Final Report

Evaluation of Diesel Particulate Filter Systems at Stobie Mine

March, 2006

Diesel
Emissions
Evaluation
Program

INCO

Prepared by: Bruce R. Conard

Assisted by:
Jozef Stachulak
Andreas Mayer
George Schnakenberg
Aleksandar Bugarski
Mahe Gangal
Gregory Nault
Rick Mayotte
Robert Coppal
Gilles Bedard

Preface

The Stobie project to test diesel particulate filter systems underground was truly a team effort. Many people having a variety of expertise contributed to the success of the project. By naming a few contributors to this Final Report, I intend to recognize the specific efforts of some key individuals, but I do not want to diminish the work of the many people who gave their time, energy and skill. I hope most of these people are listed below.

In preparing this Report I have taken responsibility for its organization, presentation, text and choices of tables and figures. I have used extensively the detailed work conducted by the Stobie team and its primary consultants and the content of the Report reflects their work, not mine. If there are errors of omission, misconceptions of technical matters, or problems with the clarity of writing, they are mine, not the team's.

Joe Stachulak, the Project's principal investigator, and I want to thank the following individuals for their work on and/or interest in the project.

The stakeholders of DEEP	The DEEP Management Board
The DEEP Technical Committee	The Ontario Workers Safety and Insurance Board
The United Steelworkers of America	

Technical Assistance

George Schnakenberg	Aleksandar Bugarski	Mahe Gangal	Brent Rubeli	Andreas Mayer
Paul Nöthiger	David Young	Vince Feres	Don Dainty	Addy Majewski
Mike Kingston	Fred Delabbio	Bill Howell	Robert Dougherty	

Inco Ontario Division administration

Ron Aelick	Alistair Ross	Scott MacDonald	Brian Maynard
Mark Cutifani	Michel Winship	Alex Henderson	Terry Van Kempen
Glen Lyle	Mike Sylvestre	John O'Shaughnessy	Steve Wood

Stobie Mine Operations

Keith Boyle	Larry Lauzon	Joe Loring	Mike MacFarlane
Bob Steinke			

Stobie central team and support

Lindy Agnello	Gilles Bedard	Tim Beres	Bob Coupal	Dan Dubuc
Mike Dupuis	Dave Fram	John Huggins	Denis Lafebvre	Mike Leclair
Ernie Leduc	Rick Mayotte	Don McGraw	Greg Nault	Simon Nickson
Rick Nelson	Doug O'Connor	Don Peloquin	Gilles Pilon	Ron Pilon
Jim Rouselle	Jim Sharpe	Dan Stefanczyk	Terry Turcott	Ken Zayette

Trainers

Tracy Cardinal	Mike Doniec	Fred Goulet	Denis Lefrancois	Gary McGee	Tony McGuire
Lynn Mitchell	Mike Palkovits	John Whitehead			

Operators

L. Albrechtas	R. Anand	A. Anger	D. Archambault	R. Audet	A. Barrette
J Beaudin	W. Beckerleg	G. Bergeron	R. Bernard	P.Boucher	K. Brouse
R. Brunette	K. Castonguay	J. Chenier	P. Christine	J. Conrad	D.Corriveau
J. Daoust	D. Decker	M. Demore	D. Drake	K.Eadie	B. Falkner
F. Fournier	P. Fournier	G. Foy	R. Gagnon	R. Gauvin	G.Gillis
M. Gionet	E. Girard	R. Godin	D.Hansen	E. Hearty	K.Hill
T. Jaculak	J. Larocque	P. Lasalle	M. Lavallee	R. Leblanc	G. Macmillan

L. MacNamatra	R. Mathieu	A. McGuire	R. Melcher	R.Niemelainen	D.Noel
R. Pancel	D. Plante	M.Plante	E. Poisson	R. Proulx	K. Raby
S. Rayner	K. Renaud	R. Rodden-Aubut	J. Rollins	L. Samuels	R. Savoie
R.Schneider	D. Sikatowsky	J. Sioni	D. Smith	J. Smith	R.Stevens
C. St.Georges	B. St.Pierre	H. Suchit	T. Thompson	D. Vergunst	J. Villeneuve
Y. Villeneuve	B. Walker	D. Yentha	D. Yantha	B. Young	

Maintenance, Electrical

M. Bruno	S. Campbell	R. Currie	A. Baronette	G. Bergeron	P. Brouillard
S. Campbell	R.Campeau	J.Charbonneau	D. Coffin	R. Condie	R. Connie
D. Cormier	P. Cranford	R. Currie	J. Dajczak	G.Dumont	J. Dajczak
G.Favot	R.Gareau	T. Giambattista	A.Gregoire	M. Gregoire	S. Heikkila
K. Hill	R. Imbeau	D. Jones	D. Lamoureux	P. Lance	J. Lawrence
M. Leclair	K. Maciborka	B. Mercer	J.Mercier	S. Michaud	R. Moncion
G. Moratz	C. Parent	G. Pilon	S. Powers	E. Ross	D.Ryan
K. Schutt	C. Theriault	C.VanDenBrock			

Engine and vehicle manufacturers

Cast:	Myles Bruce
Detroit Diesel	Mike Meadows, Brian Gillespie, George Hedge
Deutz	Jamie Sauerteig, Peter Prince, John Stimson, Joe Unseth
Kubota:	Brad Oliver
Truck and Wheels:	Conrad Houle

Control equipment, fuel suppliers, and measuring equipment manufacturers

3M:	Kevin Manuel
Arvn-Meritor:	Ed Kinnaird, John Barley, Brooke Huntington, Prasad Tumati
Clean Diesel Tech:	Mark Hildebrandt, J. Valentine
DCL:	Steve Finnemore, George Swiatek, Paul Terpin, Joe Aleixo
Deutz:	H. Breuer
ECOM:	Drue Wilson
ECS:	Edward Richards, Ted Tadrous, Don Malgast, Cesar Baumann, Rocky Karim, Tom Levander
Engelhard:	Aleksander Gorel, J. Kusan, A. Mullen
Finnkatalyst:	Arno Amberla, P. Wiklund
Greentop:	Marcel Lees
HUSS:	H. Rembor
Levitt Safety:	Dan Menard
Matter Eng.:	Dr. Ulrich Matter, Dr. Markus Kasper
Oberland-Mangold:	Bernard Kahlert, Hicham Agna, John Stekar
Johnson Matthey:	Peter Werth, Joe Stevenson, Marco Conrad, Richard O'Sullivan
Rhodia Catalysts:	Matthew Quigley, Steven Deutsch
Sandvik Mining:	Bill Maki, Wayne O'Link

International interests

Australia:	G. Fawcett
Austria:	R. Antretter
Germany:	Dr. Henrik Soenksen, Dr. Dirk Dahmann, Wolfgang Ruether, Dr. Paul Zelenka
Japan:	Hiroshi Matuoka, Toru Saito
Sweden:	Karl-Erik Ranman, Lennart Mukka, Tommy Eriksson, Bodil Melbloom, Par Jones, Lars Hergart
Switzerland:	Prof H. Czerwinski,
USA:	Edward Thimons, Bob Timko, Dr. Win Watts, Dr. Bruce Cantrell, Bob Waytulonis, Dr. David Kittelson, Dr. Susan Bagley, Bob Haney, Bill Pomroy, James Noll, Darrick Zarling, Dr. Richard Martin, Mukaram Syed, George Sassen

Inco Technical Services Limited (Sheridan Park)

Scott Price	Dawn Greville

Table of Contents

Executive Summary

Project context:

Testing the long-term effectiveness of diesel particulate filter systems (PFSs) to reduce the concentration of diesel particulate matter (DPM) in underground environments was conducted under the auspices of the Diesel Emissions Evaluation Program (DEEP) at Inco's Stobie mine from April 2000 to December 2004. Of particular concern was the ability of PFSs to sustain long-term filtration efficiencies under the often harsh physical environment that exists for equipment operating in mining service.

Previous use of PFSs by the mining industry several decades ago had yielded mixed results and technology at that time was considered impractical for routine use on underground diesel equipment. The primary reason for the past failures of PFSs in mining was recognized as being an improper matching of a PFS to the vehicle on which it was expected to perform. This matching was deemed to be critical, not only with respect to the sizing of the filter, but most importantly to the method used for filter regeneration. The testing at Stobie wanted to show how to optimize the PFS-vehicle matching via preliminary duty cycle monitoring and to demonstrate the effectiveness and ruggedness of PFSs in production service.

Stobie Mine and Project Management:

Inco's Stobie mine is located on the south rim of the Sudbury ore basin. It started operations in 1886 and is currently an important mine in Inco's Sudbury nickel-copper ore mining. It uses a diesel fleet that is typical of hard-rock mining across the Canadian mining industry.

A team of Stobie personnel were gathered to work on the Stobie project in addition to their normal duties. The team was led by Dr. J. Stachulak, with outside technical advice being received from Mr. A. Mayer (European diesel PFS experience in tunnel construction), Drs. A Bugarski and G. Schnakenberg (U.S. NIOSH), and the DEEP Technical Committee under the chairmanship of M.Grenier (Natural Resources Canada, CANMET). The team was responsible for all aspects of the testing and for interacting with Stobie operations. This latter aspect was critical because the vehicles being used for the testing were employed in routine production mode (that is, the testing was not carried out in a research mode in a non-production part of the mine, but rather was carried out while the vehicles were performing normal services.

Diesel vehicles used for the Project:

Five heavy duty Load/Haul/Dump (LHD) scooptrams were selected as representing the primary heavy duty workhorse in underground mining. One of these units had a dual exhaust Deutz engine and the other four had Detroit Diesel DDEC 60 engines. The engines spanned a range of age and service use. Four Kubota tractors were selected as being representative of light duty vehicles, which are increasingly being used in transporting underground personnel. PFS service on light duty vehicles underground had not been studied anywhere at the time the Stobie Project was started. Their inclusion in the Stobie testing was considered important because the proportion of light duty vehicles in use is steadily increasing relative to heavy duty vehicles and the need to decrease the contribution of DPM to mine air from light duty vehicles will become very important as strategies are developed to improve the quality of underground air.

Duty cycle monitoring:

The duty cycles of the candidate vehicles were monitored for six months prior to selecting the PFSs for testing. Temperature sensors and pressure sensors were installed in the exhaust manifolds. Signals on a one second periodicity were sent to dataloggers mounted on the vehicles. These dataloggers and their associated hardware had been used with success by a European consortium investigating PFS application in tunnel construction. Training of over fifty Stobie personnel in the operation and maintenance of this equipment was a key component of their successful use at Stobie.

The data obtained for each vehicle were analyzed to reveal exhaust temperature history (including the dwell times at temperature). These data were used to judge whether engine-produced exhaust temperature could be achieved and sufficiently sustained to ignite and burn soot captured by the PFS filter. These data were found to be essential in selecting the optimum PFS (and its regeneration method) for a particular vehicle and its duty cycle.

Results clearly and surprisingly showed that heavy duty vehicles did not routinely achieve high enough exhaust temperatures for long enough periods in normal service to fully regenerate the filters. This meant that assistance was needed for burning the soot and PFSs based on catalysts for soot ignition (“passive” systems) or PFSs based on providing additional heat (“active” systems) would be required for LHDs. Data on light duty vehicles clearly showed the need for “active” regeneration. The data on all vehicles indicated that engine backpressure would be an important diagnostic tool for monitoring the status of the soot filters.

Selection of PFSs:

<u>For heavy duty LHDs:</u>

•Two completely passive systems were used.

The **Oberland-Mangold** PFS had a knitted glass fiber filter and a fuel-borne catalyst.

The **Engelhard** PFS had a cordierite honeycomb filter the internal surfaces of which had been coated with a catalyst.

• Three completely active systems were used.

Two were from **ECS/Unikat** having a SiC honeycomb filter and used on-board electrical heating for regeneration.

The other unit was from **Arvin Meritor**, having a cordierite honeycomb filter with a built in burner for regeneration.

• One system from **Johnson Matthey** was a mixed passive-active system with SiC or cordierite honeycomb filters. The passive part of the system used a fuel-borne catalyst and the active part used on-board electrical heaters. This system was used for the dual exhaust Deutz engine.

For light duty tractors:

- Three active systems were tested.

ECS/3M used a ceramic fiber filter medium and an on-board electrical heater.
ECS/Unikat used a SiC honeycomb filter and an on-board electrical heater**.**
DCL used a SiC honeycomb filter and an off-board electrical heater.

