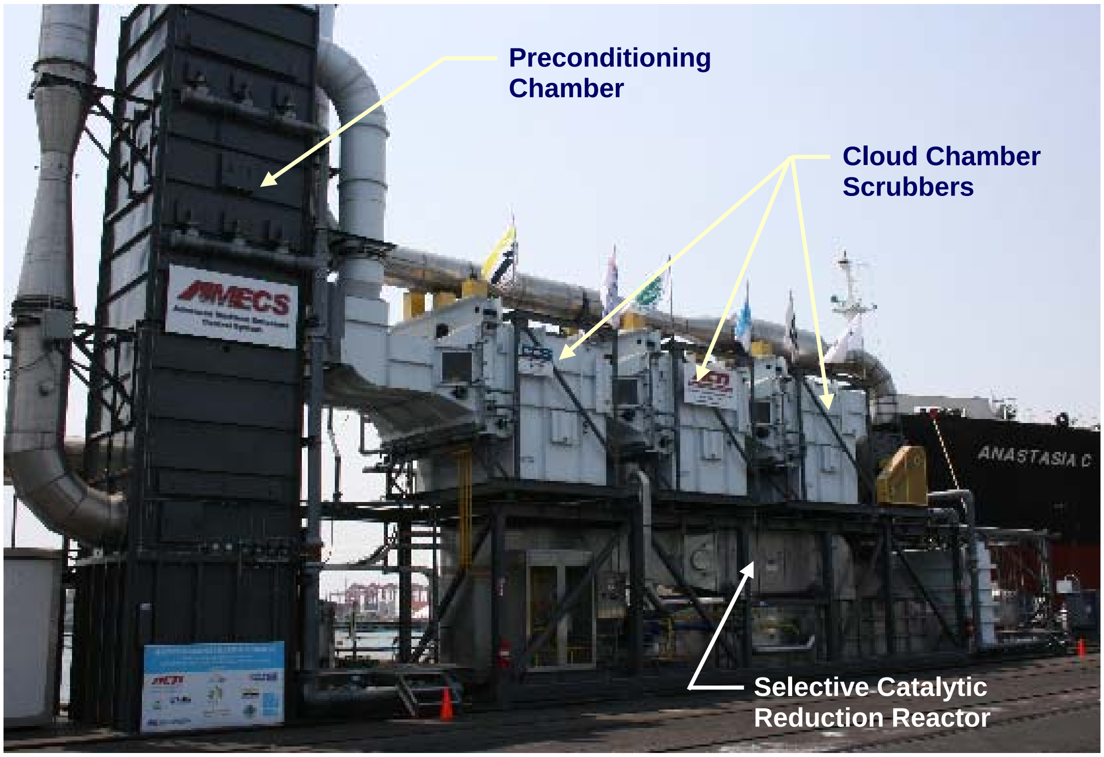


**Figure 8. Emissions Treatment System**

The first unit the exhaust gas encounters as it enters the system is the Preconditioning Chamber which serves several functions. First, it cools the gas through a countercurrent flow water spray and in the process increases the water vapor content to near saturation. This feature is required by the following stage, which cannot accept hot gas. Secondly, it removes water soluble VOC. Third, the water is rendered caustic by means of a metered injection of sodium hydroxide to remove $SO_2$.  The fourth function of the PCC is to cause the nanometer size PM particles to agglomerate into larger particulate globules, which facilitates their removal. Many of these larger particles are captured by the liquid spray and enter the PCC water stream where they are carried to an inline filter.  The particulates that are larger than the effective pore size of the filter bags are captured and retained in the bags for later removal and disposal.

For those particles that are not captured by the water stream in the PCC, they continue effectively as an aerosol in the gas stream, but those that have been enlarged in size through interaction with other PM particles and water vapor in the PCC are more efficiently captured downstream in the CCS.

The path of the captured exhaust emissions flow through the ETS, along with the relative positions of the major components is shown in Figure 9.

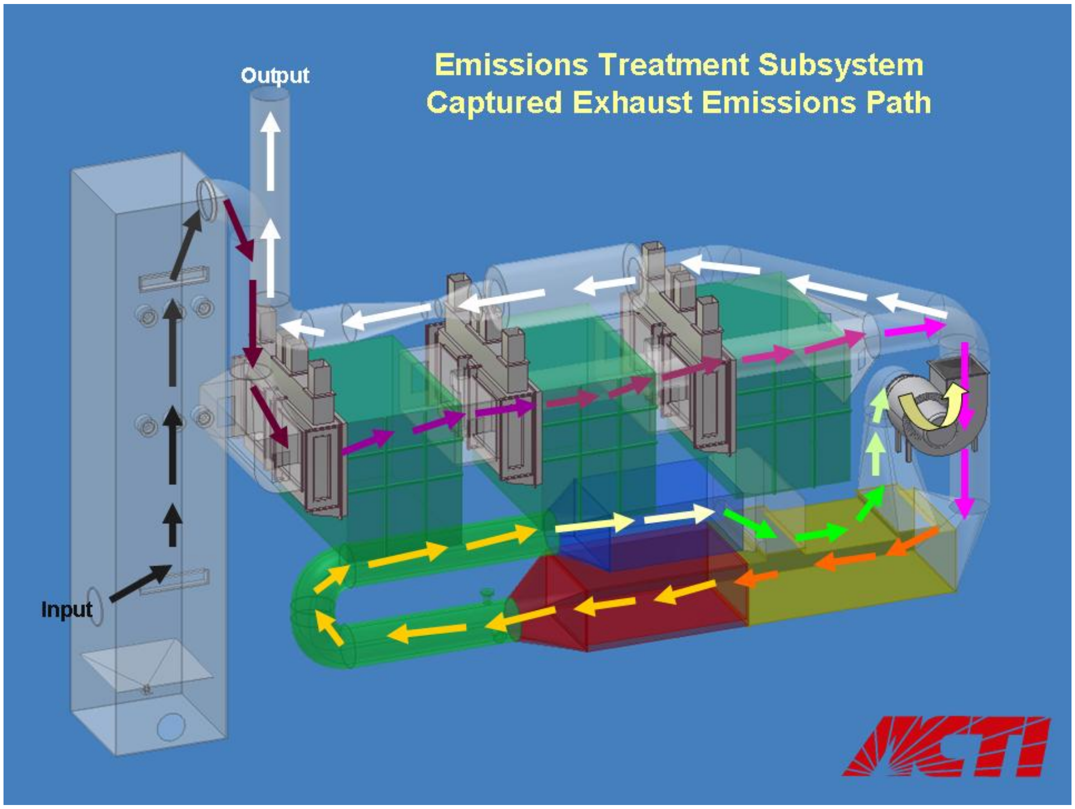


**Figure 9.  Emissions Treatment System Captured Exhaust Emissions Path**

The CCS is composed of three stages that are identical except for the polarity of the charge imparted to the water droplets.  Each CCS stage or chamber generates a fog of very fine water droplets and charges them to a high voltage.  PM particles, including ultrafine particles, are attracted to these micron-size water droplets.

The water, which now has many PM particles adhering to each water droplet, coalesces into a stream of water and is routed to a second filter where the agglomerated PM particles are filtered out, as in the PCC. Also as in the PCC, sodium hydroxide is metered into the water streams of the CCS stages to remove the remaining sulfur dioxide.

The particles thus collected in the water reservoir are flushed through a solids removal system where they are collected for subsequent removal from the premises and disposal using approved regulatory means. The removal system consists of a solids separation device for inline solids removal, water extraction, and compaction.

The Selective Catalytic Reduction (SCR) Reactor is designed to remove NOx. Liquid urea is injected into the hot gas stream ahead of the SCR. The urea is converted to ammonia by the hot gas, and the ammonia reacts with the NOx in the presence of the catalyst to form nitrogen gas and water vapor, which are vented to atmosphere. A 40% or less solution of urea, a non-hazardous compound, is used rather than ammonia, which is hazardous, to increase safety and simplify storage and transport.

The SCR Reactor subassembly includes a Heat Management System comprised of a heat exchanger and burner. The heat exchanger is used to recover heat from the SCR discharge for preheating the exhaust gas entering the SCR. The SCR requires a gas temperature of 570 to 650 °F at the inlet. The exhaust gas exiting the CCS is cooled to about 140 °F and stripped of $SO_2$, PM, soluble hydrocarbons, and condensed (particulate) hydrocarbons and sulfates. This clean but cool gas must then be reheated. The additional heat required is provided by a natural gas or propane fired burner (an electric heater could also be used).

The heat exchanger uses the heat of the cleaned exhaust gas exiting the SCR to heat the exhaust gas prior to it entering the SCR. The heat exchanger captures 80% of the heat that would otherwise be exhausted. The duct burner is therefore required to provide a temperature boost of only about 100 °F, minimizing fuel usage as well as keeping burner emissions to a low level.

Refer to Figure 10 for the component locations of the Heat Management System.

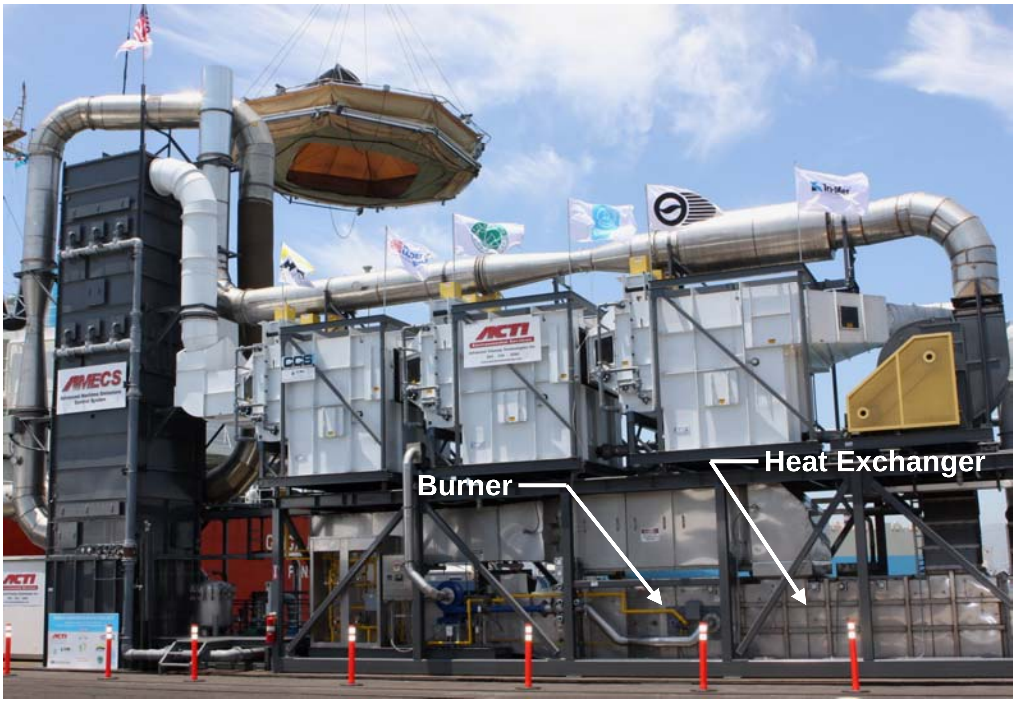


Figure 10. ETS: SCR Heat Management System

A second function of the burner is to remove any remaining VOC that are not water-soluble, and those that are water-soluble that were not removed in the PCC and CCS. As the exhaust emissions pass through the ducting leading from the heat exchanger through the burner to the SCR reactor, the gas flow is deliberately perturbed to provide turbulent flow and subsequent thorough mixing of the urea/ammonia with the exhaust gas as well as maximal efficiency of the plate-type heat exchanger.

An Induced Draft (ID) fan is located downstream of the SCR Reactor and Thermal Management System, and a silencer is located downstream of the ID fan. This fan draws the exhaust gas from the vessel through the ducting into the ETS. The flow and pressures are controlled by dampers and the fan's variable speed drive motor.

The silencer (downstream of the ID fan) reduces the system's operating noise level to an acceptable level.

## Control System Description

The AMECS Control System is an integrated network which automatically operates and monitors all aspects of the AMECS operation. The ETS has its own Operational Control Unit (OCU), which controls all the ETS processes. The OCU houses all sensing, monitoring, recording and control system functions for AMECS. These systems acquire, monitor, store and transmit the data required to maintain efficient emissions control operations as well as to document emissions reduction performance.

Failsafe strategies are built into the control system. This system keeps all ECS and ETS operational parameters within design limits, makes automatic adjustments where appropriate, switches to redundant components or systems in the event of a malfunction or out-of-spec condition, and records significant parameters to verify performance.