Methods for testing performance:

Tests on the PFSs were conducted every 250 hours of vehicle operation for heavy duty machines and monthly for light duty machines. During these routine periodic tests an ECOM instrument was used to analyze for NO, NO_2, CO, CO_2 and O_2 and measure Bacharach smoke numbers upstream and downstream of each filter.

Three more extensive periods of testing all PFSs were conducted during the summers of 2001, 2002, and 2004. These tests used three reproducible steady state engine conditions and analyzed gases and smoke numbers upstream and downstream of the filters, measured particulate concentrations using a photoelectric aerosol analyzer, measured particle size distributions using a Scanning Mobility Particle Sizer, and measure exhaust opacity.

Industrial Hygiene (IH) Measurements:

Even though the test vehicles were operating in normal production mode with the potential for other non-filtered vehicles to be operating nearby, it was decided to conduct some IH measurements before and after installation of some of the PFSs. Each test consisted of taking 10 air samples (3 for RCD analysis and 3 for elemental carbon analysis located just behind the driver of test vehicle), two for elemental carbon at the fresh air supply and two for elemental carbon at the exhaust air outtake. Air flow measurements were also taken for each test period. The results showed a reduction in elemental carbon in the mine air when filters were being used, but quantitative conclusions cannot be made because the with-filter and without-filter measurements were usually conducted while the vehicle was doing different kinds of work and the airflow to the area of its operation varied depending on where the vehicle was doing its work.

PFS-specific Results:

Engelhard on an LHD: This system had low complexity and required little special attention. Filtration efficiency of soot was in excess of 98% throughout its 2221 hours of operation. Smoke numbers were reduced to an average of 0.6 downstream from 7.1 upstream. The system showed considerable robustness when it survived an accident with the LHD during which mud was able to penetrate into the discharge side of the filter. The system was removed from testing when the engine's turbo failed and caused an oil fire. It is not clear what role the filter may have played in the turbo failure.

ECS/Unikat Combifilter on an LHD: Two of these systems were tested. The first one had marginal filtration efficiencies of 92-94% after about 300 hours of service, and concerns were raised about whether active regeneration was being routinely practiced by operators. Datalogging records showed that backpressures were fairly high and were not returning to normal after a shift when the filters should have been regenerated. After a total of 940 hours the filter was observed to have physical cracks and holes in the honeycomb structure. This was surmised as being the result of inattention to regeneration and the filter was removed. The Stobie team then undertook increased training of operators in the importance of their attention to regeneration after every shift and improvements were made to facilitate easier access to the regeneration station. New ECS/Unikat Combifilters (in parallel) were installed and this system had very good performance, achieving up to >98% over 1.5 years of service. Smoke numbers averaged 1.0 downstream compared with 7.1 upstream and opacity was excellent at 0.4%. Industrial hygiene air sampling showed elemental carbon levels of about 0.01 mg/m^3 with the filter installed compared to about 0.11 mg/m^3 without the filter. The system had to be removed from the vehicle following an accident where a muck pile collapsed and buried part of the LHD, resulting in significant damage to the vehicle. Testing of each of these filters was carried out at CANMET following the testing in the mine. Reductions in emissions during 8-mode tests gave 93-99.8% DPM removal for one of the filters and 56-85% in the other filter. The ranges represent efficiencies based on DPM mass, number of particles and the elemental carbon component. Inspection of the filters showed some loss of honeycomb bonding ceramic. Some evidence of soot blowthrough was seen on the outlet side of the filters. Borescope images of individual channels showed the existence of a few cracks.

Johnson Matthey on an LHD: Two identical filters were used because of the need to filter both sides of the dual exhaust from a Deutz engine. Relatively higher than desired backpressures were experienced by this system and this indicated that the amount of fuel-borne catalyst being used was insufficient to achieve passive filter regeneration. Also, the continued high backpressures indicated that active regeneration was not being routinely practiced by operators. Filtration efficiencies remained fairly good ranging from 84% to >99%. Industrial hygiene air sampling showed a reduction of elemental carbon to 0.04 mg/m^3 with the filter compared to a range of 0.05-0.13 mg/m^3 without the filter. After 2057 hours of operation one of the SiC honeycomb filters (driver's side) showed excessive separation between it and its canister. As a consequence, soot filtration efficiencies decreased and smoke numbers increased. A new cordierite honeycomb filter was installed as a replacement and accumulated an additional 173 hours of operation before the project ended. One of the filters was sent to CANMET for post-use testing. A large dent was observed on the outside shell of the filter, but the inside canister at this location was undamaged. The mat holding the ceramic monolith in place in the canister was severely degraded and this was likely the cause of the filter being able to move within the canister. Where the filter had separated from the canister, there was evidence of soot blowthrough. The filter had efficiencies of 89% (DPM mass), 98.4% (DPM particles) and 72.6 % (elemental carbon component of DPM).

Arvin Meritor on an LHD: This system was complex and required significant pre-installation fail-safe testing before it was permitted underground because of the existence of the diesel fuel burner as the central component for regeneration. After only 116 hours of operation the smoke numbers downstream were seen to be increasing to 3 compared to the upstream numbers ranging 6-7. The problems encountered with the control software for this system, combined with the indication of soot breakthrough, caused the testing to be terminated.

Oberland-Mangold on an LHD: This system was complex due to the controls needed to regulate pumping the fuel-borne catalyst into the vehicle's fuel tank. Despite considerable team resources being used to install the system according to the manufacturer's criteria, and despite an intensive week of training of two Stobie mechanics in Germany, the system showed very inefficient filtration of soot, ranging from 3-70% and downstream smoke numbers of 5.5 compared to 7.0 upstream. The system was deemed to have failed with essentially zero hours of operation.

ECS/Unikat Combifilter on a tractor: This filter successfully achieved 577 hours of operation over nearly three years. Excellent soot filtration efficiencies of >99% were measured with concomitant very low opacity and downstream smoke numbers. NO_2 decreased across the filter due to conversion of NO_2 to NO by the filter medium. The ash from burning the soot was collected from this filter. Great care was required to avoid excessive contamination of the burned soot ash with unburned soot. The best ash sample obtained was analyzed by scanning electron microscope x-ray spectra of specific particles. The sample contained complex phosphates and sulfates of calcium and iron with some presence of iron oxides and zinc oxide also indicated. Industrial hygiene air sampling at the vehicle equipped with the filter showed elemental carbon to be reduced to about 0.05 mg/m^3 from the without filter sampling at about 0.09mg/m^3. This system appears to be a good candidate for light duty vehicle service. The post-testing done at CANMET showed the filtration efficiencies to be 94% (DPM mass), 99.9% (DPM particles) and 82% (elemental carbon component). The filter was physically sound except for broken welds on the spider support.

DCL Titan on a tractor: This filter successfully operated for nearly three years achieving 864 hours of operation. Two alternating filters were used: one in use while the other was being regenerated externally. Both filters maintained excellent soot filtration efficiencies of about 99%. The quick disconnect fittings made swapping the filters very easy. Industrial hygiene air sampling with the filter installed showed elemental carbon at about 0.03 mg/m^3 compared to the without filter concentrations of about 0.10 mg/m^3. This system appears to be a good candidate for light duty service. One of the filters was examined in post-use at CANMET. The filtration efficiencies were 95% (DPM mass), 97.8% (DPM particles) and 89% (elemental carbon component). The discharge side of the filter showed a small area of the honeycomb where soot blowthrough was occurring and borescope images confirmed very small microcracks in some of the channels.

ECS/3M on a tractor: The system compiled 453 hours of operation with marginally acceptable soot filtration efficiency ranging from 77% to 94%. Relatively high smoke numbers of 3.5 were measured downstream compared to 9.0 upstream. Opacity was marginal at 5%. The system was removed from the testing because 3M announced its cessation of manufacturing the glass fibers employed as the filter medium.

Ash Samples:

Samples of ash were collected from several filters after multiple regeneration cycles and these were analyzed using digestion and ICP-MS. Low magnification optical images and scanning electron microscope images were also obtained. Sampling of the ash turned out to be a difficult matter because unburned soot contaminated most samples. A special sampling of the ash from the ECS filter (from tractor #3013)was done by sampling dust from the regeneration oven itself. X-ray diffraction of this dust identified possible phases as calcium phosphate, calcium iron phosphate, anhydrite (calcium sulfate) and hematite (iron oxide). X-ray spectra of selected particles were obtained using an electron microscope. The x-ray spectra showed the presence of calcium, phosphorus, iron, sulfur and oxygen (in agreement with the diffraction results) and also zinc (as a zinc oxide or phosphate).

General conclusions:

(1) Both heavy duty and light duty vehicles in underground mining operations can be retrofitted with high efficiency Particulate Filter Systems (PFSs) for DPM removal. However, all of the systems tested in the Stobie Project required more close attention than was desired, although there existed a wide variation in the amount of attention needed. Ideally, a PFS would be invisible to a vehicle's operator and almost invisible to the maintenance department. That is, people would go about their jobs in a conventional manner and would not need to pay attention to the filter or its regeneration. This was clearly NOT the case for any of the filters being tested in the Stobie Project and this remains a critical issue in any successful program for retrofitting or for installing PFSs as OEMs.

(2) Taking time to correctly match the vehicle duty with an appropriate PFS is essential for a retrofitting program to be successful.
   a. This matching must be done to correctly size the filter medium so that an acceptable soot collection period is obtained. Too small a filter will result in loading the filter too quickly and will negatively impact on vehicle productivity. Too large a filter will result in cramped space for the unit on the vehicle and this could negatively impact safe use of the vehicle and ease of its maintenance.
   b. This matching must be done to obtain the optimum method of regeneration of the filter. The optimum method of regeneration must take into account issues such as the complexity of the regeneration system, the period of time needed for regeneration, maintenance of components of the regeneration system, ease of installation and use, and cost.

(3) Proper communication with vehicle operators is essential. The presence of a filter on the exhaust manifold of an engine means that the filter, when working, will cause an increase in the backpressure of the engine. Operators must be attentive to non-conventional alerts and alarms for high backpressure or else serious harm could be done to the engine.

(4) Simple, but effective, dashboard signals of the state of the filter are needed in order to give information to the vehicle operator about the filter's effectiveness.

(5) The increased emission of noxious gases is often a consequence of the way in which some PFSs regenerate and these emissions, particularly NO_2 must be watched carefully.

While there may exist ways to control such emissions, system complexity by adding on components is undesirable.

(6) An emissions-based maintenance component of an overall vehicle/engine maintenance program is essential. Proper functioning of a PFS should be evaluated as part of routine maintenance. Training of maintenance personnel in the specifics of each PFS is essential.

List of Tables

Vectors

List of Figures

<u>Instruments for measuring performance</u>

Data treatment

Major events in project

Results

ECS/Combifilter on tractors #2180 and #3013

DCL Titan on tractors #621 and #017

ECS/Combifilter on LHD #213

Engelhard on LHD #362

Comparisons of PFSs

Industrial Hygiene Measurements

Ash Residue Analyses

GLOSSARY

ACRONYMS and TERMS

3M	Minnesota Mining and Manufacturing Inc.
A/D	Analog (voltage) to Digital (numerical) Conversion
ACGIH	American Conference of Governmental Industrial Hygienists
ASCII	American Standard Code for Information Interchange
CANMET	Natural Resources Canada Laboratories in Ottawa
DC	Direct Current
DCL	Diesel Control Limited
DDEC	Detroit Diesel Electronically Controlled
DEEP	Diesel Emission Evaluation Program
DPM	Diesel Particulate Matter
ECS	Engine Control Systems
HEI	Health Effects Institute
IARC	International Agency for Research on Cancer
IH	Industrial Hygiene
ISO	International Standards Organization
JM	Johnson Matthey
LHD	Load, Haul, Dump
MSHA	Mines Safety and Health Administration (United States)
NIOSH	National (United States) Institute of Occupational Safety and Health
OEL	Occupational Exposure Level
PFS	Particulate Filter System
PILP	National Research Council's Program for Industrial/Laboratory Projects
RAM	Random Access Memory
RCD	Respirable Combustible Dust
TLV	Threshold Level Value
VERT	Curtailment of diesel engine emissions at tunnel sites, a joint project Swiss and Austrian occupational health agencies, the Swiss and German environmental protection agencies, the German association of construction engineers, and several engine manufacturers and particulate filter system manufacturers
WHO	World Health Organization

UNITS

nm	nanometers = 10^{-9} meters
µm	micrometer = 10^{-6} meters
mg/m^3	milligrams per cubic meter
rpm	revolutions per minute
hp	horsepower
mBar	millibars (1 Bar = atmospheric pressure)
T	ton

CHEMICALS

NO	Nitrogen oxide
NO_2	Nitrogen dioxide
NOx	Summation of nitrogren oxide and nitrogen dioxide
PAH	Poly-aromatic hydrocarbons
CO	Carbon monoxide
CO_2	Carbon dioxide
O_2	molecular oxygen
HC	hydrocarbons

1. INTRODUCTION

This document reports results of testing the effectiveness of several types of diesel particulate filter systems that are candidates to be used to reduce the concentration of diesel particulate matter in underground air. The tests were conducted at Inco's Stobie Mine over the period April 2000 to December 2004 as part of the Diesel Emission Evaluation Program (DEEP).