As part of the control system, measured data (including failures) are recorded into a Microsoft SQL (Structured Query Language) Database, a Relational Database Management System, to assist in determining the failure mode, identifying the failure to a most probable cause. The software is used to identify trends so that corrective action can be taken proactively.

In addition, the Barge-Based Emissions Capture Systems would be equipped with a Global Positioning System (GPS) that will provide barge location and status, such as connected to a vessel, on standby, requires service, etc. The Barge-Based design was not part of AMECS demonstration at the POLB.

The Continuous Emissions Monitoring System (CEMS) measures the following parameters:

- At the ETS inlet (source measurement)
    - NOx
    - SOx
    - VOC
    - Flow
    - Temperature

- At the ETS outlet (discharge to atmosphere)
    - NOx
    - SOx
    - VOC
    - $NH_3$ (ammonia)
    - Flow
    - Temperature

PM would also be measured at the ETS inlet and outlet, but the measurements would not be continuous, nor in real time like the CEMS. PM measurements will be performed periodically (depending upon the local air quality agency) by withdrawing the particulate isokinetically from the source and collecting them on glass fiber filters for gravimetric analysis. These measurements could be used to supplement the emissions inventory database for the port.

The CEMS instrumentation consists of gaseous stack gas analysis equipment. Typically, a chemiluminescent analyzer is used for NOx measurement, a non-dispersive infrared analyzer for SOx, and a flame ionization analyzer for measuring total hydrocarbons.

The sample conditioning system includes a solid state thermoelectric pre-cooler with stainless steel impingers, a solid state thermoelectric sample cooler, primary and secondary particulate filters, an acid mist catcher, magnetically coupled sample pump and booster pump, temperature controller for the heated sample line, temperature controller for the sample probe primary filter, automatic temperature and pressure control, and automatic system calibration.

Figure 11 is a picture of the CEMS utilized in the ALECS demonstration testing.

**Figure 11. Continuous Emission Monitoring System**

## 2.4 System Installation for Demonstration at the POLB

The ETS of AMECS came from the 2006 demonstration of the Advanced Locomotive Emission Control System (ALECS) tested at the Union Pacific Railroad’s J. R. Davis Rail Yard in Roseville, California (TIAX, 2007). Figure 12 shows an aerial view of the approximate location of the AMECS demonstration test location in the POLB. The overall layout of AMECS on the dock for purposes of this demonstration is shown in Figure 13. The 1,200 foot marker near the location of the crane is approximately across from where the ship stack was located when the vessel was berthed. In this configuration, flexible ducting conveyed the exhaust gas from the bonnet to the ETS. The ETS was mounted on a temporary foundation that provided a level surface for the ETS.

Figure 12. Aerial View of the POLB Site where AMECS was Installed

.

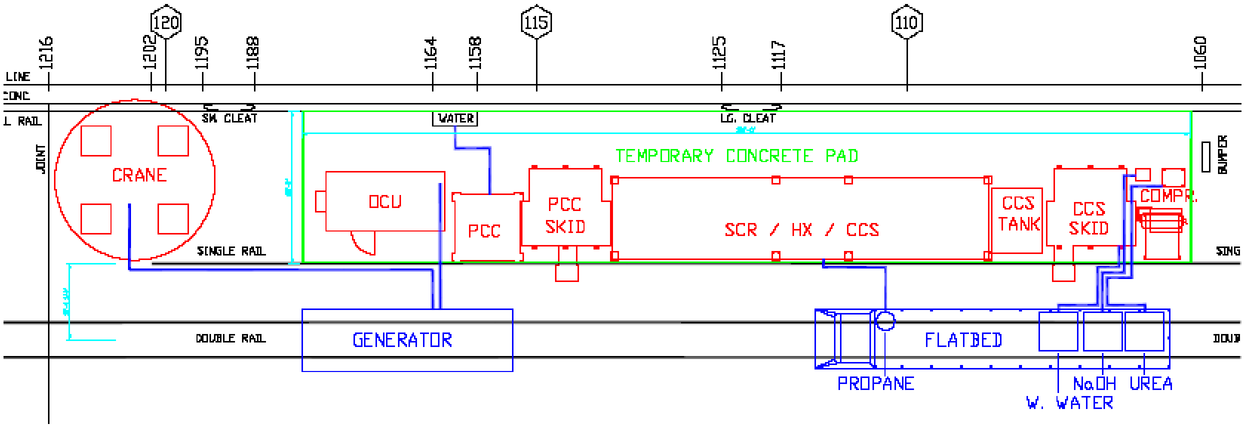


Figure 13. AMECS equipment arrangement on the dock at berth G-214

# 3. Testing of System

## 3.1 Overall Test Plan

The test program consisted of testing the emissions of two vessels at the POLB. Both are bulk cargo vessels that frequent the Metropolitan Stevedore facility. Duplicate emissions tests were conducted at AMECS' ETS inlet and outlet for NOx, CO, $SO_2$, VOC, and PM. Ammonia was tested only on the outlet of the ETS for ammonia slip from the SCR. There were no emissions measured at the vessel stack outlet. The complete source test protocol is included in Appendix A.

The test program only tested one vessel at a time operating in its normal hotelling mode, which consisted of operating an auxiliary engine(s) and one auxiliary boiler.

## 3.2 Vessels Tested (Queen Lily and Angela)

The larger of the two vessels tested with the ETS was the bulk carrier, the Queen Lily. The smaller vessel tested with the ETS, the Angela, is also a bulk carrier. The exhaust emissions were tested while the vessels conducted their normal operations docked at berth (such as being loaded with petroleum coke). Table 6 summarizes the ocean-going vessel characteristics. Auxiliary boilers were operating intermittently in addition to the auxiliary engine operating during testing, but Boiler specifications and operational data during emissions testing were not available.

**Table 6. Vessel Characteristics**

| | Ocean-Going Vessel | |
|---|---|---|
| | **Queen Lily** | **Angela** |
| **Year Built** | 2004 | 2004 |
| **Cargo Capacity (dwt)** | 76,629 | 52,571 |
| **Ship Identification Number** | 9316660 | 9274915 |
| **Number of Auxiliary Engines** | 3 | 3 |
| **Auxiliary Engine Model** | Yanmar 6N21L | Daihatsu 3DK-20 |
| **Auxiliary Engine Type** | Four-stroke | Four-stroke |
| **Number of Cylinders** | 6 | 3 |
| **Rated Power Output (kW)** | 615 | 440 |
| **Engine Speed (rpm)** | 720 | 900 |
| **Test Date** | May 26, 2008 | July 16, 2008 |
| **Engines on During Test** | 2 | 1 |
| **Ave. Power During Test** | 88 and 151 kW | 210 kW |

Repeated attachment and detachment of the ECS to the Queen Lily (Figure 14), the Angela (Figure 15), and the Ginga Merlin (Figure 7) was successfully demonstrated. Deployment and recovery of the ECS had proven to not interfere with normal Metropolitan Stevedore operations. Robert Waterman, Assistant Vice-President of Bulk Operations for Metropolitan Stevedore, stated that he had not heard of nor saw any adverse affects to their normal operations during AMECS operation. There had been a total of at least 20 separate attachments and detachments of AMECS to various vessels during the demonstration period without any adverse affect on Metropolitan Stevedore operation.[4] There was no noted damage or adverse effect on the vessels, the auxiliary engines, nor the auxiliary boilers due to the operation of AMECS. ACTI personnel were present in the ship's engine control room throughout all the tests. The ship's engineer did not report any observable effect (from available instrumentation) due to ECS attachment, operation of AMECS, and ECS detachment.

**Figure 14. Emission Capture System Attached to the Queen Lily**

---

[4] Communication with Robert Waterman, Assistant Vice-President of Bulk Operations for Metropolitan Stevedore , on November 17, 2008

**Figure 15. Emission Capture System Attached to the Angela**

## 3.3 Emission Measurements

The emissions testing were performed by Professional Environmental Services, Inc. of Irwindale. Simultaneous emissions measurement of NOx, CO, $SO_2$, PM, VOC, $CO_2$, and $O_2$ were conducted at the inlet and outlet of the ETS of AMECS. Ammonia ($NH_3$) slip from the SCR was only tested at the outlet of the ETS. Duplicate test runs were conducted at the inlet and outlet locations while the auxiliary engines on the vessels were running. Table 7 summarizes the test methods, number of test runs, and duration of tests performed by Professional Environmental Services. Due to the scheduling difficulties, the triplicate runs in the testing protocol were reduced to duplicate runs. There was insufficient time to conduct the third set of tests.

**Table 7. Test Methods, Number of Tests, and Duration of Tests per Vessel**

| | Test Method | Test Runs/Duration |
|---|---|---|
| **Volumetric Flow Rates** | SCAQMD Methods 1.1-4.1 | Continuous |
| **NOx, CO, $CO_2$, $O_2$** | SCAQMD Methods 100.1 | 2 runs – 60 minutes each |
| **$SO_2$** | SCAQMD Methods 6.1 | 2 runs – 60 minutes each |
| **$NH_3$ (outlet only)** | SCAQMD Methods 207.1 | 4 runs – 30 minutes each |
| **PM** | SCAQMD Methods 5.2 | 2 runs – 60 minutes each |
| **VOC** | SCAQMD Methods 25.1 & 25.3 | 2 runs – 60 minutes each |

## 4. Test Results

The NOx, PM, VOC, $SO_2$, CO, and $NH_3$ test results are presented here. The full emission source test reports are presented in the appendices. The emission source test report for the Queen Lily is presented in Appendix B. Appendix C contains the emission source test report for the Angela.

### 4.1 Emissions Results

South Coast Air Quality Management District's (SCAQMD) Source Test Engineering evaluated the emission source test reports and concluded that the results required some corrections and clarifications. The SCAQMD memorandum (documented in Appendix D) concluded:

- Recalculations performed by SCAQMD and the results presented in the SCAQMD's memorandum should supersede the original emission source test reports.
- Testing did not include quantification of the small amount of visible fugitive emissions observed to be coming from the vessel stack to bonnet interface.
- PM deposition on the inner surfaces of the bonnet and ducting were not quantified.
- The reported control efficiencies only represent AMECS' control efficiencies, and do not represent the percentage reduction over uncontrolled emissions from the vessel stack (which may be higher if the PM deposits were disposed in a manner that prevented discharge to the atmosphere).

Table 8 presents the inlet and outlet emission results to the Emissions Treatment System of AMECS for the Queen Lily (tested on May 26, 2008) and the Angela (tested on July 16, 2008). A urea pump failed during the second run for the Queen Lily. This invalidated the NOx measurement on the outlet. A broken trap in the testing laboratory using SCAQMD Method 25.1 for the Angela's first run on the ETS inlet and having a greater than 20% difference between the paired sample results (one is a quality assurance duplicate) invalidated the VOC measurement.

The overall emission control efficiencies of the major pollutants of interest are presented in Table 9. The CO reduction efficiency for the Angela was not determined because the measurements for both runs for the inlet and outlet were below the detection limit. The overall control efficiency for NOx was reduced by 1.5% (for this report's analysis) to account for the degradation of the SCR Catalyst over time.

The ammonia slip from the use of urea in the SCR system was low. Measurements for $NH_3$ were only conducted on the outlet of the ETS. The failing of the urea pump during the second run for the Queen Lily invalidates the $NH_3$ measurement. The three remaining $NH_3$ measurements (corrected to 15% O2) are 8.4 ppm (Queen Lily run 1), 0.5 ppm (Angela run 1), and 4.0 ppm (Angela run 2). This results in an average $NH_3$ slip of 4.3 ppm (@ 15% O2).