1.1 The Use of Diesels in Underground Mining

Since their introduction into underground mining operations in the mid-1960s, diesel-powered equipment has become increasingly employed and recognized as the workhorse in mining. Diesel engines provide a relatively simple power from combustion of a petroleum fuel. The engines are simpler than their gasoline-fuelled internal combustion cousins and therefore diesel engines are easier to maintain and generally have lower operating costs. Because of the simpler design, diesel engines are more robust than most other engines and therefore have shown the ability to sustain high performance in a physically harsh environment.

In terms of safety, diesel engines have several advantages over gasoline engines. First, diesels operate in a lean fuel/air ratio and produce very low levels of carbon monoxide in exhaust. This is particularly important for engine exhausts going into a workplace with limited fresh air supply, such as is present in underground workings. Second, the diesel fuel itself has a fairly high flash point and this property reduces the possibility of unwanted fuel ignition and fires underground.

Inco Limited employs over 800 diesel-powered units at its Ontario mining operations in the Sudbury basin. While the use of alternative power (e.g., electricity, fuel cells) is being explored, Inco and most other Canadian deep-rock mining companies realize that diesel engines will continue to be a very important component of a working fleet of vehicles for many years to come. In view of this, it is imperative to lessen diesels' undesirable features such as noxious substances in its exhaust.

1.2 Characteristics of diesel exhaust

Diesel exhaust is complex in terms of the number of distinct substances (in solid, liquid and gaseous phases) and its chemical composition. The gaseous phase includes carbon monoxide, carbon dioxide, sulfur dioxide and sulfur trioxide from the sulfur in the fuel, nitrogen oxides (NO and NO_2, in combination termed NOx) and a number of low molecular weight hydrocarbons such as simple aldehydes.

The liquid phase includes condensed hydrocarbons of varying molecular structures (e.g. polyaromatic hydrocarbons, PAHs). Sulfuric acid, formed by the combination of sulfur trioxide with water, can also be present.

The solid phase is predominantly elemental carbon that arises from unburned fuel. It contains extremely small particles of carbon (15-40 nanometers equivalent diameter for what is termed the nucleation mode) with some of these accumulating into somewhat larger particles (60-100 nanometers in what is called the accumulation mode) and some relatively coarse particles (100-1000 nanometers). Virtually all of these diesel-produced particles are respirable (that is, less than 10 micrometers). Due to the small particle sizes, the elemental carbon particles have large surface areas, on which extensive adsorption of gaseous and liquid hydrocarbons can occur. In addition to elemental carbon, the solid phase also contains metal oxides and sulfates. The metals contained in these compounds were present as impurities in the fuel in most cases, but metal additives are often introduced to the fuel to act as catalysts in subsequent exhaust treatment. Metal sulfates result from the reaction of metal oxides with sulfur dioxide and water in the exhaust manifold.

A schematic of the components of diesel exhaust is shown in Figure 1, their typical proportions are shown in a pie chart in Figure 2 and a typical particle size distribution summed over the operating modes of a diesel engine is shown in Figure 3.

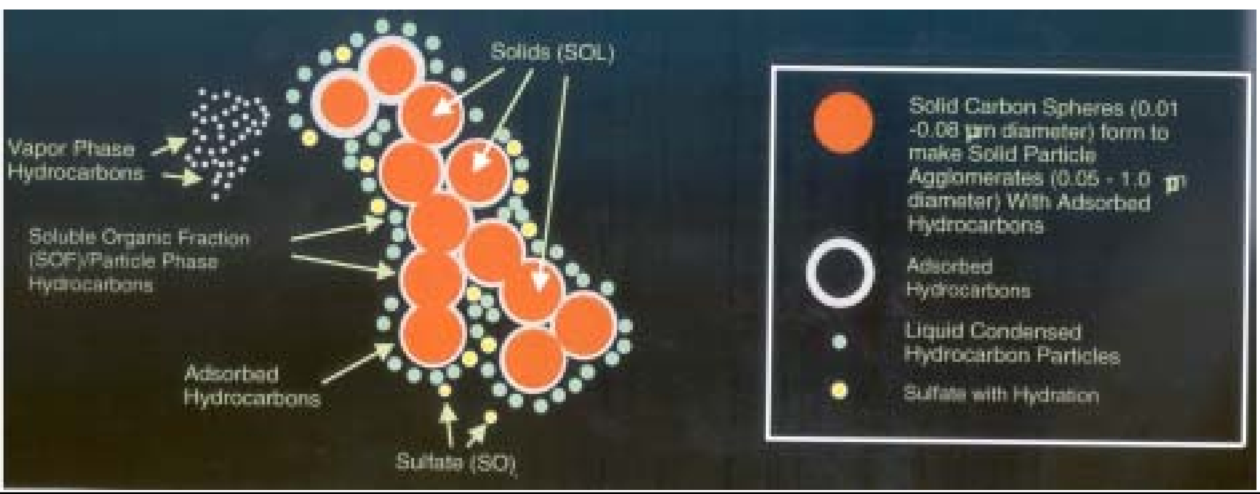


Figure 1:Schematic of diesel exhaust particulate

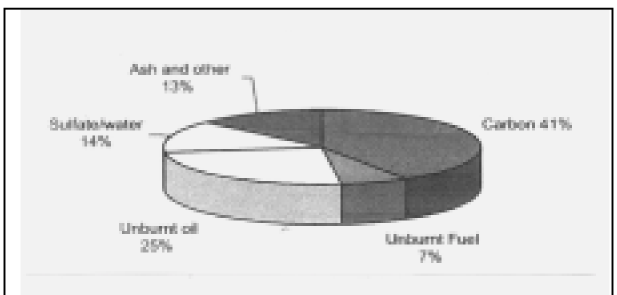


Figure 2: Typical constitution of diesel exhaust (after Burtscher, 2005).

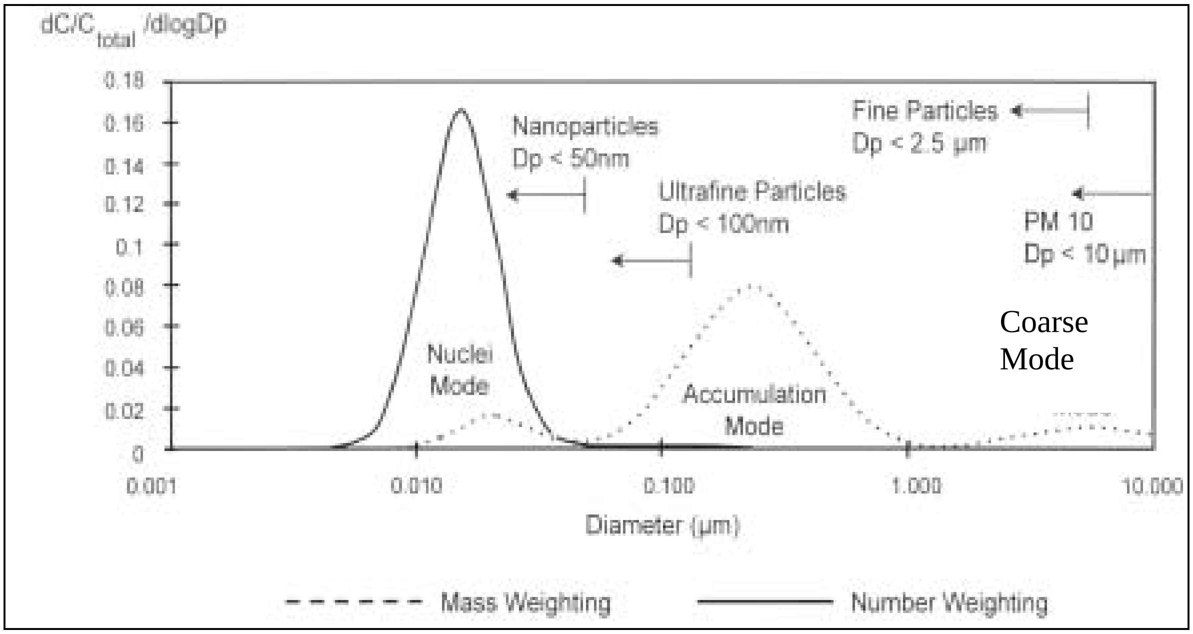


Figure 3: Typical particle size distribution of DPM (after Kittelson, 1998)

The specific overall composition and size distribution of a diesel engine's exhaust will vary as a function of variables such as the type of fuel and its impurity content, age of the engine, engine design, engine maintenance, fuel/air control, the duty being performed by the engine, the operator of the vehicle, and conditions in the working environment (e.g. humidity). It is important to recognize that certain trade-offs exist in trying to minimize potentially harmful substances present in diesel exhaust. For example, improvements in burning efficiency by altering engine design and fuel injection will likely result in decreasing the mass of elemental carbon in the exhaust, but will also probably result in increasing the number of extremely fine carbon particles, which may be more harmful if inhaled (see below). Another example is improving the combustion of fuel by enriching the air to fuel ratio, which will decrease the mass of elemental carbon in the exhaust, but will simultaneously increase the concentration of noxious nitrogen dioxide.

While many exhaust treatment technologies can assist in reducing unwanted substances, their successful implementation is technically and operationally challenging. The general approach in minimizing the toxic properties of the exhaust includes (a) having engines in good working condition, (b) controlling the formation of certain noxious compounds during combustion (for example, using low sulfur fuels to decrease sulfate formation and using lean air/fuel mixtures to limit NOx formation), (c) balancing elemental carbon formation against NOx formation during combustion, and (d) installing devices to remove or to chemically alter substances prior to the tailpipe (for example, using diesel oxidation catalysts to limit carbon monoxide and hydrocarbon emissions).

1.3 Health Concerns

Following a number of occupational epidemiological and animal studies conducted over the past several decades, concern has increased over the toxicity of whole diesel exhaust and on certain components within the exhaust. The solid phase of diesel exhaust, termed diesel particulate matter (DPM), has been of particular concern because of its very small size and its ability to adsorb very complex and potentially toxic hydrocarbons and bring them into the alveolar region of the lungs of workers. There exist several toxic endpoints due to DPM. For example, mucous membrane inflammation of the eyes is known to occur with prolonged exposure to modest concentrations of diesel exhaust. In the lungs, tissue inflammation and chronic bronchitis may occur. Due to the presence in diesel exhaust of hydrocarbon substances known to be carcinogenic at high concentrations, there is concern about the possibility of respiratory tract cancers.

The Health Effects Institute (HEI, 1995) and the World Health Organization (WHO, 1996) issued comprehensive reports on knowledge about the health consequences of diesel exhaust, but were unable to set quantitative cancer risks. The International Agency for Research on Cancer (IARC, 1989) has determined that diesel exhaust is “probably carcinogenic” and the U.S. National Institute of Occupational Safety and Health (NIOSH, 1988) has stated that diesel exhaust is “a potential occupational carcinogen”. While it is not clear whether the elemental carbon particles themselves (without the adsorbed substances) are carcinogenic, it is clear that the small particles are able to carry other noxious substances deep into the lungs. There has also been increasing concern by public health officials about the deleterious effects of nanoparticles in ambient air, due to a link seen in urban studies between respirable particle concentrations and hospitalization frequency or death rate in the general population. Research about nanoparticles in underground air is generally absent, but health concerns for workers mirror the concerns that exist for the general population.

There is little doubt that reducing miners’ exposure to diesel exhaust would have a positive influence on sustaining good health.

1.4 Regulatory initiatives

The American Conference of Governmental Industrial Hygienists (ACGIH) is the body that establishes recommendations for threshold limit values (TLVs) for workplace exposures. In 1995 the ACGIH notified stakeholders that it intended to adopt a TLV for DPM at 0.15 mg/m^3 with a classification of “suspected carcinogen” (ACGIH, 1995).[1] While the ACGIH does not have a regulatory mandate, governmental agencies with such authority usually use the TLV of a substance as the starting point for setting an Occupational Exposure Limit (OEL).

[1] It should be noted that the ACGIH did not adopt the 0.15 mg/m^3 value, but notified stakeholders that it intended to adopt an even lower value of 0.05 mg/m^3 and then subsequently announced a lower value of 0.02 mg/m^3. Most recently, the ACGIH has withdrawn its notice for DPM entirely. It is likely that a new notification will come forward with improved designations of exactly what is meant by DPM.

The Mine Safety and Health Administration (MSHA, 2005) in the United States has recently used the ACGIH information, together with practical considerations, to establish a metal/non-metal mining OEL for the elemental carbon portion of DPM. It is clear that other jurisdictions world-wide have already adopted or are considering such regulations.

Some years ago many provinces in Canada, in consultation with the mining industry, adopted a target of 1.5 mg/m^3 for the respirable combustible dust (RCD) concentration in underground mines. Most mines operate well below this target at 0.5-0.8 mg RCD/m^3. Experience in mines having a combination of diesel equipment and pneumatic drills has indicated that the DPM portion of RCD is about two-thirds (the remainder being a combination of oil mist and mineral dust). This means that the target DPM in most Canadian mines at the present time is about 1.0 mg/m^3. If an ACGIH TLV for DPM were to be adopted by regulatory agencies in Canada, it is very likely that the value would be significantly lower than the current target and operating levels in Canadian underground mining operations.

Indeed, the mining industry in Canada became concerned (a) with the technology for sampling and analyzing DPM at extremely low levels and (b) about proven technology that would allow decreasing DPM emissions from diesels so that these flexible and robust engines could continue to be used to great advantage without causing adverse health outcomes in miners.

1.5 Formation of DEEP

In April 1997 several mining companies joined with several unions, Canadian government departments (both provincial and federal), diesel engine manufacturers, emission control equipment manufacturers and fuel suppliers to form the Diesel Emission Evaluation Program (DEEP). The objectives of DEEP were to prove the feasibility of reducing miners' exposure to DPM in a reliable and effective manner using existing technology and to establish the ability of measuring DPM underground with needed precision and accuracy at the targeted very low levels of DPM desired.

The work of DEEP initially focused on using alternative fuels to reduce DPM, then evolved into improving engine maintenance programs and comparing analytical methods for DPM. Information about DEEP's research can be obtained at www.deep.org.

While some benefits in decreasing DPM emissions from diesel engines were found during DEEP's projects, it became apparent that fuel, maintenance, engine design improvements and operational and ventilation optimization would accomplish only a fraction of the targeted 90% reduction in DPM. It became apparent that removal of particulate from the exhaust stream prior to the tailpipe was likely to be an integral part of any dramatic reduction in DPM emissions. DEEP therefore initiated two projects on Particulate Filter Systems (PFSs), one hosted by Noranda's Brunswick mine (McGinn, 2004) and the other hosted by Inco's Stobie mine. These companion projects aimed to test existing PFS technologies in operating mines in order to determine if these systems were able to operate with effectiveness over a prolonged period in often harsh physical environments.

2. PARTICULATE FILTER SYSTEMS

2.1 General comments

The term "system" is used in conjunction with particulate filters in this report to denote that a successful filtration of DPM relies upon several components. One component is the filtration medium itself. Another component is the instrumentation that may be necessary to monitor engine parameters. Yet another component is a control system that may initiate certain actions depending on pre-determined values of engine parameters. Finally, there may be components such as electrical heaters (on-board as well as off-board) or exhaust manifold burners that are used to ignite the filtered mass of carbon and regenerate the filter for continued effective performance. The term "system" refers to the integration of all these components into a working partnership for effective and prolonged filtration efficiency.

Filtration media vary in chemical composition and morphology. All media must be able to withstand the relatively high exhaust temperatures that may occur during normal diesel engine operation. Some filtration media must withstand higher temperatures associated with ignition and burning of the filtered carbon mass. A number of media are employed, ranging from ceramics such as cordierite and silicon carbide, woven glass and metal fibers, and metal foams. A variety of effective pore sizes are available and, accordingly, filters vary in their filtration efficiencies as a function of particle size of the DPM. Filter media also vary in the mechanism of filtration with many essentially being wall filters and others being bed filters. In either case, the filtration is achieved by having a porous structure which allows transmission of the gas phase, but captures solid and liquid aerosols above a particular particle size-exhaust stream velocity combination.

Some of the most common materials for filter media are cordierite (magnesium aluminum silicate) and silicon carbide honeycomb structures made by extrusion. In these filters neighbouring channels of the honeycomb are plugged at alternate ends, as shown in the schematic in Figure 4. This configuration requires the soot-laden intake gases to enter half of the channels, be filtered by passing through the porous walls and then be exhausted through the other half of the channels.

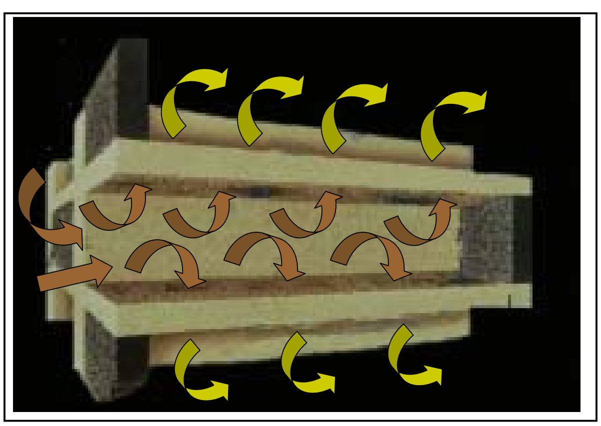


Figure 4: Representative view of the magnified honeycomb structure with opposing channels blocked at alternate ends. Brown arrows show incoming exhaust containing soot and yellow arrows show filtered exhaust. (DCL International, with permission)

2.2 Past experience in underground service

Many applications of filtration media have been started in on-road vehicles and then have been modified in order to perform in underground equipment. The first ceramic filter for use in underground diesels was developed by Corning Glass in collaboration with Natural Resources Canada (CANMET) scientists. In the early 1980s prototype filters were laboratory-tested and then taken underground for field trials (McKinnon, 1989; Dainty et al., 1985). Inco was involved in testing a prototype at Little Stobie Mine and in implementing what was then considered to be a successful technology via the National Research Council's Program for Industry/Laboratory Projects (PILP) run under the auspices of the Collaborative Diesel Research Advisory Panel.

However, successful implementation was not uniform. While all filters appeared to work when first installed, many were found to plug rapidly, resulting in unacceptable engine backpressures. Because backpressure limitations existed on engine warranties, engines exhibiting excess backpressures had to be serviced or loadings limited, both of which severely impacted the ability of miners to conduct their work efficiently. As a result, many of these newly installed filters were discarded by vehicle operators. Mine management, as well as workers, became skeptical of most filters. Since the late 1980s DPM filtration has been done on a very limited basis at Inco.

Some filters worked well on certain equipment. It is now recognized that the performance of a filter is intimately associated with successful periodic removal (burning off) of carbon soot built up on the filter. Likely the early implementation of filters on underground equipment relied on this removal being done by the heat in the engine exhaust itself and, as now realized, this was not achieved for many filters because of a combination of lower than expected exhaust temperatures and/or a lack of sufficient time at high exhaust temperature to complete the burning of the soot mass.

2.3 Methods of filter regeneration

The successful filtration of diesel exhaust by any medium will result in a build up of solids on the engine side of the filter, resulting in increasing backpressure. In order to restore the backpressure to acceptable values, the carbon mass must be removed. This can be done by several means:

(a) the filter can be physically cleaned by hand. This is not a practical solution for the relatively high frequency that would be needed, both because of the labour involved and the removal of the vehicle from productive use.

(b) the filter can be restored by temporarily taking the vehicle out of service and blowing air in a reverse direction through the filter. While this may be an effective way to remove residual ash build up (consisting of unburnable metal oxides and sulfates) on a very infrequent basis, it is not a technique that can be practiced with the frequency needed for carbon soot removal in most cases.

(c) the filtered carbon mass can be ignited and burned to form carbon dioxide which passes through the filter as a gas. **Passive regeneration systems** perform this ignition and burning without operator attention. Such systems rely on high enough temperatures and oxygen concentrations of the exhaust to ignite the carbon soot and continue the burn to completion. When the exhaust temperature is considered to be too low for this to be reliably performed, some systems use a filtration medium that has a catalytic coating applied to it so that the temperature of carbon ignition is lowered. Other systems may achieve this catalytic action by adding small amounts of components to the diesel fuel. When the fuel is burned, these components deposit with the carbon in the filtered mass and their presence within the carbon lowers its ignition temperature.

(d) the filtered carbon mass can be ignited and burned by an auxiliary heat source. These systems are termed **active regeneration systems**. A variety of heat sources can be used, ranging from electric heaters to auxiliary burners located within the exhaust manifold.

Operating personnel usually favor passive systems because they require little attention when working properly. However, to be successful, such systems must be matched to the duty cycle of the vehicle and must sustain high enough temperatures for a sufficient time. If such matching is not done, then the operator risks ineffective regeneration, which will lead to increased frequencies of productivity interruptions and ultimately to a rejection of the PFS.

2.4 Recent PFS experience in Europe

European workers have continued to experiment with newer filtration systems with good success. For example, a multi-year project to examine diesel soot reduction in tunneling operations was initiated by the national accident insurance institutions of Germany, Austria and Switzerland, and the Swiss Environmental Protection Agency. Both laboratory testing and field evaluations were conducted by the program, termed VERT, between 1993 and 1998. Thus, just as DEEP was considering its own projects for DPM reduction, VERT was completing its work. Discussions between DEEP and Andreas Mayer, VERT's technical director, assisted greatly in developing the Stobie project's scope of work. The knowledge gained by VERT in successfully matching engine-PFS characteristics was particularly valuable (VERT, 1997, 2000, 2004).

Sudwestdeutsche Salzwerke AG and Kali und Salz also had been conducting trials on operating diesel equipment and had shown the necessity of obtaining good regeneration performance as a critical factor in PFS use underground. A technical cooperation agreement was signed between DEEP and Kali und Salz to share experience in diesel-related issues.