### Table 8. AMECS Inlet/Outlet Emissions

| | Inlet Emissions (lbs/hr) | | | | | Outlet Emissions (lbs/hr) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | NOx | PM | VOC | $SO_2$ | CO | NOx | PM | VOC | $SO_2$ | CO |
| **QUEEN LILY** | | | | | | | | | | |
| Run 1 | 5.63 | 1.39 | 1.32 | 5.65 | 0.76 | < 0.02 | 0.025 | 0.053 | 0.009 | 0.39 |
| Run 2 | 7.04 | 0.54 | 1.49 | 5.49 | 0.70 | * | 0.011 | 0.064 | 0.005 | 0.43 |
| **Average** | 6.34 | 0.97 | 1.41 | 5.57 | 0.73 | < 0.02 | 0.018 | 0.0585 | 0.007 | 0.41 |
| **ANGELA** | | | | | | | | | | |
| Run 1 | 3.02 | 0.864 | N/A | 3.11 | < 0.27 | 0.073 | 0.072 | 0.11 | 0.006 | < 0.28 |
| Run 2 | 4.91 | 0.925 | 3.11 | 3.01 | < 0.27 | < 0.04 | 0.074 | 0.09 | 0.007 | < 0.28 |
| **Average** | 3.97 | 0.895 | 3.11 | 3.06 | < 0.27 | < 0.06 | 0.073 | 0.10 | 0.007 | < 0.28 |

* Data not included due to urea pump failure (NOx was non-detect until the urea pump failed)

N/A = Not Available due to broken trap and >20% difference between paired sample results

### Table 9. Average AMECS Control Efficiencies

| | NOx | PM | VOC | $SO_2$ | CO |
|---|---|---|---|---|---|
| **QUEEN LILY** | >99.7% | 98.1% | 95.9% | 99.9% | 43.8% |
| **ANGELA** | >98.6% | 91.8% | 96.8% | 99.8% | ND |
| **Average Control Efficiency** | >99.1% | 95.0% | 96.3% | 99.8% | 43.8% |
| **Adjusted Average Control Efficiency[1]** | >97.6% | 95.0% | 96.3% | 99.8% | 43.8% |

ND = Not Determined

[1] Assumed 1.5% reduced NOx control efficiency to allow for SCR catalyst degradation over time

VOC reduction was found to occur primarily in the hot sections of the ETS (heat-exchanger, burner, ducting between the burner and the SCR Reactor, and the SCR Reactor portions of the ETS). ACTI performed an analysis on VOC destruction that can be found in Appendix E. Based on the collected data most of the measured VOC destruction is occurring in the burner section of the ETS (forty foot ducting connecting the burner with the SCR Reactor) and in the SCR Reactor.

## 4.2 Utility, Energy, and Chemical Consumption Rates

ACTI collected operating process data on the AMECS and provided the estimates shown in Table 10 on the utility, energy, and chemical consumption rates per hour of operation treating the exhaust volume of 12,500 scfm (capacity of one ETS). Propane was the fuel used for reheating the exhaust prior to the SCR in the demonstration, but natural gas or electrical power is expected to be available in a permanent installation of the AMECS. The amount of natural gas required to heat the 12,500 scfm of exhaust is 1.01 million Btu/hr. Also, in the demonstration test, portable diesel engine generators were used to produce the electricity needed, but electricity from the local utility will be used in normal operation. The diesel engine generators and propane were used due to the temporary AMECS installation for the demonstration.

**Table 10. AMECS Utility, Energy, and Chemical Consumption Rates**

| Consumables | Quantity | Units |
|---|---|---|
| **Electricity** | 350 | kWh/hr |
| **Natural Gas** | 1.01 | MMBtu/hr |
| **Water** | 310 | gal/hr |
| **Aqueous Urea (40%)** | 0.38 | gal/kg NOx |
| **Sodium Hydroxide (30%)** | 0.82 | gal/kg SOx |

### 4.3 Waste Generation

Liquid and solid waste (PM) is produced by the Preconditioning Chamber and the Cloud Chamber discharge of the AMECS.

Solid waste accumulated from the ETS was estimated to be produced at a peak rate of 2.2 lb/hr. This estimate is based upon data collected by ACTI during the demonstration testing. Captured solid waste was stored in drums that hold around 400 pounds of material each.

Liquid wastewater was being produced at a rate of 2.7 gallons per hour. Analysis of ALECS wastewater showed it could be considered safe enough to be discharged to a publicly owned treatment system, but local policies specific to each location will need to be identified (TIAX, 2007).

### 4.4 Overall System Evaluation

Conventional stationary emission control technology has been demonstrated to be very effective in treating emissions from ocean-going vessel sources. The Dock-Based ECS demonstrated the ability to capture emissions from single vessels. The demonstration at the POLB utilized a system that was installed to handle a single vessel at a time; a simultaneous multi-vessel emissions capture system with multiple vessels was not tested. The Barge-Based ECS was not tested at the POLB.

# 5. Life Cycle Cost Analysis

## 5.1 Methodology

The life cycle cost analysis estimates the total cost of the AMECS incurred over the life of the system and is used along with the emission estimates to determine the system cost effectiveness per ton of pollutant reduced. The life cycle cost analysis entails Cost Element Definition, Data Collection, and Evaluation.

## 5.2 Cost Element Definition

Cost elements are broken down into Initial Capital Costs, Operating and Maintenance Costs including Utility/Energy Costs, Repair and Replacement Costs, Downtime Costs, Environmental Costs, and Salvage Value.

A) Initial Capital Costs include engineering and design (drawings and regulatory issues), bidding process, purchase order administration, hardware capital costs, testing and inspection, inventory of spare parts, foundations (design, preparation, concrete and reinforcing), installation of equipment, connection of process piping, connection of electrical wiring and instrumentation, one-time licensing/permitting fees, and the start up (check out) costs.

B) Operating and Maintenance Costs include items such as labor costs of operators, inspections, insurance, warranties, recurring licensing/permitting fees, and all maintenance (corrective and preventive maintenance). Also included are yearly costs of consumables such as the utility/energy costs (electricity, natural gas, and water) and chemical costs (such as sodium hydroxide and urea).

C) Repair and Replacement Costs are the costs of repairing and replacing equipment over the life of the AMECS. These costs are included in the operation and maintenance costs.

D) Port impact costs include estimates of costs incurred by the Port of Long Beach due to the operation or non-operation of the AMECS. AMECS is not expected to affect the normal operations of ocean-going vessels hotelling.

E) Environmental Costs are associated with the disposal of wastewater and solid waste.

F) The Salvage Value of the system would be the net worth of the AMECS in its final year of the life cycle period. If the system can be moved and salvaged for useful parts/purposes, there would be a reduction in life cycle costs.

The estimates in this report are based upon data and observations taken during the operation and demonstration testing of the AMECS.

## 5.3 Data Collection and Assumptions

Data for this evaluation was provided by ACTI based upon the data collected from the demonstration at the Port of Long Beach. Accuracy of input data is important to improve the certainty of the life cycle cost prediction. The data obtained are the most accurate information available. Where actual data were not available, literature searches, theoretical calculations, and engineering estimates were utilized. The ETS would be common among installations at different berths, however, the ECS would need to be tailored to each specific installation dependent upon the size and activity of ocean-going vessels at each berth (multiple vessels could be treated simultaneously). ACTI has also designed a barge based ECS (which uses an ETS installed on the dock or on the barge, depending upon the specific application) that has not been demonstrated on an ocean-going vessel yet.

ACTI provided information on the initial capital costs (see Table 11). The ETS (12,500 scfm capacity) in the POLB demonstration is the full size design (there is no scaling required for production units sold by ACTI). However, ACTI also states that the current standard ETS design of 12,500 scfm could be scaled up to a maximum of 27,000 scfm for a single ETS unit. For this analysis, if more than 12,500 scfm needs to be treated, a second (or more) 12,500 scfm unit is added. The costs include burden and markup. The costs include the proprietary direct and indirect capital costs which include items such as shipping, engineering support, construction & field expenses, contractor fees, start-up, performance test, and contingencies. Assumptions of reduced prices from multiple production runs of around 20 units, split between rail and marine applications were included based upon the experience of demonstrating the ALECS at Union Pacific Railroad's J. R. Davis Rail Yard in Roseville, California, and the AMECS for this POLB demonstration.

**Table 11. AMECS Initial Capital Costs**

| Dock-Based Initial Capital Costs | Cost/Unit |
|---|---|
| Emissions Treatment System (ETS) | $ 4,215,596 |
| Emissions Treatment System Installation | $ 954,525 |
| Exhaust Capture System (ECS) | $ 1,672,188 |
| Exhaust Capture System Manifold | $ 318,989 |
| Exhaust Capture System Installation | $ 1,240,883 |

The recurring operation and maintenance (O&M) costs are presented in Table 12. The consumables and utilities are based upon the AMECS demonstration experience. The electricity and natural gas prices are based upon the Energy Information Administration's forecasted 2008 Industrial prices for the California/Pacific region[5]. The SCR catalyst is estimated to be replaced every six years. The 6 year life of the catalyst is based upon the removal of sulfur and PM prior to the SCR which extends the life of the catalyst. The SCR catalyst replacement cost is included in the maintenance costs. It is assumed that there will not be a salvage value of the AMECS at

---

[5] The 2006$ were converted to 2008$ based upon the estimated 2008 Consumer Price Index (CPI) (average of monthly CPI through September 2008).

the end of its useful life and any salvage value would be offset by any costs associated with shutting down the AMECS.

AMECS will be staffed 24 hours a day, 365 days a year by full time fully trained personnel with labor rates ranging from $75/hr to $115/hr.

**Table 12. AMECS Recurring Operation and Maintenance Costs**

| Dock-Based Recurring Operating Costs | Cost/Unit |
|---|---|
| Full Time Personnel | $ 1,283,696 /ETS/year |
| Service Personnel (ECS) | $ 88.20 /hour |
| Maintenance | $ 70,177 /ETS/year |
| Insurance | $ 39,875 /ETS/year |
| Sodium Hydroxide (30%) | $ 1.75 /gal |
| Urea (40%) | $ 2.18 /gal |
| Solid Waste Disposal | $ 1.15 /pound |
| Liquid Waste Disposal | $ 0.25 /gal |
| Water | $ 0.0038 /gal |
| Electricity | $ 0.11 /kWh |
| Heat (Natural Gas) | $ 8.24 /MMBtu |
| Central Facility | $ 364,062 /ETS/year |

Table 13, Table 14, and Table 15 presents the auxiliary engine and boiler emission factors, rated power, load factors, operating loads, and fuel distribution (CARB, June 2008). Auxiliary engines primarily use heavy fuel oil with almost a third using distillate (0.5% sulfur marine distillate). It is assumed that all auxiliary boilers use heavy fuel oil.

The auxiliary engine load represents the total average auxiliary engine power used per vessel (combining multiple engines if there were operating simultaneously). The auxiliary boiler fuel use rates were converted to equivalent kilowatts (CARB, June 2008). Estimated Average and Peak exhaust flows for vessels from ACTI are based upon auxiliary engine and boiler loads. Appendix F presents an ACTI analysis on auxiliary boiler emissions and exhaust flow rates.

**Table 13. Auxiliary Engine & Boiler Emission Factors, g/kWh**

| FUEL | PM g/kWh | NOx g/kWh | SOx g/kWh | VOC g/kWh | CO g/kWh |
|---|---|---|---|---|---|
| Engine[1]: Heavy Fuel Oil (HFO) | 1.5 | 14.7 | 11.1 | 0.46 | 1.1 |
| Engine[1]: Marine Distillate (0.5% S) | 0.38 | 13.9 | 2.1 | 0.52 | 1.1 |
| Boiler: Heavy Fuel Oil (HFO) | 0.8 | 2.1 | 16.5 | 0.11 | 0.2 |

[1] Medium speed auxiliary engine

**Table 14. Auxiliary Engine Power, Load Factor, and Fuel**

| Vessel Type | Rated Power kW | Load Factor % | Hotelling Load kW | Fuel Share HFO % | Fuel Share Distillate % |
|---|---|---|---|---|---|
| Auto Carrier | 2,999 | 26% | 780 | 71% | 29% |
| Bulk | 2,459 | 10% | 246 | 71% | 29% |
| Container Ship | 8,156 | 18% | 1468 | 71% | 29% |
| General Cargo | 1,799 | 10% | 180 | 71% | 29% |
| Passenger | 44,042 | 16% | 7047 | 92% | 8% |
| Reefer | 3,605 | 32% | 1154 | 71% | 29% |
| Roll-on/Roll-off | 2,605 | 26% | 677 | 71% | 29% |
| Tanker | 2,339 | 26% | 608 | 71% | 29% |

**Table 15. Auxiliary Engine & Boiler Hotelling Loads and Flow Rates per Vessel**

| Vessel Type | Auxiliary Engine(s) Ave. Load kW | Auxiliary Engine(s) Ave. Flow scfm | Auxiliary Engine(s) Peak Flow scfm | Auxiliary Boiler Ave. Load kW | Auxiliary Boiler Ave. Flow scfm | Auxiliary Boiler Peak Flow scfm |
|---|---|---|---|---|---|---|
| Auto Carrier | 780 | 2,339 | 4,139 | 278 | 1,112 | 1,668 |
| Bulk | 246 | 738 | 3,393 | 82 | 328 | 492 |
| Container Ship | 1,468 | 4,404 | 11,255 | 380 | 1,520 | 2,280 |
| General Cargo | 180 | 540 | 2,483 | 99 | 396 | 594 |
| Passenger | 7,047 | 21,140 | 60,778 | 750 | 3,000 | 4,500 |
| Reefer | 1,154 | 3,461 | 4,975 | 348 | 1,392 | 2,088 |
| Roll-on/Roll-off | 677 | 2,032 | 3,595 | 82 | 328 | 492 |
| Tanker | 608 | 1,824 | 3,228 | 1,593 | 6,372 | 9,558 |

Table 16 presents the total auxiliary engine and boiler exhaust flow rates. Estimates are based upon the ECS capturing all of the exhaust with 5% excess ambient air (vessel exhaust represents 95% of total volume of gases being treated by the ETS). The number of vessels serviced by each ETS is based upon the total peak flow rate (which is not normally expected in hotelling mode) and the ETS capacity of 12,000 scfm (which can treat up to 12,500 scfm). The vessels/ETS ratio was adjusted such that the fraction of vessels less than 0.5 vessels was adjusted down to a whole vessel. In the Auto Carrier example, the 2.1 vessels/ETS was adjusted to 2.0. This analysis is based upon a per vessel cost basis, which means although the ETS can process 2.1 vessels, it will only be given credit for processing 2.0 vessels and half of the ETS costs will be attributed to a single vessel instead of only 48% of the ETS cost (if the 2.1 vessels/ETS were used in the calculations). If the fractional part of the vessels/ETS ratio was greater than or equal to 0.5 vessels, the value remained unchanged. This has the effect of applying a premium on the ETS cost to accommodate the estimated peak flow rate. In the Container ship example, the ETS is estimated to only process 0.9 vessels (based upon the peak flow rate), which will have the effect of putting an extra 11% premium on the ETS cost to accommodate the excess in peak flow rate (a single ETS could accommodate 2 vessels running at the estimated average flow rate of the Container vessel). These assumptions are considered conservative.