3. THE STOBIE PFS TESTING PROJECT

The prevailing explanation of the formation of the Sudbury area nickel-copper ore body is that a meteor impact occurred about 1.85 million years ago. The impact is estimated to have released heat with about 10,000 times the current supply of the world's nuclear bomb stockpiles. This heat caused melting of the earth's crust and an up-welling of underlying magma rich in

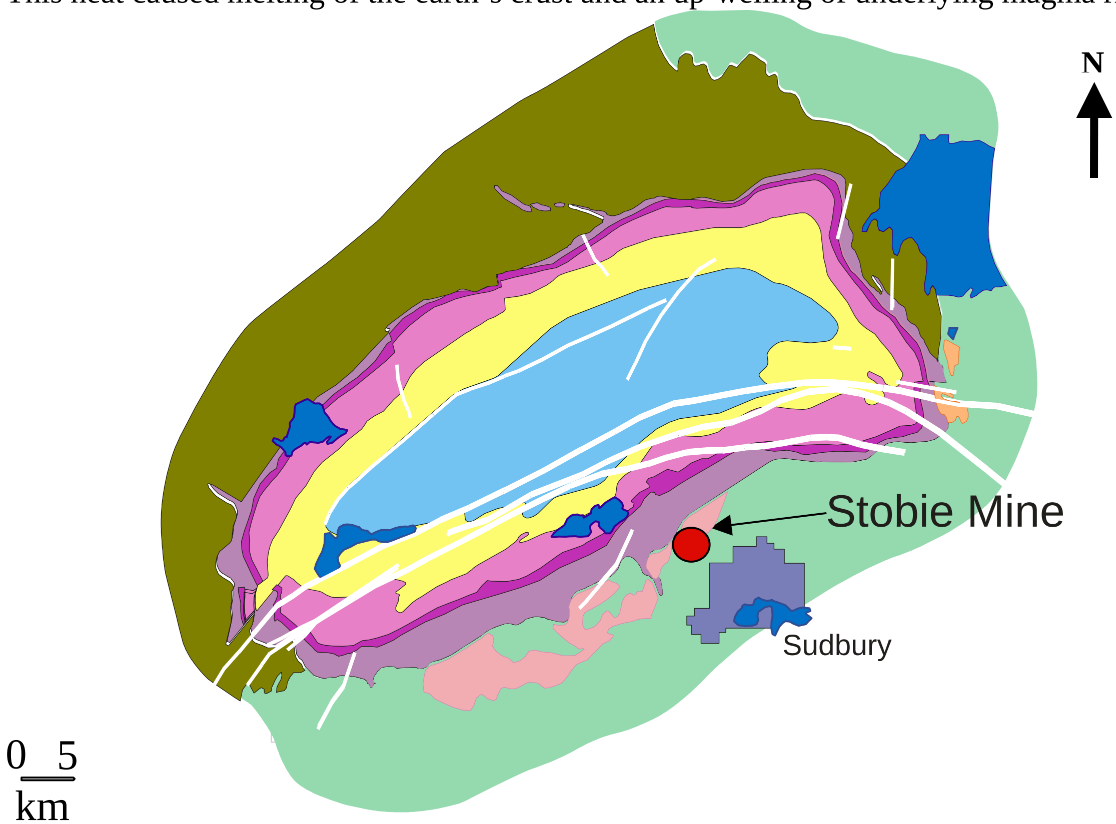


Figure 5: Schematic of Sudbury basin showing Ni-Cu ore in purple and pink colours in the shape of an elongated bowl. The City of Greater Sudbury is on the south side of the basin. Stobie Mine is just to the northwest of the urban centre of Sudbury

nickel and copper sulfides. The resulting orebody is in the shape of an elongated bowl, shown in the diagram in Figure 5.

Mining of ore started in this region in 1883 and the Frood-Stobie complex was among the first workings. Since 1886 Stobie mine has produced about 250,000,000 tonnes of ore. The mine is located on Frood Road just to the north of the urban area of Sudbury.

3.1. Development of the Project

Writing a proposal for conducting PFS evaluations at Stobie started in early 1998. Many changes to the scope of work occurred over the following year with input from the DEEP Technical Committee and outside consultants. Partial funding was obtained from agencies outside the DEEP organization. The official approval by DEEP was given in mid-1999.

The scope of the project was to test six PFSs on six vehicles doing production service in an operating Inco mine. In order to keep organizational issues minimized, one Inco mine, of the many operating Inco mines in the Sudbury area, was approached by the Principal Investigator to host the project. Having one mine host the project avoided having to interact with multiple mine managers, superintendents and operating and maintenance personnel.

The acceptance by Inco's Stobie Mine to host the project was given with recognition of the urgency of testing the effectiveness of PFSs in order to meet potential regulatory actions. A concern by mine management was the amount of in-kind costs and potential loss of ore production that would occur by using production vehicles during the project. In balancing this concern, it was recognized that the education and training of personnel in technically sophisticated systems would serve the mine well in the years ahead and would enable the mine to implement successful systems in a more timely and efficient manner.

Originally planned to be conducted over roughly 2.5 years, the testing was extended until December 2004 primarily to enable reasonable operating hours to be accumulated by the PFSs so that an evaluation of long-term ruggedness was possible. Project delays were chiefly associated with technical liaisons and with setting up operational agreements between the project team and PFS manufacturers, with training Inco personnel in new equipment and software, and with a lack of operating time of certain vehicles.

3.2 Objectives of the Stobie Project

The objectives of the Stobie tests were to:

- Develop methods for selecting PFSs for mining vehicles, including the use of duty cycle monitoring for gaining information about filter regeneration feasibility;

- Determine the ability of current PFSs to reduce tailpipe DPM emissions without significantly increasing other noxious substances and to evaluate the long-term durability, reliability, and maintenance costs for such PFSs in a production mode;

- Develop Canadian expertise with PFS technology and DPM measurement methods so that implementation of best-performing PFSs in Canadian mines could be accomplished as efficiently as possible.

3.3 Team Organization

The primary personnel comprising the Stobie Project team are shown in Figure 6. Dr. Josef Stachulak, Inco's Chief Mines Ventilation Engineer, was the principal investigator responsible for all aspects of the project. He communicated with Inco management through Mr. Joe Loring (currently Mr. Mike MacFarlane), Manager of Stobie mine, through Mr. Mike Sylvestre (recently Mr. Brian Maynard), Manager of Mines Technical Services, and through Dr. Bruce Conard, who was Inco's corporate vice-president for Environmental and Health Sciences (retired in 2004). Dr. Stachulak also communicated with the DEEP Technical Committee (not shown). The outside consultants assisting the team reported to Dr. Stachulak and consisted of Mr. Andreas Mayer (past Director of the VERT program in Europe), Mr. Paul Nöthiger (datalogger manufacturer and data analyst), and Drs. George Schnakenberg and Aleksandar Bugarski (scientists at the U.S. National Institute of Safety and Health research center in Pittsburgh).

The site champion in the pre-project planning phase was Mr. Don Peloquin. The site champion for the project was Mr. Greg Nault, who was chiefly responsible for interfacing with Stobie mine personnel regarding the project. Aspects of the project were split into five subjects. The work of the heavy duty mechanics assigned to assist the project in equipment installation, maintenance and datalogging was organized by Mr. Rick Mayotte, who reported to the Maintenance General Foreman.

Training of personnel (for example, the vehicle operators) was conducted by a team supervised by Mr. Ken Zayette.

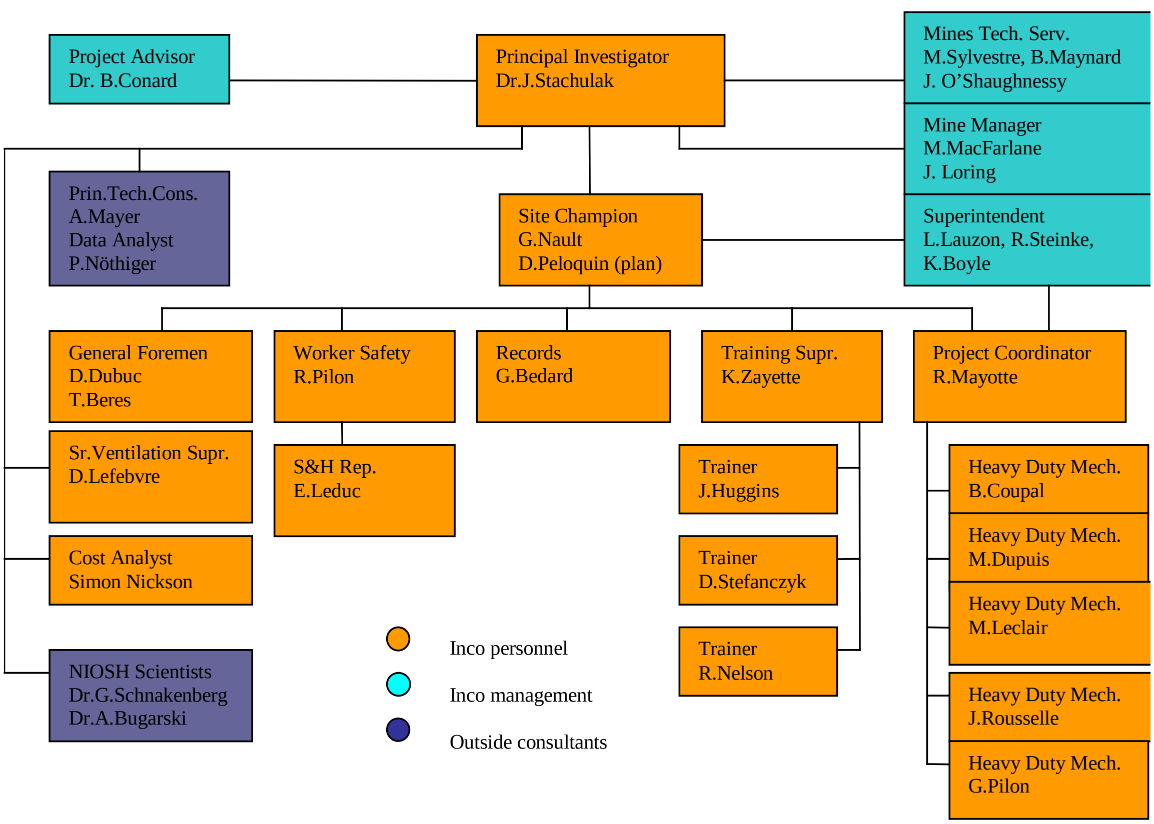


Figure 6: Stobie project team.

Ventilation and industrial hygiene measurements were conducted and/or supervised by Mr. Denis Lefebvre.

Specific attention to worker safety issues was given by Mr. Ron Pilon and Mr. Ernie Leduc.

All records pertaining to project business (for example, Minutes of all Stobie project team meetings over four years) were the responsibility of Mr. Gilles Bedard.

3.4 Stages of Work

Stage 1: Planning, site preparations and training

The core team from Stobie conducted weekly status meetings throughout the project life (meeting minutes are available for those interested). These meetings reviewed results, discussed problems, forecasted needed work and adjusted schedules and staff accountabilities. Part of the planning was conducted through Inco's "Management of Change Methodology". The principal task in this process was to conduct hazard analyses of all new equipment being brought underground in order to reduce risks of fire, unwanted emissions, injuries to mining personnel, and equipment damage. (Minutes of these meetings are also available). Included in planning were discussions (negotiations) with engine manufacturers and equipment leasing companies regarding engine warranty criteria. Included in site preparation were fuel preparation areas (where needed) and off-board filter regeneration stations. The training of operators and maintenance personnel in new equipment was organized by Inco's Mines Training Department, assisted by agents from equipment manufacturers where desired. (Training manuals specific to this project were created and are available for those interested.)

Stage 2: Selection of candidate vehicles

Discussions were held with mine management to select vehicles most representative of heavy duty and light duty diesel horsepower in underground mining. Consideration was given to maximizing the use of the vehicles in production service so that long-term testing of PFS technologies could be obtained.

Stage 3: Duty cycle monitoring of vehicles

Initially six vehicles had temperature and pressure sensors and dataloggers installed. Software for controlling the dataloggers was provided by the datalogger manufacturer and training in hardware operation and maintenance and in software for downloading data was carried out by the manufacturer in association with Inco's Mine Training Department. E-mailings of these data to the Principal Technical Consultant (A.Mayer) were done about weekly.

Stage 4: PFS selection

In November 2000 a duty cycle review session (see Appendix A) was held at Stobie and engine manufacturers, emission control equipment manufacturers, Inco and non-Inco technical personnel and consultants participated. The outcome of this meeting was the selection of PFSs for the six test vehicles.

Stage 5: Installation of PFSs

With guidance supplied by the manufacturers and technical consultants, installation of each PFS was carried out by Inco personnel. Equipment manufacturers were invited to Stobie to assist in installation and to train maintenance personnel in specific requirements of each PFS.

Stage 6: Production use and regeneration logging

Vehicles were put into normal operation except that vehicle operators were trained to keep a log of operational performance for each shift. Each use of an active regeneration system was recorded in a log book.

Stage 7: Periodic monitoring by maintenance personnel

After every 250 hours of vehicle operation, a preventive maintenance procedure was carried out on the vehicle, its engine, its datalogger-sensors and its PFS. Measurement of undiluted tailpipe gases and opacity/smoke were carried out by Inco maintenance personnel.

Stage 8: Industrial hygiene monitoring of mine air

Even though the vehicles being used were not in an isolated area of the mine away from non-PFS-equipped vehicles, attempts were made to determine if the air in the mine in the immediate area around the test vehicle was improved with respect to DPM content.

Stage 9: Detailed efficiency measurements

Three times during the four year project special sessions of efficiency measurements were conducted in conjunction with U.S. NIOSH scientists. These measurements included particulate concentrations upstream and downstream of a filter; filter efficiencies for removing diesel exhaust components; particle size distributions; gaseous components (NO, NO_2, CO, CO_2, and O_2) upstream and downstream of a filter; exhaust opacities; and smoke numbers.