**Table 16. Total Auxiliary Engine & Boiler Flow Rates**

| Vessel Type | Total Average Flow Rate scfm | Adjusted Total Average Flow scfm | Total Peak Flow Rate scfm | Number of Vessels per ETS | Adjusted Number of Vessels per ETS |
|---|---|---|---|---|---|
| Auto Carrier | 3,451 | 3,633 | 5,807 | 2.1 | 2.0 |
| Bulk | 1,066 | 1,122 | 3,885 | 3.1 | 3.0 |
| Container Ship | 5,924 | 6,236 | 13,535 | 0.9 | 0.9 |
| General Cargo | 936 | 985 | 3,077 | 3.9 | 3.9 |
| Passenger | 24,140 | 25,411 | 65,278 | 0.2 | 0.2 |
| Reefer | 4,853 | 5,108 | 7,063 | 1.7 | 1.7 |
| Roll-on/Roll-off | 2,360 | 2,484 | 4,087 | 2.9 | 2.9 |
| Tanker | 8,196 | 8,628 | 12,786 | 0.9 | 0.9 |

The pollutant emission rates for the auxiliary engine and auxiliary boiler for each vessel type are presented in Table 17 and Table 18. They were calculated from the hotelling loads of the auxiliary engine/boiler and their respective emission factors. The auxiliary engines are assumed to run on a mix of heavy fuel oil and marine distillate (see Table 14). The auxiliary boilers are assumed to burn only heavy fuel oil continuously while hotelling (CARB, June 2008).

**Table 17. Auxiliary Engine Emissions per Vessel Type, lb/hr**

| Vessel Type | PM lb/hr | NOx lb/hr | SOx lb/hr | VOC lb/hr | CO lb/hr |
|---|---|---|---|---|---|
| Auto Carrier | 2.02 | 24.87 | 14.59 | 0.82 | 1.89 |
| Bulk | 0.64 | 7.84 | 4.60 | 0.26 | 0.60 |
| Container Ship | 3.80 | 46.83 | 27.48 | 1.55 | 3.56 |
| General Cargo | 0.47 | 5.74 | 3.37 | 0.19 | 0.44 |
| Passenger | 21.91 | 227.38 | 161.26 | 7.22 | 17.09 |
| Reefer | 2.99 | 36.80 | 21.59 | 1.21 | 2.80 |
| Roll-on/Roll-off | 1.75 | 21.60 | 12.68 | 0.71 | 1.64 |
| Tanker | 1.58 | 19.40 | 11.38 | 0.64 | 1.47 |

**Table 18. Auxiliary Boiler Emissions per Vessel Type, lb/hr**

| Vessel Type | PM lb/hr | NOx lb/hr | SOx lb/hr | VOC lb/hr | CO lb/hr |
|---|---|---|---|---|---|
| Auto Carrier | 0.49 | 1.29 | 10.11 | 0.07 | 0.12 |
| Bulk | 0.14 | 0.38 | 2.98 | 0.02 | 0.04 |
| Container Ship | 0.67 | 1.76 | 13.82 | 0.09 | 0.17 |
| General Cargo | 0.17 | 0.46 | 3.60 | 0.02 | 0.04 |
| Passenger | 1.32 | 3.47 | 27.28 | 0.18 | 0.33 |
| Reefer | 0.61 | 1.61 | 12.66 | 0.08 | 0.15 |
| Roll-on/Roll-off | 0.14 | 0.38 | 2.98 | 0.02 | 0.04 |
| Tanker | 2.81 | 7.38 | 57.95 | 0.39 | 0.70 |

The average California hotelling times for each vessel call are given in Table 19 (CARB, June 2008). It is expected that AMECS will be installed in a location with a high berth occupancy rate to fully utilize AMECS' capacity. "Maximum calls to berth" are the theoretical maximum if the berth has 100% occupancy (full utilization). Both the Barge-Based and the Dock-Based ECS design utilize the same ETS that would be installed on the dock. It is possible that the Barge-Based ECS would have a higher utilization rate than the Dock-Based ECS due to the Dock-Based ECS being limited to only treating vessels moored next to the dock. The Barge-Based ECS has not been demonstrated yet.

**Table 19. Hotelling Time and Utilization**

| Vessel Type | Average Hotelling Time hours/call | Maximum Calls to Berth calls/year | Dock Utilization % | Dock Usage calls/year |
|---|---|---|---|---|
| Auto Carrier | 18.4 | 476 | 65% | 310 |
| Bulk | 64.5 | 136 | 65% | 88 |
| Container Ship | 34.9 | 251 | 65% | 163 |
| General Cargo | 46.1 | 190 | 65% | 123 |
| Passenger | 11.7 | 751 | 20% | 150 |
| Reefer | 41.9 | 209 | 65% | 136 |
| Roll-on/Roll-off | 28.4 | 308 | 65% | 200 |
| Tanker | 33.5 | 262 | 65% | 170 |

For this analysis, the Dock-Based ECS utilization (AMECS utilization assumed to be equal to dock occupancy) is assumed to conservatively be 65% (90% is also considered possible) (Environ, 2006). The exception is the estimated 20% dock utilization for the passenger/cruise vessels which is based upon ACTI's research and observations.

The resulting estimated emissions per vessel call to a berth are given in Table 20 with the annual emissions in Table 21.

**Table 20. Auxiliary Engine & Boiler Emissions per Vessel, tons/call**

| Vessel Type | PM ton/call | NOx ton/call | SOx ton/call | VOC ton/call | CO ton/call |
|---|---|---|---|---|---|
| Auto Carrier | 0.023 | 0.240 | 0.227 | 0.008 | 0.019 |
| Bulk | 0.025 | 0.265 | 0.245 | 0.009 | 0.020 |
| Container Ship | 0.078 | 0.847 | 0.720 | 0.029 | 0.065 |
| General Cargo | 0.015 | 0.143 | 0.161 | 0.005 | 0.011 |
| Passenger | 0.136 | 1.347 | 1.100 | 0.043 | 0.102 |
| Reefer | 0.075 | 0.804 | 0.717 | 0.027 | 0.062 |
| Roll-on/Roll-off | 0.027 | 0.312 | 0.222 | 0.010 | 0.024 |
| Tanker | 0.073 | 0.448 | 1.160 | 0.017 | 0.036 |

**Table 21. Auxiliary Engine & Boiler Emissions per Vessel, tons/year**

| Vessel Type | PM ton/yr | NOx ton/yr | SOx ton/yr | VOC ton/yr | CO ton/yr |
|---|---|---|---|---|---|
| Auto Carrier | 7.1 | 74.5 | 70.3 | 2.5 | 5.7 |
| Bulk | 2.2 | 23.4 | 21.6 | 0.8 | 1.8 |
| Container Ship | 12.7 | 138.3 | 117.6 | 4.7 | 10.6 |
| General Cargo | 1.8 | 17.6 | 19.8 | 0.6 | 1.4 |
| Passenger | 20.4 | 202.2 | 165.2 | 6.5 | 15.3 |
| Reefer | 10.3 | 109.3 | 97.5 | 3.7 | 8.4 |
| Roll-on/Roll-off | 5.4 | 62.6 | 44.6 | 2.1 | 4.8 |
| Tanker | 12.5 | 76.2 | 197.4 | 2.9 | 6.2 |

## 6. Cost Effectiveness

The cost effectiveness of the AMECS is determined by dividing the total AMECS life cycle cost by the total weighted emissions reduced by AMECS over the life of the system. The use of weighted reduced emissions is based upon the Carl Moyer Memorial Air Quality Standards Program. The Carl Moyer program was established in 1998 to offer monetary incentives to encourage the voluntary purchase of cleaner-than-required engines, equipment, and emission reduction technologies (CARB, April 2008). The Carl Moyer program considers NOx, VOC and $PM_{10}$ emission reductions in one calculation where weighting factors are applied. For NOx and VOC emission reductions, a weighting factor of one is used. CARB has identified particulate emissions from diesel-fueled engines as toxic air contaminants, and believes emission reductions of $PM_{10}$ should carry additional weight in the calculation because, for an equivalent weight, these emissions are more harmful to human health. CARB uses a PM weighting factor of 20. The Carl Moyer method utilizes the Annualized Cash Flow method which multiplies the initial capital cost by a capital recovery factor to obtain an equivalent end of year annual capital cost payment (but not the recurring annual operation and maintenance costs).[6] This report estimates the Total Life Cycle Costs (2008$) by combining the annualized initial capital costs adjusted for the time value of money (Annualized Cash Flow method) and the discounted annually recurring future costs which is calculated by determining the present value of the costs from buying, operating, and maintaining the equipment over the life of the equipment (Discounted Cash Flow method).

The weighted cost effectiveness formula for AMECS analysis is:

$$\frac{\text{Total Life Cycle Cost (2008\$)}}{\text{(NOx + VOC + 20*PM) (weighted tons reduced over life of AMECS)}}$$

Table 22 summarizes the weighted emissions reduced based upon the AMECS control efficiencies (with the 1.5% reduction in NOx control efficiency to account for the SCR degradation over time). The total pollutants reduced do not include the SOx emissions (Moyer methodology).

The initial capital costs in Table 23 are on a costs per vessel basis. The ETS per vessel percentage calculates the fraction of the capital costs attributed to a single vessel (note that this is based upon the peak exhaust flow rate, not the average exhaust flow rate). It is expected for AMECS to be installed such that the optimum amount of treatable exhaust would be available. For example, the Auto Carrier berth that has one ETS would not be installed in an area that only has one ECS installed because it would only be capable of using about 50% of the ETS' capacity when the auxiliary engine and boiler are running at full load. The Auto Carrier berth should be installed with two ECS for each ETS installed to optimally utilize AMECS' ETS capacity.

---

[6] The Moyer method does not consider annual operating and maintenance costs.

## Table 22. Emissions Reduced per Vessel

| Vessel Type | PM[1] ton/yr | NOx ton/yr | VOC ton/yr | TOTAL[2] ton/yr | SOx[3] ton/yr |
|---|---|---|---|---|---|
| Auto Carrier | 135.8 | 72.7 | 2.4 | 210.9 | 70.2 |
| Bulk | 42.3 | 22.9 | 0.8 | 65.9 | 21.6 |
| Container Ship | 242.0 | 135.0 | 4.5 | 381.5 | 117.4 |
| General Cargo | 34.7 | 17.2 | 0.6 | 52.5 | 19.8 |
| Passenger | 386.7 | 197.4 | 6.2 | 590.3 | 164.9 |
| Reefer | 194.8 | 106.8 | 3.6 | 305.2 | 97.3 |
| Roll-on/Roll-off | 102.7 | 61.1 | 2.0 | 165.8 | 44.5 |
| Tanker | 237.2 | 74.4 | 2.8 | 314.4 | 197.0 |

[1] Moyer weighting factor of 20 was applied to the PM emissions reduced.
[2] Total emissions only include PM, NOx, and VOC for cost effectiveness calculations.
[3] SOx emissions reduced is provided in this table for informational purposes only.