Stage 10: PFS post-use analysis

Efficiency measurements at the end of the project were carried out on selected filters by Natural Resources Canada (CANMET) engineers. The original PFS manufacturers had the opportunity to examine the internal states of their filters to determine either the mode of failure (for those that failed during the project) or to determine the internal status of a filter (for those exhibiting a good efficiency at the end of the project).

Stage 11: Integrate results and form conclusions

Stage 12: Technology Transfer

Near the end of the project, in July 2004, interested parties were invited to attend a workshop to review the results of the Stobie testing. A summary of this workshop is in Appendix B.

Stage 12: Write Final Report

4.0 CHOICES OF VEHICLES TO BE TESTED

4.1 Criteria for vehicle selection

Since the scope of the project was to test diesel vehicles representing a significant amount of horsepower used in underground mines generally, the vehicles were chosen because they were known to be similar to heavy and light duty vehicles employed by many mines.

The vehicles had to be in good condition and were to be neither the oldest nor the newest. Older vehicles were excluded because they were considered to be “on-the-way-out” and would not represent a significant portion of a fleet within a few years time. While newer vehicles (and engines) might be perceived as being the best choice, the project did not want to use a vehicle that had not already put in some work and had its “newness” worked out so that it could be expected to log significant operating hours.

The selected vehicles had to have an expectation of heavy use because the project schedule demanded that PFS systems being tested would have their service time maximized within several years. Load-haul-dump (LHD) scoops are ubiquitous heavy duty vehicles with high use in underground mining. The Atlas Copco Wagner ST8B scoop is commonly used throughout the mining industry to perform high load jobs such as mucking. A variety of engines may be used to power an LHD vehicle and the project wanted to look at an older engine, as well as a newer engine, to make sure that the ability to retro-fit a complete heavy duty diesel fleet was covered. An older Deutz engine and a newer electronically-controlled Detroit Diesel engine were chosen for LHDs.

Haulage trucks are also common heavy duty vehicles and the project started out with a 26 ton 4-wheel drive end-dump truck identified as being representative of such vehicles. Unfortunately, this truck was retired from service shortly after the project was started and a substitute truck was not identified.

The project also wanted to test light duty vehicles because their contribution to the total underground horsepower was increasing and because the companion DEEP project at Brunswick mine had not tested such vehicles. The choice of light duty vehicles for testing in this project was not as critical as for the heavy duty vehicles because passive filter systems were not a viable option and therefore the precise duty cycles and exhaust temperatures attained by light duty vehicles was not as relevant as it was for heavy duty vehicles. Tractors commonly used at Stobie for personnel transport were determined to be good light duty vehicles for the project.

Another criterion for vehicle choices was that they had to be accessible for servicing that might be required. In the case of certain DPSs it was also necessary to ensure that the vehicle could be routinely returned to a certain place within the mine to receive active regeneration of its DPS.

A final criterion was that all vehicles chosen had to be able to be taken out of production for a week's time annually for special emission testing.

4.2 Vehicles selected for monitoring

Each vehicle used underground has an Inco vehicle number. The vehicles selected for duty cycle monitoring are listed in Table 1.

Table 1: Vehicles selected for duty cycle monitoring

Inco No.	Type of vehicle	Engine	Vehicle Start date
820	LHD	Deutz (12 cyl)	Nov 9/98 (new engine)
445	LHD	DDEC 60	Oct 21/98
362	LHD	DDEC 60	Jun 03/98
735	Haulage truck	Deutz (12 cyl)	Oct 28/98
621	Kubota tractor	Kubota	May 28/98
2180	Kubota tractor	Kubota	Oct 26/98

Specifications of these vehicles are given below.

Vehicle #820: Atlas Copco Wagner Scooptram ST8B, shown in Figure 7 with specifications shown in Table 2.

Vehicle used as: heavy-duty, load-haul-dump
Engine: Deutz F12L413FW
Engine displacement: 19.14 liters
Engine Type: 12 cylinders, V configuration, 4 stroke, mechanically controlled, turbocharged
Rated Power: 280 HP @ 2300 rpm
Transmission: automatic

Figure 7: Wagner ST8B scooptram with Deutz engine (vehicle #820)

Table 2: Specifications for Wagner ST8B scooptram

Capacity — kg (lbs)
Breakout Force, Digging ... 22371 ... (49,327)
Tramming Capacity ... 13608 ... (30,000)

Bucket – S.A.E. Rating — m3 (yd3)
Nominal Heaped ... 6.5 ... (8.5)
Struck ... 5.4 ... (7.0)
Boom Raising Time ... 6.8 Seconds
Boom Lowering Time ... 8.0 Seconds
Bucket Dump Time ... 7.0 Seconds

Vehicle Speeds – Loaded
Forward or Reverse with 3% Rolling Resistance

Gear	1st	2nd	3rd	4th
Speed in km/h	4.7	8.0	13.4	22.3
Speed in mph	2.9	5.0	8.3	13.9

Gradeability
Maximum ... See Performance Curve

Engine
Deutz Diesel ... F12L-413FW
MSHA Power Rating @ 2,300 rpm ... 207 kW (277 hp)
Maximum Torque @ 1,500 rpm ... 975 Nm (719 ft-lbs)
Number of Cylinders ... 12, In "V"
Displacement ... 19.1 L (1,168 in3)
Cooling ... Air
MSHA Ventilation ... 679 m3/min (24,000 cfm)

Exhaust Conditioner
Catalytic Purifier Plus Exhaust Silencer

Electrical System
24 Volt Starting, 24 Volt Accessories

Torque Converter
Single Stage, Clark ... C-8000 Series

Transmission
Modulated Power Shift, 4 Speeds Forward/Reverse
Clark ... 5000 Series

Axles
Spiral Bevel Differential, Full Floating, Planetary Wheel End Drive
Rock Torque® ... 508 Series

Standard Brakes
Service ... SAHR®
Spring Applied Hydraulically Released; Fully Enclosed, Force-Cooled Multiple Wet Discs at Each Wheel End
Parking and Emergency ... Same (SAHR)

Tires
Tubeless, Nylon, Smooth Tread Design, For Underground Mine Service, On Demountable Rims
Tire Size, Front & Rear ... 26.5 x 25, 32 Ply, L-5S

Steering
Articulated Hydraulic Power Steering, Pilot Operated, Monostick Control
Turning Angle ... 85° (42.5° each way)
System Pressure ... 15.8 MPa (2,300 psi)

Hydraulic System
Dump and Hoist Control ... Pilot Operated, Single Lever
Cylinders ... Double Acting, Chrome Plated Stems
Steering Cylinders (2) Diameter ... 152 mm (6.0 in)
Hoist Cylinders (2) Diameter ... 228 mm (9.0 in)
Dump Cylinder (1) Diameter ... 228 mm (9.0 in)
Pumps ... Heavy Duty Gear Type
Dump/Hoist ... 208+208 lpm (110 gpm) @ 2,200 rpm
Steering ... 208 lpm (55 gpm) @ 2,200 rpm
Filtration ... Pilot Flow: 10 Micron; Suction: 25 Micron
Dump/Hoist System Pressure ... 13.8 MPa (2,000 psi)

Tank Capacities — liters (gallons)
Fuel ... 380 ... (100)
Hydraulic ... 360 ... (95)

Oscillation
Rear Axle, Trunion Mounted, Synthane Bushings
Degree of Oscillation ... Total 18°

Operator's Arrangement
Side Seating For Bi-Directional Operation and Maximum Visibility

Operating Weight — kg (lbs)
Empty, Approximate ... 36750 ... (81,020)

Manufactured with an MSHA Title 30, Part 32, (Schedule 24) Certified Engine.
Under our policy of continuous improvement, we reserve the right to change specifications and designs without prior notice.

Vehicle #362: Atlas Copco Wagner ST8B Scooptram, shown in Figure 8 with specifications given in Table 3.

Vehicle #445: Atlas Copco Wagner ST8B Scooptram

Vehicles used as :	Heavy duty, load-haul-dump
Engines:	Detroit Diesel Series 60
Engine displacement:	11.1 liters
Engine Type:	6 in-line
Rated Power:	325 HP @ 2100 rpm (engines are derated to 285 HP)
Transmissions:	automatic

Figure 8: Scooptrams #362 (left) and #445 (right).

Table 3: Wagner scooptram specifications for vehicle with DDEC 60 engine (derated to 285 HP).

Capacity — kg (lbs)
Breakout Force, Digging — 22311 — (49,325)
Tramming Capacity — 13600 — (30,000)

Bucket – S.A.E. Rating — m3 (yd3)
Nominal Heaped — 6.5 — (8.5)
Struck — 5.4 — (7.0)
Boom Raising Time — 6.8 Seconds
Boom Lowering Time — 4.0 Seconds
Bucket Dump Time — 7.0 Seconds

Vehicle Speeds – Loaded
Forward or Reverse with 2% Rolling Resistance

Gear	1st	2nd	3rd	4th
Speed in km/h	5.3	9.0	15.3	24.6
Speed in mph	3.3	5.6	9.4	15.3

Gradeability
Maximum — See Performance Curve

Engine
Detroit Diesel — Series 60
MSHA Power Rating @ 2,100 rpm — 242 kW (325 hp)
Maximum Torque @ 1,200 rpm — 1559 Nm (1150 lb-ft)
Number of Cylinders — 6 In Line
Displacement — 11.1 L (677 in3)
Cooling — Water
MSHA Ventilation — [illegible]

Exhaust Conditioner
Catalytic Purifier Plus Exhaust Silencer

Electrical System
24 Volt Starting, 24 Volt Accessories

Torque Converter
Single Stage, Clark — C-8000 Series

Transmission
Modulated Power Shift, 4 Speeds Forward/Reverse
Clark — 8000 Series

Axles
Spiral Bevel Differential, Full Floating, Planetary Wheel End Drive
Rock Tough® — [illegible] Series

Standard Brakes
Service — SAHR
Spring Applied Hydraulically Released, Fully Enclosed, Force-Cooled Multiple Wet Discs at Each Wheel End
Parking and Emergency — Same (SAHR)

Tires
Tubeless, Nylon, Smooth Tread Design, For Underground Mine Service, On Demountable Rims
Tire Size, Front & Rear — 26.5 x 25, 32 Ply, L-5S

Steering
Articulated Hydraulic Power Steering, Pilot Operated, Monostick Control
Turning Angle — 85° (42.5° each way)
System Pressure — [illegible]

Hydraulic System
Dump and Hoist Control — Pilot Operated, Single Lever
Cylinders — Double Acting, Chrome Plated Stems
Steering Cylinders (2) Diameter — [illegible]
Boom Cylinders (2) Diameter — [illegible]
Dump Cylinder (1) Diameter — [illegible]
Pumps — Heavy Duty Gear Type
Dump/Hoist — [illegible] @ 2,100 rpm
Steering — [illegible] @ 2,100 rpm
Filtration — Pilot Flow: 10 Micron, Suction: 25 Micron
Dump/Hoist System Pressure — [illegible]

Tank Capacities — liters (gallons)
Fuel — [illegible]
Hydraulic — [illegible]

Oscillation
Rear Axle, Trunnion Mounted, Synthetic Bushings
Degree of Oscillation — Total 16°

Operator's Arrangement
Side Seating For Bi-Directional Operation and Maximum Visibility

Operating Weight — kg (lbs)
Empty, Approximate — [illegible]

Manufactured with an MSHA, Title 30, Part 7, (Schedule 7) Certified Engine.
Under our policy of continuous improvement, we reserve the right to change specifications and designs without prior notice.

Vehicle # 621 : Kubota Tractor (M-5400), shown in Figure 9 with specification given in Table 4.

Vehicle #2180 :Kubota Tractor (M-5400)

Vehicle used as:	light-duty, man and material transport
Engine:	Kubota Model F2803-B
Engine displacement:	2.7 liters
Engine Type:	4 cylinder in-line, 4 stroke, mechanically controlled, naturally aspirated
Rated power:	55.5 HP @ 2700 rpm
Transmission:	Manual

Figure 9: Kubota tractors #621(left) and #2180 (right).

Table 4: Specifications for Kubota tractors

M4700 · M5400 WSM, 11790 SPECIFICATIONS

SPECIFICATIONS

Model			M4700		M5400	
			2WD	4WD	2WD	4WD
PTO power (Factory observed)			31.3 kW (42 HP, 2600 rpm)		37.3 kW (50 HP, 2700 rpm)	
Engine	Model		F2803-LA		F2803-A	
	Type		Vertical, water-cooled, 4-cycle diesel engine			
	Number of cylinders		5			
	Total displacement		2746 cm³ (167.6 cu.in.)			
	Bore and stroke		87 × 92.4 mm (3.4 × 3.6 in.)			
	Engine rated output		35.1 kW (47 HP)		40.3 kW (54 HP)	
	Rated revolution		2600 rpm		2700 rpm	
	Maximum torque		158 N·m (16.1 kgf·m, 116.5 ft·lbs)/ 1400 to 1600 rpm		175 N·m (17.8 kgf·m, 129 ft·lbs)/ 1400 to 1600 rpm	
	Battery		CCA 615 K, RC160 min (12 V)			
	Fuel		Diesel fuel No.1-D [below –10 °C (14 °F)] Diesel fuel No. 2-D [above –10 °C (14 °F)]			
	Fuel tank capacity		65 L (17.2 U.S.gal., 14.3 Imp.gal.)			
	Engine crankcase capacity		8.0 L (8.5 U.S.qts., 7.03 Imp.qts.)			
	Engine coolant capacity		6.2 L (6.6 U.S.qts., 5.7 Imp.qts.)		8.0 L (8.5 U.S.qts., 7.03 Imp.qts.)	
Dimensions	Overall length		3495 mm (137.6 in.)	3405 mm (134.1 in.)	3495 mm (137.6 in.)	3405 mm (134.1 in.)
	Overall width (Minimum tread)		1700 mm (66.9 in.)		1650 mm (65.0 in.)	
	Overall height (with ROPS)		2357 mm (93.0 in.)		2375 mm (93.5 in.)	
	Wheel base		2000 mm (78.7 in.)			
	Tread	Front	1420 to 1820 mm (55.9 to 71.7 in.)	1330 mm (52.4 in.) 1430 mm (56.3 in.)	1420 to 1820 mm (55.9 to 71.7 in.)	1330 mm (52.4 in.) 1430 mm (56.3 in.)
		Rear	1420 to 1720 mm (55.9 to 67.7 in.)			
	Minimum ground clearance		430 mm (16.9 in.) (BRACKET DRAWBAR)		460 mm (18.1 in.) (BRACKET DRAWBAR)	
Weight (with ROPS)			1650 kg (3637 lbs)	1800 kg (3968 lbs)	1730 kg (3813 lbs)	1850 kg (4078 lbs)
Traveling system	Standard tire size	Front	6.5-16	9.5-22	7.5-16	9.5-22
		Rear	14.9-28		16.9-28	
	Clutch		Dry, Single plate			
	Steering		Full hydrostatic power steering			
	Transmission		Shuttle synchromesh, 8 forward and 4 reverse			
	Brake	Traveling	Wet type, multiple discs (mechanical)			
		Parking	Connected with the travelling brake			
	Differential		Bevel gears (with differential lock)			
Hydraulic system	Hydraulic control system		Position, draft and mix control			
	Pump-up capacity		34.7 L (9.2 U.S.gal., 7.6 Imp.gal.)/min.		41.6 L (11.0 U.S.gal., 9.2 Imp.gal.)/min.	
	Three point hitch		Category I & II			
	Maximum lifting force		1900 kg (4189 lbs) at lower link end 1500 kg (3307 lbs) at 610 mm (24 in.) behind lifting point			
	System pressure		18.6 MPa (190 kgf/cm², 2702 psi)			
PTO	Independent clutch		Wet type, multiple discs			
	Live PTO	Direction of turning	Clockwise, viewed from tractor rear			
		PTO speed	540 rpm at 2295 engine rpm			
Traction system			Swing drawbar, adjustable in direction			

11790Z00040

Vehicle #735: Eimco Jarvis Clark 26 Ton Truck, with specifications shown in Figure 10.

Vehicle used as:	Heavy duty: Ore transport
Engine:	Deutz F12-413FW
Engine displacement:	19.1 liters
Engine Type:	V12, air cooling
Rated power:	277 HP @ 2300 rpm
Transmission:	Automatic

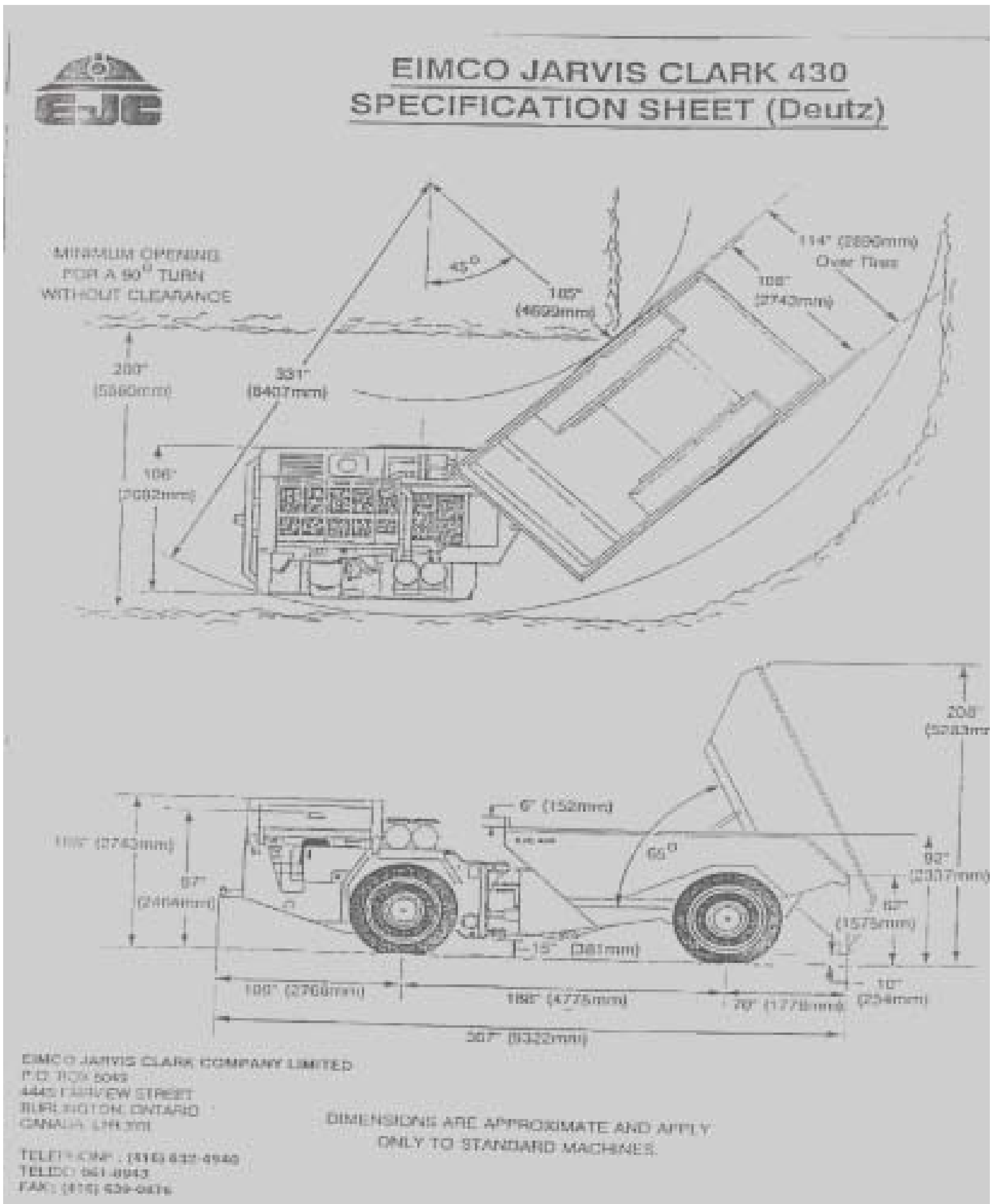


Figure 10: #735 26-Ton Truck

5. DUTY CYCLE MONITORING

5.1 Sensors and Dataloggers

The European VERT Project had motivated the development of a new datalogger with the ability to accept relevant measured diesel engine variables and with appropriate software for interactive, archival, and data presentation options. With extensive experience gained in working with VERT, Paul Nöthiger Electronic was contracted to supply the technology for the dataloggers and sensors.

5.1.1 Sensors

The temperature sensors were type TS-200 EGTS from Heraeus, shown in Figure 11. The sensor, connected to a male connector, fit into a female stainless steel A 182-68 nut, which was welded onto the exhaust manifold. This sensor was able to operate between –40 to 1000^{o}C with an accuracy of ±1.5%. The signal sensitivity was > 1mV per ^{o}C.

Figure 11: Temperature sensor

The temperature sensors were installed in the exhaust manifold at the muffler inlet and outlet (the ultimate PFS for testing was to be inserted in place of the muffler). The pressure probe was installed on the engine side of the muffler (see Figure12). The RPM signal was taken from the alternator.

The pressure sensor initially installed was a Series BT8000 from Sensor Technics. It had an operating pressure of 0-1 bar (relative to atmospheric pressure) and a response time of 1 millisecond. Limitations on its use were from -40^{o}C to 100^{o}C, 0-98% relative humidity, and 50 grams mechanical shock. The output signal was in the range 0-10 volts. Unfortunately, this sensor showed signal drift and possible adverse effects from vibration that could not be corrected by the U.S. manufacturer. Consequently, replacement pressure sensors were obtained from Keller/Winterthur. As shown in Figure 13 the sensors were placed inside the datalogger box (sensor shown to the left of the green circuit board).

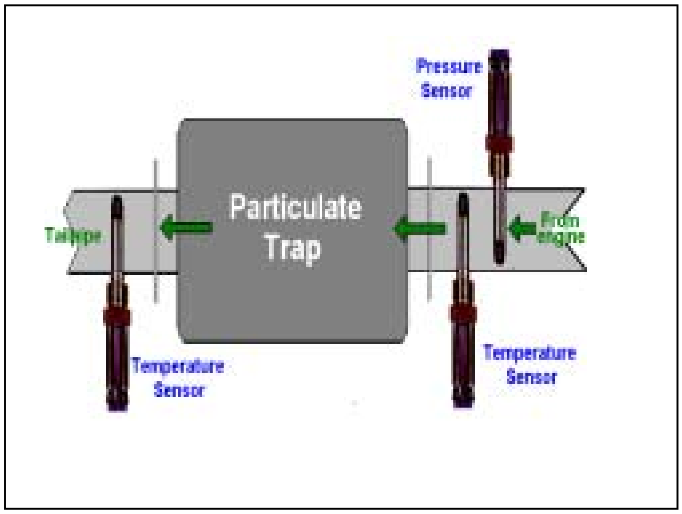


Figure 12: Positions of the sensors. The particulate trap occupies the space normally taken by the muffler.

Pressure sensor

Figure 13: Pressure sensor inside datalogger.

5.1.2 Dataloggers

Model FCD-001 of the datalogger from Paul Nöthiger Electronics is shown inside its protective case (made at Stobie) in Figure 14 and as received in Figure 15.

Figure 14: Datalogger inside protective box.

Figure 15: As-received datalogger. The five I/O ports (left to right) are for pressure, multi-use temperatures-rpm, power, and power alarm.

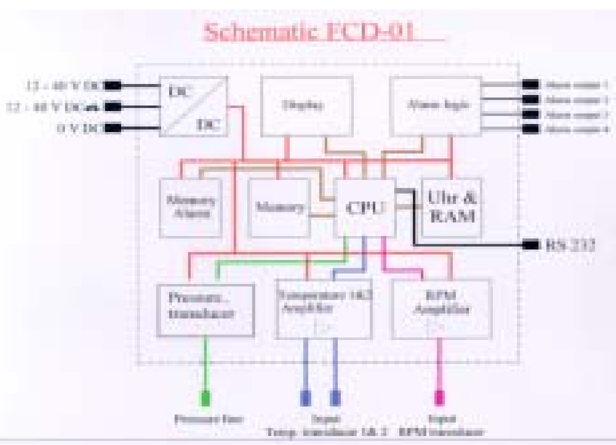


Figure 16: Schematic diagram of datalogger.

The block component diagram for a datalogger FCD-01 is shown in Figure 16. Typically four diesel parameters signals, namely, backpressure, temperature before and after the particulate filter, and engine rpm were scanned by the CPU approximately every second. The ranges of the parameters were 0-500 mBar backpressure, 0-750^{o}C temperature, and 0-8000 rpm. The values of each signal were stored in the working memory (RAM). One data channel could be viewed in real time data collection. The maximum values of the parameters were stored permanently in memory. An alarm module was used to compare a pre-determined upper limit of a parameter with the measured parameter. The alarm could be used simply to alert the operator visually and/or audibly, and it could also be used to control the engine to prevent possible damage from occurring should excessive values occur for prolonged periods.