Table 23. ETS per Vessel and Initial Capital Costs per Vessel

| Vessel Type | ETS per Vessel | ETS Costs/Vessel | | ECS Costs/vessel (Dock-Based) | | | TOTAL COSTS $/VESSEL |
|---|---|---|---|---|---|---|---|
| | | Equipment | Install | Tower | Manifold | Install | |
| Auto Carrier | 50% | 2,107,798 | 477,263 | 1,672,188 | 318,989 | 1,240,883 | 5,817,120 |
| Bulk | 33% | 1,391,147 | 314,993 | 1,672,188 | 318,989 | 1,240,883 | 4,938,200 |
| Container Ship | 113% | 4,763,624 | 1,078,613 | 1,889,573 | 360,457 | 1,402,197 | 9,494,465 |
| General Cargo | 26% | 1,096,055 | 248,177 | 1,672,188 | 318,989 | 1,240,883 | 4,576,291 |
| Passenger | 544% | 22,932,845 | 5,192,616 | 9,096,703 | 1,735,300 | 6,750,401 | 45,707,865 |
| Reefer | 59% | 2,487,202 | 563,170 | 1,672,188 | 318,989 | 1,240,883 | 6,282,431 |
| Roll-on/Roll-off | 34% | 1,433,303 | 324,539 | 1,672,188 | 318,989 | 1,240,883 | 4,989,901 |
| Tanker | 107% | 4,510,688 | 1,021,342 | 1,789,241 | 341,318 | 1,327,744 | 8,990,334 |

Table 24 contains the Dock-Based capacity factor, consumables and utilities usage rate. These usage rates are based upon the average exhaust flow rates of each vessel type and the fraction of AMECS 12,000 scfm capacity that each vessel utilizes.

## Table 24. ETS Capacity Factor, Consumables, and Utilities Usage Rate per Vessel

| Vessel Type | %ETS Exhaust Capacity | Liquid Waste gal/hr | Solid Waste lb/hr | Urea gal/hr | NaOH gal/hr | Water gal/hr | Electric Power kW | Heating MMBTU/Hr |
|---|---|---|---|---|---|---|---|---|
| Auto Carrier | 30% | 0.83 | 0.66 | 4.51 | 9.24 | 90.1 | 106 | 0.29 |
| Bulk | 9% | 0.26 | 0.20 | 1.42 | 2.84 | 27.8 | 33 | 0.09 |
| Container Ship | 52% | 1.42 | 1.14 | 8.38 | 15.44 | 154.6 | 182 | 0.50 |
| General Cargo | 8% | 0.22 | 0.18 | 1.07 | 2.61 | 24.4 | 29 | 0.08 |
| Passenger | 212% | 5.80 | 4.64 | 39.80 | 70.51 | 630.2 | 741 | 2.05 |
| Reefer | 43% | 1.17 | 0.93 | 6.62 | 12.81 | 126.7 | 149 | 0.41 |
| Roll-on/Roll-off | 21% | 0.57 | 0.45 | 3.79 | 5.86 | 61.6 | 72 | 0.20 |
| Tanker | 72% | 1.97 | 1.57 | 4.62 | 25.93 | 214.0 | 252 | 0.70 |

The berth utilization (AMECS utilization) in Table 25 determines the amount of consumable and utility costs per year for each vessel.

**Table 25. Dock-Based Berth Utilization, Consumables, and Utilities Cost**

| Vessel Type | Berth Utilization % | Liquid Waste $/year | Solid Waste $/year | Urea $/year | NaOH $/year | Water $/year | Electric Power $/year | Heating $/year |
|---|---|---|---|---|---|---|---|---|
| Auto Carrier | 65% | 1,882 | 6,924 | 89,292 | 146,845 | 1,968 | 67,734 | 13,743 |
| Bulk | 65% | 581 | 2,138 | 28,070 | 45,083 | 608 | 20,915 | 4,244 |
| Container Ship | 65% | 3,230 | 11,886 | 165,850 | 245,472 | 3,379 | 116,269 | 23,591 |
| General Cargo | 65% | 510 | 1,877 | 21,152 | 41,417 | 534 | 18,364 | 3,726 |
| Passenger | 20% | 4,050 | 14,903 | 242,465 | 344,790 | 4,236 | 145,777 | 29,579 |
| Reefer | 65% | 2,646 | 9,737 | 131,104 | 203,569 | 2,768 | 95,241 | 19,325 |
| Roll-on/Roll-off | 65% | 1,287 | 4,735 | 75,040 | 93,074 | 1,346 | 46,316 | 9,398 |
| Tanker | 65% | 4,469 | 16,445 | 91,390 | 412,058 | 4,674 | 160,863 | 32,640 |

The ETS per Vessel percentage in Table 26 affects the labor, maintenance, insurance and central facility costs per year. The consumables and utilities in Table 25 are summarized in Table 26. Burden and markup have been applied to all costs except for the utilities (e.g. electricity, natural gas, and water), as these will be supplied by the port. Maintenance and labor will supplied by a third party operator/owner. AMECS will be staffed 24 hours a day, 365 days a year.

**Table 26. Annual Operation and Maintenance Cost**

| Vessel Type | ETS per Vessel % | Labor Cost $/year | Maintenance & Insurance $/year | Consumables & Utilities $/year | Central Facility $/year | Total Cost $/year |
|---|---|---|---|---|---|---|
| Auto Carrier | 50% | 990,391 | 55,026 | 328,389 | 182,031 | 1,555,836 |
| Bulk | 33% | 522,972 | 36,317 | 101,639 | 120,140 | 781,069 |
| Container Ship | 113% | 1,467,444 | 124,358 | 569,678 | 411,390 | 2,572,870 |
| General Cargo | 26% | 472,744 | 28,613 | 87,580 | 94,656 | 683,594 |
| Passenger | 544% | 1,452,704 | 598,681 | 785,799 | 1,980,498 | 4,817,682 |
| Reefer | 59% | 910,504 | 64,931 | 464,389 | 214,797 | 1,654,620 |
| Roll-on/Roll-off | 34% | 662,098 | 37,418 | 231,195 | 123,781 | 1,054,492 |
| Tanker | 107% | 1,475,272 | 117,755 | 722,539 | 389,546 | 2,705,113 |

The total life cycle cost of the AMECS is based upon the discounted cash flow of costs in the future (which brings the costs to their present value), and the annualized payments of the initial capital costs to account for the time value of money. The costs are summed to produce the total life cycle cost of the AMECS. The interest (discount rate) is assumed to be 4 percent based upon the value used in the Carl Moyer program (CARB, April 2008). The system is designed and projected to have a life of 20 years (the EPA Air Pollution Control Cost Manual uses a 20 year economic lifetime for a SCR system) (EPA, January 2002). Table 27 summarizes the fully loaded (with burden and markup) cost elements. In the Auto Carrier example, $5.8 million capital is annualized with an adjustment for the time value of money (4 percent interest for 20 years) to be $0.4 million per year with a cumulative 20 year cost of $8.6 million. The net present value (NPV), which accounts for the changes in value of money over time, of the annually recurring operation and maintenance cost ($1.6 million) over the life of AMECS is $22 million. Figure 16 graphically shows the total project life costs with the capital cost and O&M cost components (per vessel basis).

**Table 27. Annual Cost and Total Project Life Cost (2008$) per Vessel**

| Vessel Type | Berth Utilization | Initial Capital Cost | Yearly Cost Element | | 20 Year Total | |
|---|---|---|---|---|---|---|
| | | | Annualized Capital Cost | O&M Cost | Annualized Capital Cost | NPV O&M Cost |
| Auto Carrier | 65% | 5,817,120 | 428,034 | 1,555,836 | 8,560,678 | 21,990,095 |
| Bulk | 65% | 4,938,200 | 363,361 | 781,069 | 7,267,227 | 11,039,575 |
| Container Ship | 65% | 9,494,465 | 698,619 | 2,572,870 | 13,972,386 | 36,364,790 |
| General Cargo | 65% | 4,576,291 | 336,732 | 683,594 | 6,734,630 | 9,661,879 |
| Passenger | 20% | 45,707,865 | 3,363,265 | 4,817,682 | 67,265,294 | 68,092,826 |
| Reefer | 65% | 6,282,431 | 462,272 | 1,654,620 | 9,245,446 | 23,386,299 |
| Roll-on/Roll-off | 65% | 4,989,901 | 367,166 | 1,054,492 | 7,343,313 | 14,904,121 |
| Tanker | 65% | 8,990,334 | 661,524 | 2,705,113 | 13,230,490 | 38,233,901 |

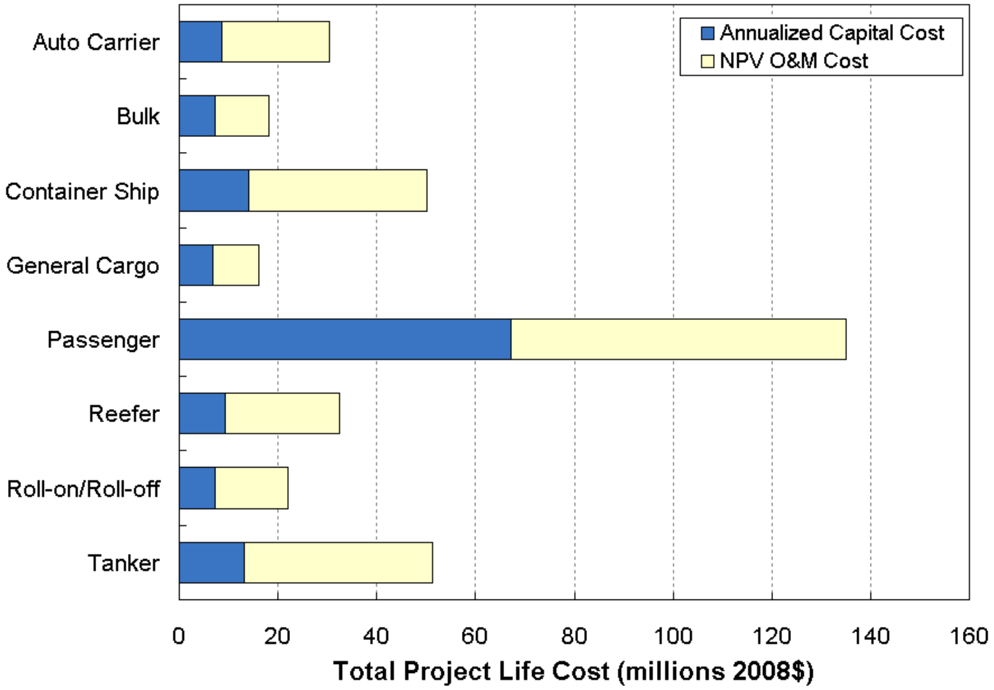


**Figure 16. Total Project Life Cost (per Vessel)**

Table 28 presents the total project cost over the estimated 20 year AMECS life and the adjusted controlled emissions weighted with the factor of 20 applied to the PM emissions reduced. The total cost and emissions reduced are on a per vessel basis.

**Table 28. Cost Effectiveness Over 20 Year AMECS Life, per Vessel**

| Vessel Type | Total Cost 2008$ | Weighted Emissions Reduced, tons | Cost Effectiveness 2008$/ton |
|---|---|---|---|
| Auto Carrier | 30,550,773 | 4,218 | 7,242 |
| Bulk | 18,306,802 | 1,318 | 13,890 |
| Container Ship | 50,337,176 | 7,630 | 6,597 |
| General Cargo | 16,396,509 | 1,049 | 15,627 |
| Passenger | 135,358,120 | 11,807 | 11,465 |
| Reefer | 32,631,744 | 6,103 | 5,347 |
| Roll-on/Roll-off | 22,247,434 | 3,317 | 6,707 |
| Tanker | 51,464,390 | 6,288 | 8,184 |

To estimate the costs of a total AMECS installation that will utilize the ETS capacity (for a minimum of one vessel), Table 29 was created to summarize the initial capital costs (ECS and ETS) and recurring annual O&M costs for AMECS installations based upon the ETS per OGV factor (which was based upon the peak exhaust flow rate and the single ETS unit capacity of 12,000 scfm). The number of ECS units is also the number of vessels that the AMECS can service simultaneously.

**Table 29. Total AMECS Installation for Full ETS Utilization (2008$)**

| Vessel Type | ETS per OGV | Number of ECS units | Number of ETS units | Total ECS Cost/AMECS | Total ETS Cost/AMECS | Total O&M Cost/year per AMECS |
|---|---|---|---|---|---|---|
| Auto Carrier | 50% | 2 | 1 | 6,464,119 | 5,170,121 | 3,111,672 |
| Bulk | 33% | 3 | 1 | 9,696,178 | 5,118,420 | 2,343,206 |
| Container Ship | 113% | 1 | 1 | 3,652,227 | 5,842,237 | 2,572,870 |
| General Cargo | 26% | 4 | 1 | 12,928,238 | 5,376,926 | 2,734,377 |
| Passenger | 544% | 1 | 5 | 17,582,404 | 28,125,461 | 4,817,682 |
| Reefer | 59% | 2 | 1 | 6,464,119 | 6,100,743 | 3,309,240 |
| Roll-on/Roll-off | 34% | 3 | 1 | 9,696,178 | 5,273,524 | 3,163,475 |
| Tanker | 107% | 1 | 1 | 3,458,304 | 5,532,030 | 2,705,113 |

Table 30 presents the total project cost over the estimated 20 year AMECS life and the adjusted controlled emissions weighted with the factor of 20 applied to the PM emissions reduced. The total cost and emissions reduced are on a total AMECS installation basis. The cost effectiveness is the same as the cost effectiveness presented in Table 28 (per vessel basis). Figure 17 graphically shows the cost effectiveness of the AMECS for the various vessel types.

**Table 30. Cost Effectiveness Over 20 Year AMECS Life, Total AMECS Installation**

| Vessel Type | Annualize Capital Cost 2008$ | Present Value O&M Cost 2008$ | Total Cost 2008$ | Weighted Emissions Reduced tons | Cost Effectiveness 2008$/ton |
|---|---|---|---|---|---|
| Auto Carrier | 17,121,356 | 43,980,190 | 61,101,546 | 8,437 | 7,242 |
| Bulk | 21,801,682 | 33,118,725 | 54,920,407 | 3,954 | 13,890 |
| Container Ship | 13,972,386 | 36,364,790 | 50,337,176 | 7,630 | 6,597 |
| General Cargo | 26,938,521 | 38,647,516 | 65,586,036 | 4,197 | 15,627 |
| Passenger | 67,265,294 | 68,092,826 | 135,358,120 | 11,807 | 11,465 |
| Reefer | 18,490,891 | 46,772,598 | 65,263,489 | 12,206 | 5,347 |
| Roll-on/Roll-off | 22,029,938 | 44,712,363 | 66,742,301 | 9,951 | 6,707 |
| Tanker | 13,230,490 | 38,233,901 | 51,464,390 | 6,288 | 8,184 |

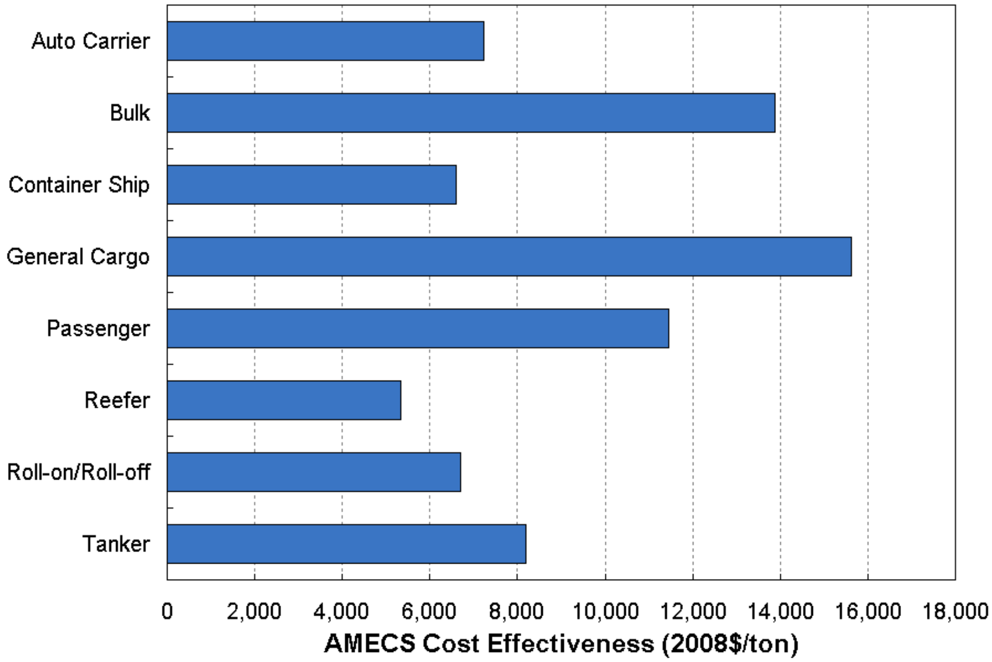


**Figure 17. AMECS Cost Effectiveness**

If AMECS were to be Barge-Based deployed, which could potentially treat any type of vessel, a weighted average calculation could give more relevance to vessels that hotel longer. The California and POLB weighting factors are based upon the vessel port visits and average hotelling time per visit in 2006 (CARB, June 2008). ACTI developed weighting factors based upon the relative applicability/marketability of AMECS to the various vessel types. Table 31 shows the weighting factor profiles for the California average, POLB average, and ACTI weighting factor profiles for each vessel type.

**Table 31. Weighting Factor Profiles**

| Vessel Type | CA Port Visits in 2006 | CA Ave. Hotelling Time hrs/visit | CA Average Weighting Factor | POLB Port Visits in 2006 | POLB Hotelling Time hrs/visit | POLB Weighting Factor | ACTI Weighting Factor |
|---|---|---|---|---|---|---|---|
| Auto Carrier | 1,006 | 18.4 | 4.9% | 247 | 17.7 | 3.6% | 15% |
| Bulk | 983 | 64.5 | 16.7% | 290 | 55.9 | 13.4% | 33% |
| Container Ship | 5,038 | 34.9 | 46.2% | 1,445 | 49.5 | 59.2% | 4% |
| General Cargo | 371 | 46.1 | 4.5% | 142 | 44.4 | 5.2% | 5% |
| Passenger | 770 | 11.7 | 2.4% | 133 | 11.0 | 1.2% | 3% |
| Reefer | 315 | 41.9 | 3.5% | 28 | 24.4 | 0.6% | 5% |
| Roll-on/Roll-off | 112 | 28.4 | 0.8% | 52 | 34.5 | 1.5% | 10% |
| Tanker | 2,391 | 33.5 | 21.0% | 536 | 34.5 | 15.3% | 25% |

Table 32 presents the simple average and various weighted averages. The simple average of \$9,382/ton assumes that each of the cost effectiveness values for each vessel type is of equivalent importance. The California and POLB weighted average cost effectiveness are lower than the simple average with the ACTI weighted average having the highest cost effectiveness of \$10,043/ton of weighted emissions reduced by AMECS.

**Table 32. Average Cost Effectiveness**

| | Cost Effectiveness 2008$/ton |
|---|---|
| Simple Average | 9,382 |
| California Weighted Average | 8,658 |
| POLB Weighted Average | 8,366 |
| ACTI Weighted Average | 10,043 |

Averaging the different cost effectiveness of the various vessel types may not be appropriate for the Dock-Based design because a single berth does not service all vessel types. The Barge-Based design would cost more, but it would also have an increased AMECS utilization due to not being constrained to only treating vessels berthed next to the AMECS and it would be able to service different vessels. The Barge-Based design (not demonstrated yet) is beyond the scope of this report. However, a single average value allows for a general examination of the sensitivity of the average cost effectiveness of all the various vessel types resulting from varying various input/assumptions.

Sensitivity analysis was performed on the higher ACTI weighted average cost effectiveness of \$10,043/ton according to the hypothetical base case parameters listed in Table 33. The results are graphed in the tornado chart in Figure 18.

Table 33. Parameters Used for the Cost Effectiveness Sensitivity Analysis

| | Better Cost Effectiveness | ACTI Weighted Midpoint Case | Worse Cost Effectiveness |
|---|---|---|---|
| **Berth/AMECS Utilization Rate**[1] | 90% | 65% | 40% |
| **Peak Exhaust Flow Rates** | -25% | --- | +25% |
| **AMECS Lifetime** | 25 years | 20 Years | 15 years |
| **Water/Electricity/NG Rates** | -50% | --- | +200% |
| **Interest (Discount Rate)** | 6% | 4% | 3% |

[1] Passenger vessels were kept constant at 20% berth utilization.

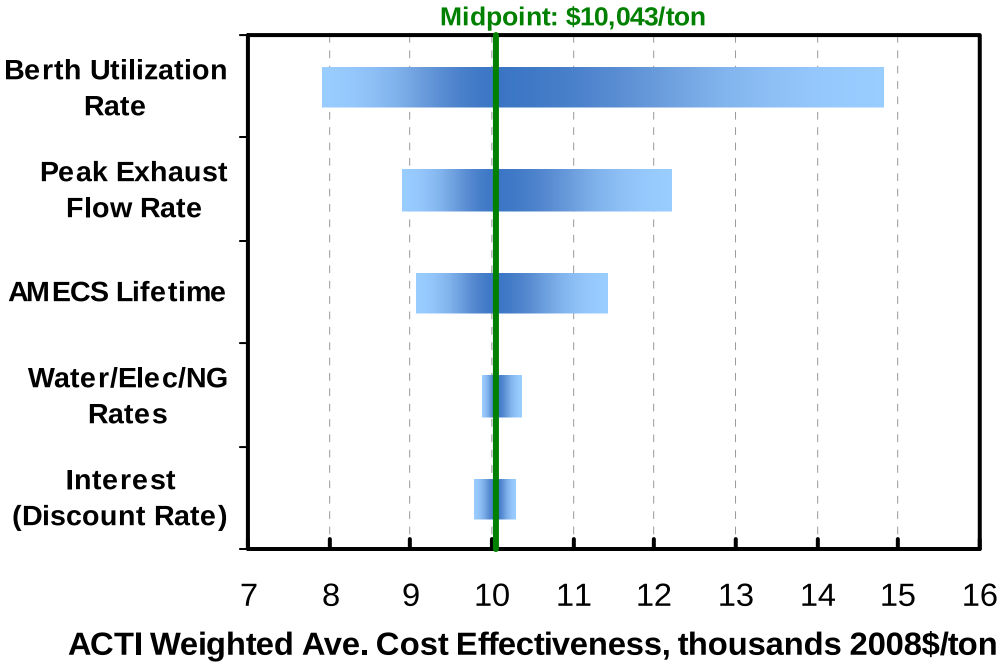


Figure 18. Cost Effectiveness Sensitivity on ACTI Weighted Average

Figure 18 highlights the importance of installing the AMECS on a berth with a high occupancy which would allow AMECS the opportunity to be utilized thereby improving its cost effectiveness. The midpoint/default scenario for the analysis was set at 65% (except for passenger vessels which were kept at a constant 20%). The maximum (worst) cost effectiveness ($14,831/ton) is based upon a berth utilization of 40% with the minimum (better) cost effectiveness ($7,916/ton) due to a 90% berth utilization/occupancy rate. The 25% drop in berth utilization produced a 48% increase in cost effectiveness value (worst), but a 25% increase in berth utilization produced a 21% improvement (decrease) in cost effectiveness.

A 25% increase in estimated peak exhaust flow rate (auxiliary engine and boiler) produced a 22% increase in cost effectiveness ($12,205/ton). A 25% decrease in peak exhaust flow rates for each vessel type produced an average 11% reduction ($8,905).

If the 20 design life of AMECS could be extended to 25 years, the cost effectiveness would improve by 10% ($9,061/ton). But if the AMECS life was reduced to 15 years, the cost effectiveness would increase by 14% ($11,417/ton).

The change in water/utility costs didn't make as much of an impact on the cost effectiveness of AMECS. Doubling the water/utility rates only increased the cost effectiveness by 3% ($10,358/ton) and cutting the rates in half only improve the cost effectiveness by 2% ($9,886/ton).

The cost effectiveness calculations based upon annualized capital costs which effectively increases the total project costs due to the interest rate is countered by the reduction in total operation and maintenance costs for the project over the AMECS life due to the discount rate bringing future O&M costs to the 2008 present value. Assuming that the interest rate and the discount rate remain equal, decreasing the rate to 3%, produced a 2% increase in cost effectiveness ($10,289/ton). However, increasing the interest/discount rate to 6% resulted in a 3% improvement in cost effectiveness ($9,780).

An additional benefit of AMECS that is not captured by the cost effectiveness analysis is the 99.8% reduction in SOx emissions and 34.8% reduction in CO emissions. Vessels not being required to be modified in order for AMECS to treat the exhaust emissions is also a benefit that is not examined by this cost effectiveness analysis.

# 7. Summary

The testing of AMECS at the POLB was to investigate the effectiveness of utilizing stationary air pollution control equipment to capture and treat hotelling emissions from vessels that were moored at berths. A major advantage of the AMECS is that no vessel modifications are required for AMECS to treat the exhaust emissions.

The objectives/criteria of the test program and its' accomplishments were:

**Objective 1:** To document the effectiveness of the AMECS system in reducing ocean-going vessel emissions of particulate matter (PM), oxides of nitrogen (NOx), volatile organic compounds (VOC) and other pollutants under typical at-berth operating conditions. The criterion for a successful demonstration will be no less than 90% reduction in PM, NOx, and VOC.

Objective 1 is accomplished by this report which documents and evaluates the AMECS pollutant control efficiencies and the AMECS costs effectiveness. The average PM, NOx, VOC, as well as SOx removal efficiencies of at least 95% from the vessel exhaust exceeds Objective 1 criteria for success.

**Objective 2:** To assure that the emission control equipment, process, and procedures do not interfere with normal Metropolitan Stevedore operations. This would include not affecting the loading/offloading operations of Metropolitan Stevedore as well as the auxiliary engine/boiler operation of the vessel

Objective 2 was accomplished. Robert Waterman, Assistant Vice-President of Bulk Operations for Metropolitan Stevedore, stated that there were no adverse affects to their normal operations during AMECS operation. There was no noted damage or adverse effect on the vessels, the auxiliary engines, nor the auxiliary boilers due to the operation of AMECS. ACTI personnel were present in the ship's engine control room throughout all the tests and confirmed with the ship's engineer that there were no observable effects due to AMECS' attachment, operation, and detachment from the ships.

Table 34 summarizes the overall average pollutant control efficiencies of the AMECS. The measured average control efficiencies are presented, but the adjusted average control efficiencies were used for this report's analysis to produce a more conservative analysis.

**Table 34. Average AMECS Control Efficiency Summary**

| | NOx | PM | VOC | SO2 | CO |
|---|---|---|---|---|---|
| **Measured Average Control Efficiency** | >99.1% | 95.0% | 96.3% | 99.8% | 43.8% |
| **Adjusted Average Control Efficiency**[1] | >97.6% | 95.0% | 96.3% | 99.8% | 43.8% |

[1] Cost effectiveness analysis assumed 1.5% reduced NOx control efficiency to allow for SCR catalyst degradation over time

Table 35 presents the total 20 year AMECS cost effectiveness and the number of ECS installed for each AMECS installation (which is the same number of vessels that can be serviced by AMECS simultaneously). Figure 19 graphs the cost effectiveness for each vessel type (assumes a berth is dedicated to a specific vessel type). Sensitivity analysis showed that placement of the

AMECS in a berth with high occupancy is important in increasing the AMECS utilization rate and consequently improve the cost effectiveness.

**Table 35. Cost Effectiveness Over 20 Year AMECS Life, Total AMECS Installation**

| Vessel Type | Maximum Number of Vessels Treated by AMECS Simultaneously | Total Life Cost 2008$ | Weighted Emissions Reduced tons | Cost Effectiveness 2008$/ton |
|---|---|---|---|---|
| Auto Carrier | 2 | 61,101,546 | 8,437 | 7,242 |
| Bulk | 3 | 54,920,407 | 3,954 | 13,890 |
| Container Ship | 1 | 50,337,176 | 7,630 | 6,597 |
| General Cargo | 4 | 65,586,036 | 4,197 | 15,627 |
| Passenger | 1 | 135,358,120 | 11,807 | 11,465 |
| Reefer | 2 | 65,263,489 | 12,206 | 5,347 |
| Roll-on/Roll-off | 3 | 66,742,301 | 9,951 | 6,707 |
| Tanker | 1 | 51,464,390 | 6,288 | 8,184 |

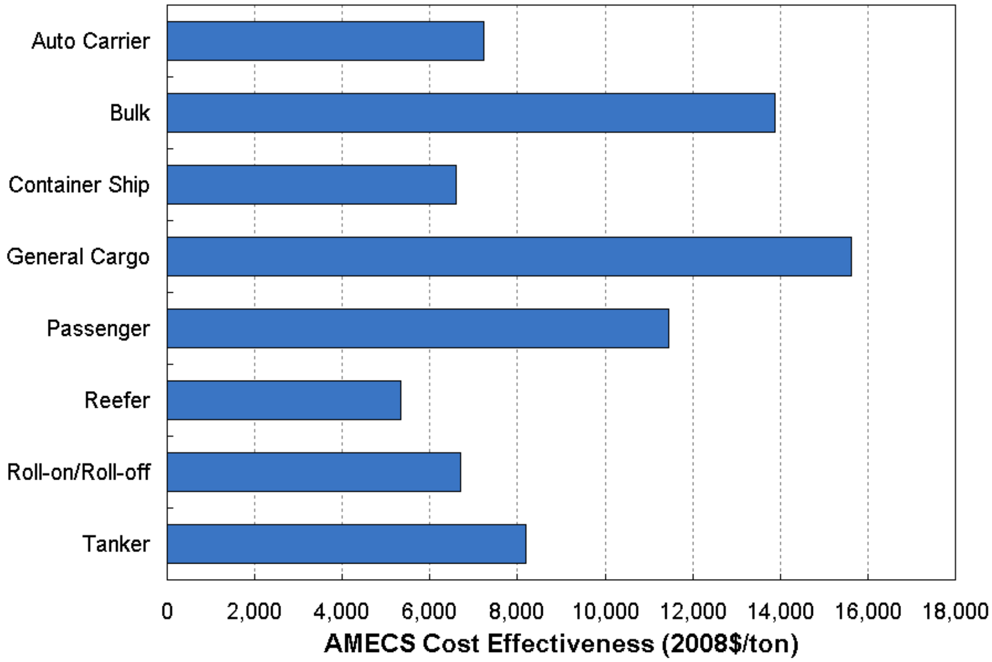


**Figure 19. AMECS Cost Effectiveness**

The successful capture efficiencies demonstrated by ALECS at the Union Pacific Railroad's J. R. Davis Rail Yard in Roseville, California, and AMECS at the Port of Long Beach resulted in a support letter from Barry Wallerstein, Executive Officer of the SCAQMD (Appendix G). The letter stated that the implementation of both systems could "provide large benefits to the South Coast Air Basin and, in particular, the communities adjacent to these sources."

## 8. List of Acronyms

| | |
|---|---|
| **ACTI** | Advanced Cleanup Technologies, Inc. |
| **ALECS** | Advanced Locomotive Emissions Control System |
| **AMECS** | Advanced Maritime Emissions Control System |
| **ARB** | California Air Resources Board |
| **Btu** | British Thermal Unit |
| **CA** | California |
| **CARB** | California Air Resources Board |
| **CCS** | Cloud Chamber Scrubber (subsystem of ETS) |
| **CEMS** | Continuous Emission Monitoring System |
| **CO** | Carbon Monoxide |
| **$CO_2$** | Carbon Dioxide |
| **dwt** | Deadweight Tonnage |
| **ECS** | Emissions Capture System |
| **EPA** | U.S. Environmental Protection Agency |
| **ETS** | Emissions Treatment System |
| **°F** | degrees Fahrenheit |
| **gal** | Gallons |
| **HFO** | Heavy Fuel Oil |
| **hr** | Hour |
| **ID** | Induced Draft |
| **kWh** | Kilowatt Hours |
| **lb** | Pounds |
| **MMBtu** | Million British Thermal Units |
| **NaOH** | Sodium Hydroxide |
| **NG** | Natural Gas |
| **$NH_3$** | Ammonia |
| **NO** | Nitric Oxide |
| **$NO_x$** | Oxides of Nitrogen |
| **O&M** | Operation and Maintenance |
| **$O_2$** | Oxygen |
| **OGV** | Ocean-Going Vessel |
| **PCC** | Preconditioning Chamber (subsystem of the ETS) |
| **PM** | Particulate Matter |
| **$PM_{2.5}$** | Particulate Matter less than or equal to 2.5 microns |
| **$PM_{10}$** | Particulate Matter less than or equal to 10 microns |
| **POLB** | Port of Long Beach |
| **ppm** | parts per million |
| **S** | Sulfur |
| **SCAQMD** | South Coast Air Quality Management District |
| **scfm** | Standard Cubic Feet per Minute |
| **SCR** | Selective Catalytic Reduction |
| **$SO_2$** | Sulfur Dioxide |
| **$SO_x$** | Oxides of Sulfur |
| **VOC** | Volatile Organic Compounds |
| **yr** | Year |

## 9. References

(CARB, October 2005). Milkey, P., Di, P., Hand, R., Lee, J., Rosenkranz, K., Santos, A., Soriano, B., Sterling, T., Yee, S., "Initial Statement of Reasons for Proposed Rulemaking: Proposed Regulation for Auxiliary Diesel Engines and Diesel-electric Engines Operated on Ocean-Going Vessels within California Waters and 24 Nautical Miles of the California Baseline," California Air Resources Board report, October 2005

(CARB, April 2006), Di, P., Servin, A., Rosenkranz, K., Schwehr, B., Tran, H., “Diesel Particulate Matter Exposure Assessment Study for the Ports of Los Angeles and Long Beach,” California Air Resources Board report, April 2006

(CARB, April 2008). California Air Resources Board, “The Carl Moyer Program Guidelines,” Approved revision 2008, released April 22, 2008

(CARB, June 2008). Soriano, B., Milkey, P., Alexis, A., Di, P., Du, S., Lu, J., Hand, R., Houghton, M., Komlenic, M., Suer, C., Williams, L., Zuo, Y., "Initial Statement of Reasons for Proposed Rulemaking: Fuel Sulfur and Other Operational Requirements for Ocean-Going Vessels within California Waters and 24 Nautical Miles of the California Baseline," California Air Resources Board report, June 2008

(CAAP, 2006) “San Pedro Bay Ports Clean Air Action Plan,” Prepared by Port of Los Angeles and Port of Long Beach in cooperation with U.S. Environmental Protection Agency, California Air Resources Board, and the South Coast Air Quality Management District, 2006

(EIA, 2008). Energy Information Administration, Short-Term Energy Outlook, November 2008 website: http://www.eia.doe.gov/emeu/steo/pub/contents.html

(Environ, 2004). Jiang, H., Lester, J., Hower, J., “Report on Evaluation of Advanced Maritime Emissions Control System,” Environ report for the Port of Long Beach, December 2, 2004

(Environ, 2006). Environ, “Port of Long Beach Southeast Basin Vessel Emission Control Project,” Environ report for the Port of Long Beach included in the Negative Declaration/Application Summary Report, Application No. HDP 06-036, August 2006

(EPA, 2002). United States Environmental Protection Agency, "EPA Air Pollution Control Cost Manual," 6th Edition, Report #EPA/452/B-02-001, January 2002

(Fuller et al., 1996). Fuller, S., Petersen, S., *Life-Cycle Costing Manual for the Federal Energy Management Program*, 1995 Edition, February 1996

(SCAQMD, 2006). Kay, M., Baez, A., Lange, H., “Best Available Control Technology Guidelines,” South Coast Air Quality Management District report, July 14, 2006

(Starcrest, March 2004). Starcrest Consulting Group, LLC, “Port of Long Beach 2002 Baseline Emissions Inventory,” Prepared for Port of Long Beach, March 2004

(Starcrest, July 2005). Starcrest Consulting Group, LLC, “Port of Los Angeles Baseline Air Emissions Inventory – 2001,” Prepared for Port of Los Angeles, July 2005

(Starcrest, June 2008). Starcrest Consulting Group, LLC, “Port of Long Beach Air Emissions Inventory – 2006,” Prepared for Port of Long Beach, June 2008

(TIAX, 2007). Chan, M., Jackson, M., “ALECS Proof-of-Concept Testing at the Union Pacific J. R. Davis Rail Yard in Roseville, California,” TIAX Report to Placer County Air Pollution Control District, April 2, 2007

Website Downloaded 10/24/08: http://www.polb.com/economics/stats/default.asp

Website Downloaded 11/10/08: http://www.arb.ca.gov/diesel/factsheets/dieselpmfs.pdf

AQMD

South Coast
Air Quality Management District
21865 Copley Drive, Diamond Bar, CA 91765-4178
(909) 396-2000 · www.aqmd.gov

*Office of the Executive Officer*
*Barry R. Wallerstein, D.Env.*
*909.396.2100, fax 909.396.3340*

September 11, 2009

Matthew F. Stewart
Advanced Cleanup Technologies, Inc.
18414 S. Santa Fe Ave.
Rancho Dominguez, CA 90221

Dear Mr. Stewart:

Congratulations! Advanced Cleanup Technologies, Inc. has been selected as a winner of a Clean Air Award in the category of Advancement of Air Pollution Technology. This prestigious award honors the visionaries in our region who have helped in the fight for clean air through innovation, leadership and exemplary service.

The 21st annual ceremony will take place at 11:30 a.m. on Friday, October 2, 2009 at the Millennium Biltmore Hotel in downtown Los Angeles. KNBC health and science reporter Dr. Bruce Hensel will be the moderator. An invitation is enclosed. A representative from our staff will contact you for more information to be featured in our event program.

Again, congratulations for a job well done. Two complimentary reservations will be held in your name at the registration table. You may request additional reservations at $40 each by calling Ms. Geri Bowen at (909) 396-2778, or email at gbowen@aqmd.gov.

We look forward to seeing you on October 2nd at the Millennium Biltmore Hotel.

Sincerely,

Barry R. Wallerstein, D.Env.
Executive Officer

BW:OA:AG:MC:dw

Enclosure/1

*Cleaning the air that we breathe...*

# Air Resources Board

**Mary D. Nichols, Chairman**
1001 I Street • P.O. Box 2815
Sacramento, California 95812 • www.arb.ca.gov

**Linda S. Adams**
*Secretary for*
*Environmental Protection*

**Arnold Schwarzenegger**
*Governor*

December 15, 2008

Mr. Ruben Garcia
Chief Executive Officer
Advanced Cleanup Technologies, Inc. (ACTI)
18414 S. Santa Fe Avenue
Rancho Dominguez, California 90221

Dear Mr. Garcia:

The Air Resources Board (ARB) supports your effort in developing the Advanced Marine Emission Control System (AMECS) for application to ships berthed at California ports. Professional Environmental Services (PES) conducted two source tests of the AMECS while connected to vessels berthed at the Metropolitan Stevedore Company's terminal at the Port of Long Beach. PES conducted the tests on May 26, 2008 (*Queen Lily*) and July 16, 2008 (*Angela*).

ARB staff reviewed the two source-test reports and evaluated the performance of the AMECS during these tests. The AMECS consists of an emission capturing device, or "bonnet," and an emissions treatment system. Assuming that the bonnet fully captures the stack emissions (i.e., no fugitive leaks) and the emissions treatment system is operating properly, ARB staff estimates the emission-reduction performance of the AMECS to have been as follows:

- Particulate matter (PM) emissions were reduced by 93 – 98 percent.
- Oxides of nitrogen (NOx) emissions were reduced by at least 95 percent.

Staff notes that for compliance with the hotelling emissions reduction regulation, the overall reduction of the hotelling emissions from the vessel would be determined by the capture efficiency of the bonnet system, the emission performance of the treatment system, the amount of time it takes to attach the bonnet and disconnect the bonnet from the ship's stack while it is docked, and any emissions resulting from the emission treatment system (e.g., supplemental burner, ICE generator). This approach is consistent with how ARB staff addressed emission reductions for grid-based shore power. Staff reduced the overall emission reduction efficiency of grid-based shore power by estimating connect/disconnect times and by considering the emissions from the power plants providing the power to the ship.

With the caveats and calculation adjustments discussed above, staff expects the AMECS system to be capable of meeting the requirements of the Regulation to Reduce Emissions from Diesel Auxiliary Engines on Ocean-Going Vessels While At-Berth at a California Port.

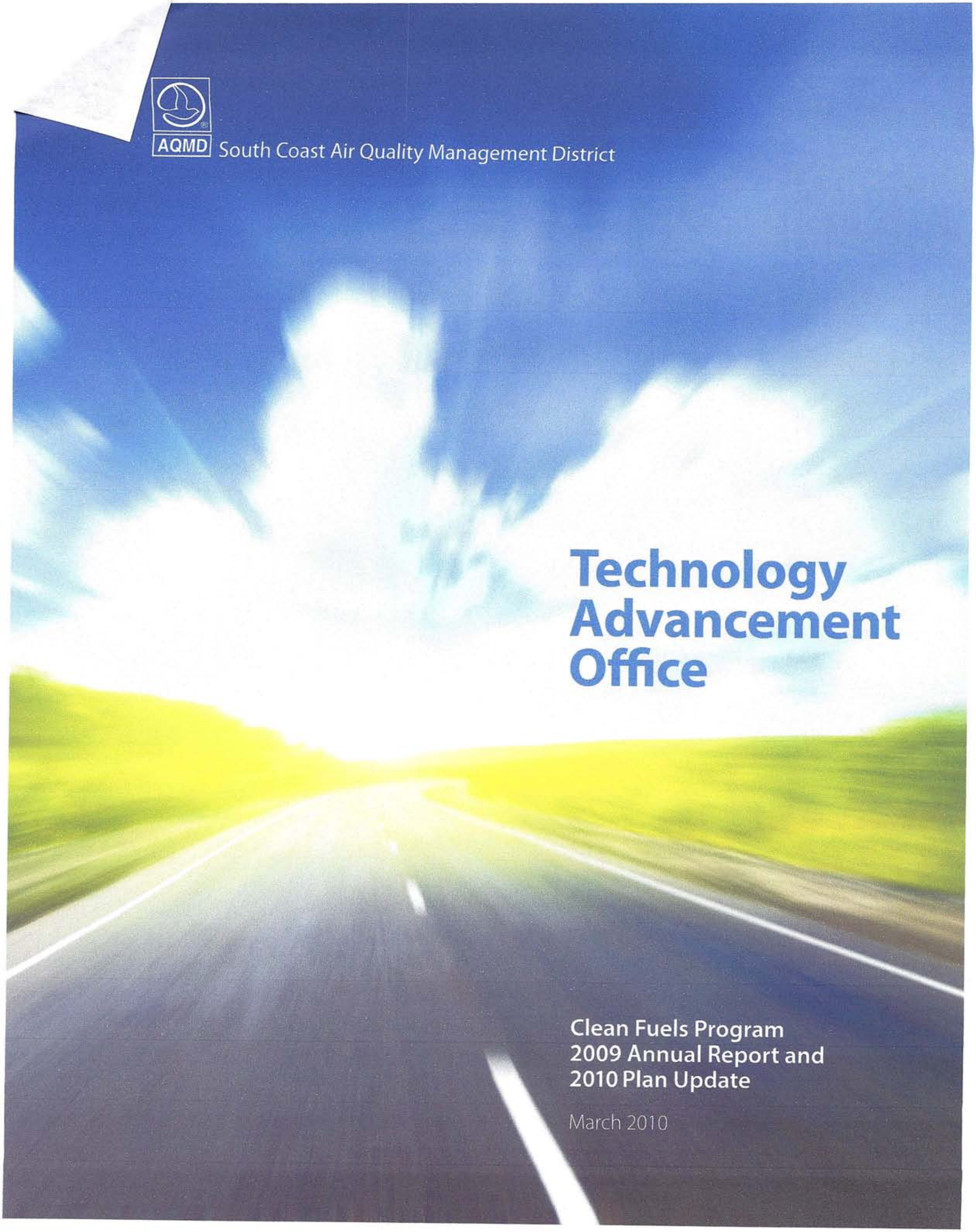
If you have any further questions regarding this matter, please contact Mike Waugh, Manager, Program Assistance Section, at (916) 445-6018 or via email at mwaugh@arb.ca.gov.

Sincerely,

Robert D. Fletcher, Chief
Stationary Source Division

cc: Mr. George L. Osborn
1127 11th Street, Suite 225
Sacramento, California 95814

Mr. Mike Waugh, Manager
Program Assistance Section



AQMD South Coast Air Quality Management District

# Technology Advancement Office

## Clean Fuels Program 2009 Annual Report and 2010 Plan Update

March 2010

**SCAQMD Contract #09150** **February 2009**

# Develop & Demonstrate Stationary Emission Control System for Marine Vessels (AMECS)

### Contractor
Advanced Cleanup Technologies, Inc.

### Cosponsors
Advanced Cleanup Technologies, Inc.
Port of Long Beach
Port of Los Angeles

### Project Officer
Mike Bogdanoff

## Background

In August 2006, the Advanced Locomotive Emissions Control System (ALECS) was successfully demonstrated at Union Pacific Railroad's rail yard in Roseville, CA. This proof-of-concept demonstration was sponsored by the U.S. Environmental Protection Agency, CARB, and others. The ALECS consists of an overhead moveable "bonnet" arrangement to collect emissions from locomotives being serviced and a ground-mounted Emission Treatment System (ETS). The ALECS demonstration reduced locomotive emissions by more than 90 percent and reduced noise by 5-7 decibels. The ground-mounted ETS was then engineered to treat emissions from at-berth ships in a system called the Advanced Maritime Emissions Control System (AMECS).

## Project Objective

The objective of this project was to further develop and demonstrate Advanced Cleanup Technologies Inc.'s (ACTI) AMECS and determine its capacity to remove emissions from at-berth ocean-going ships.

## Technology Description

AMECS captures and treats the exhaust gas from ship's auxiliary engines, generators and boilers during hotelling operations. A large bonnet is lifted over and remotely secured to the exhaust stack of the ship, which encloses several exhaust outlets. The exhaust gases are drawn from the bonnet through ducting into the dock-mounted

ETS where the pollutants are removed (see Figure 1).

The ETS utilizes a Preconditioning Chamber where metered sodium hydroxide is injected to remove $SO_x$ emissions; three Cloud Chamber Scrubbers (Tri-Mer Corp.) to remove PM emissions; and a Selective Catalytic Reduction (SCR) Reactor (Argillon Corp.) to remove NOx emissions. It is designed to remove 95 percent or more of the $SO_x$, PM and NOx from the berthed ship exhaust. A substantial percentage of VOC is incidentally removed, also.

**Figure 1: AMECS during Testing on the Queen Lily**

## Status

In May 2008, the AMECS was installed on the dock at Metropolitan Stevedore at the Port of Long Beach, Pier G, Berth 214. The bonnet capture system required significant design modifications to better accommodate the variety of ship stacks and to properly capture all the emissions. The testing of two ships, the Queen Lily and the Angela, was conducted in May and July 2008, respectively. Professional Environmental Services performed the emission tests in parallel with the Continuous Emission Monitoring System of the AMECS.

## Results

The emission testing of the Queen Lily and the

Angela yielded average reductions of 99 percent SOx, 95 percent PM, 99 percent NOx and 96 percent VOC.

## Benefits

The potential impact of implementing the AMECS technology in the Southeast Basin of the Port of Long Beach is illustrated below. This would mean coverage of Berths G212, G214, F208, F211, F204/205, and F206/207, for which two ETS's and six to eight emission capture systems would be required (see Figure 2).

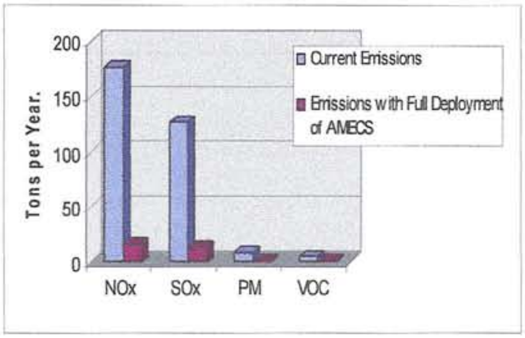


**Figure 2: Hotelling Emissions in the POLB Southeast Basin with AMECS**

Another benefit of AMECS is the ability to treat ship exhaust emissions without any modification to the ship. There is also no interference with normal ship or ship loading or unloading operations. Finally, AMECS reduces emissions from the auxiliary boilers, which shore power solutions do not address. The waste water generated by the AMECS will be suitable for disposal in an industrial sewer. The generated solid waste has been tested and found to be non-hazardous and suitable for disposal in a landfill, or it can be recycled or incinerated.

## Project Costs

The projected costs for this project were $598,211 for developing the AMECS and emission testing two ships. These costs were to be funded by:

| | |
|---|---|
| ACTI | $244,157 |
| Port of Long Beach | 149,527 |
| Port of Los Angeles | 149,527 |
| SCAQMD | 55,000 |
| | $598,211 |

The actual final costs incurred were $777,881 with ACTI paying the additional costs.

## Commercialization and Applications

The cost of an AMECS system is $12.3 million for a two-tower dock-based unit and $9.5 million for a barge based unit. The average annual operating cost is $1.0 million with an expected 20-year life. Based upon the emission reductions determined under this project, the cost-effectiveness of the AMECS has been calculated for various types of ships berthing at the Ports of Long Beach and Los Angeles. The average cost effectiveness of AMECS is about $13,000/ton.

The AMECS technology used in this project appears ready for commercialization. It is expected that the AMECS demonstration unit will be operated for another year at Pier G214 in order to further refine the system and procedures, to enhance its reliability and maintainability, and to verify its operating costs.