Power was supplied to the dataloggers as 12-40 volts DC. Batteries were used for this power so that cool-down of the engine could be observed. Having the dataloggers remain on when the vehicle was not operating also allowed examination of the possible shifts in signal stability with prolonged exposures to high humidity.

Because of its development during the VERT project, the datalogger had the following beneficial features:

- Extended data storage
- Intelligent alarm processing
- Remote data collection
- Temperature resistance
- Vibration resistance

- Anti-tampering devices

After being constructed in Switzerland, each datalogger was vibration tested, subjected to temperature cycling, calibrated using high-precision standards, and its systems checked for data storage, downloading capability, and general software performance. Each datalogger was also installed for 48 hours on an in-use heavy duty vehicle to ensure its ruggedness before being shipped to Stobie mine.

5.2 Software

The software used by the FCD-01 datalogger was supplied by Loglink Electronic GmbH. running under Windows 95/98. The main menu of the software included:

Logger:	Used for interacting with the datalogger
Export:	Used to create data in an ASCII format
Graphic:	Used to display graphs of data
E-mail:	Used to send data via e-mail to other parties
Settings	Used to input or change datalogger settings

An example of the sub-menu appearing when “Logger” was selected from the main menu:

Technical Data:	Showed collected data
Logger Read:	Extracted data from the logger
Logger Clear:	Deleted stored data
Alarm-Store Read:	Extracted alarm data
Alarm-Store Clear:	Deleted alarm data
Logger Configuration:	Allowed logger settings to be made
Real-time read:	Showed instantaneous values

The Graphics menu could display either direct LogLink data or ASCII data as a function of time. A zoom feature allowed closer inspection of information. An example of graphical information is shown in Figure 17.

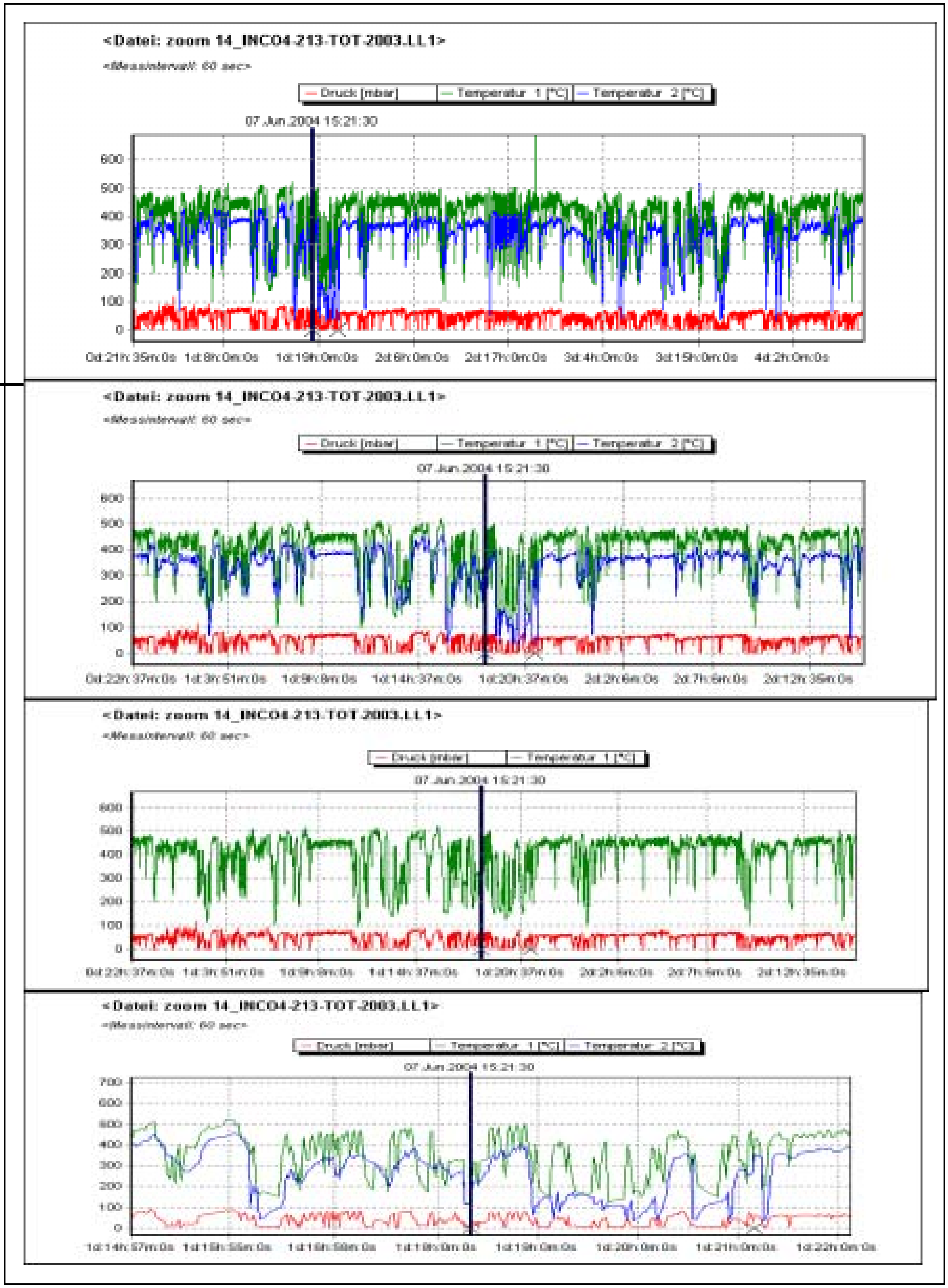


Figure 17: Data displays showing zoom capabilities. All the four displays are taken from vehicle #213 around June 7, 2004. A common time of 15h:21m:30s is shown in each display by a solid vertical black line. The three parameters shown are inlet temperature (green), outlet temperature (blue) and overpressure (red).

5.3 Installation

Datalogger installation was started in April 2000 during a visit to Stobie by P. Nöthiger and A Mayer. The position of the datalogger on each vehicle was done to allow reasonably easy access while not interfering with normal duties of the vehicle operator. Examples of datalogger installations are shown in Figure 18 and 19.

Figure 18: Installation of dataloggers on LHDs.

Figure 19: Installation of datalogger just behind driver's seat on Kubota tractor

5.4 Training

During the visit by P. Nöthiger and A. Mayer, significant time was spent with Inco's Training Department in order to write a Training Manual for the dataloggers. This Manual is the property of Inco and liability issues restrict its direct use by other parties. However, for the purposes of information, interested parties can obtain the Manual on request.

Over 50 individuals were put through an Inco training program on the datalogger operation. These people were from departments such as ventilation, maintenance, operations, and management.

5.5 Data treatment

All data records were routinely downloaded by Stobie DEEP personnel and were transmitted electronically to A. Mayer and P. Nöthiger in Switzerland. The following types of data treatment were performed by A. Mayer:

- Early in the data processing the temperature channels were switched during data transfer due to a loss of one byte of information during data downloading. This problem was quickly solved by a software repair; for the data already downloaded, the switched channels were re-assigned their correct labels in the transferred files.
- Often data spikes occurred due to stray voltage. These spikes were eliminated so that appropriate statistical parameters could be accurately calculated.
- Early in the data processing, sometimes the amount of data exceeded the pre-set limit. This was corrected in the software and the data exceeding the limit were recovered.
- Engine "off" conditions were deleted from the data records in order to calculate proper statistics for the engine "on" conditions. Criteria for excluding engine "off" were that the exhaust temperature was $< 50^{o}C$ and the engine speed was < 5 rpm.
- Data squeezing was sometimes carried out. The reason for doing this relates to the signal reading interval. The sensors deliver analog data. The software performs an analog to digital (A/D) conversion each second for each signal. For a timing sequence (selected during configuration of the datalogger) greater than one second, the software selects the highest value from the A/D conversion for storage. The highest value was selected because it represented the worst situation for backpressure. [It is noted that it would be advantageous to have capability for selecting different values for different measured parameters. For example, being able to select the mean temperature, instead of the highest temperature, during the measuring period would have been preferred.]
- Statistical analyses were then performed on the data resulting from all of the above. Calculations for each signal included: mean value, standard deviation of the mean, median value, range of values and frequency distributions and frequency dwell times.

Examples of treated ("cleaned") data are shown in Figure 20, which contains the entire exhaust manifold temperature (probe closest to the engine) history for vehicle #445 (scooptram). The data cover 21,313 minutes of monitoring (335.2 hours). This involves many shifts by many operators. The variations in temperature show the essential nature of the operation of the scoop, covering periods where full power was being used and other periods where extensive idling occurred. Included in this history are also differences in driving habits of different operators. It should be noted that the expected very high temperatures associated with fully loaded engine conditions were never seen by the sensor despite the knowledge that this scoop was periodically operating under peak load conditions. The absence of expected very high temperatures associated with such conditions is likely due to these conditions being of a relatively short duration and that the relatively small amount of very hot gases being produced under such conditions are being cooled by the thermal inertia of the exhaust manifold itself. The absence of high temperatures for such a heavy duty scoop is extremely important in deciding whether passive PFSs could work.

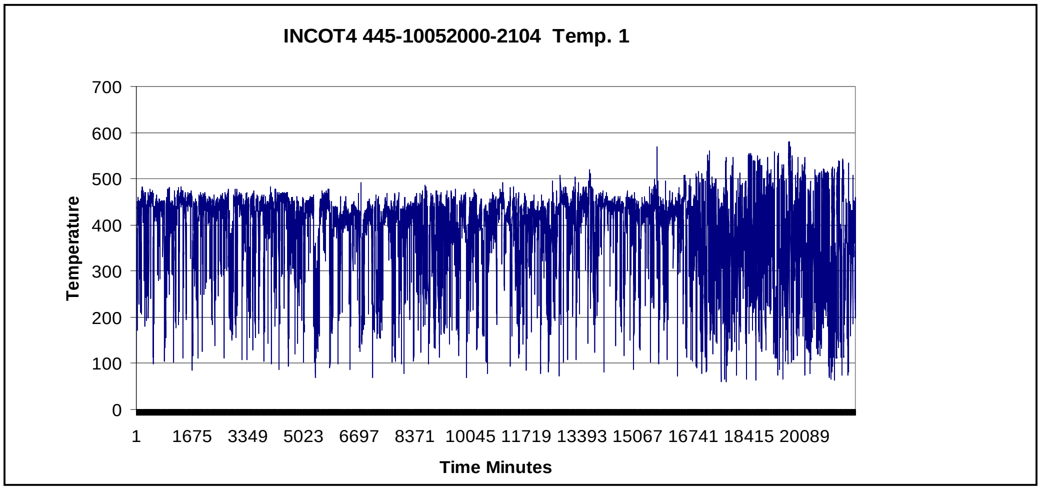


Figure 20: "Cleaned" temperature (°C) history for vehicle #445 (LHD) during 335.2 hours of duty cycle monitoring.

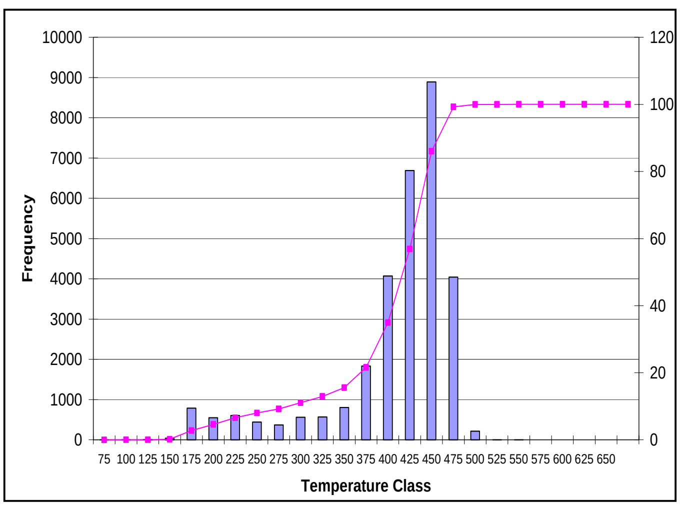


Figure 21: Simple temperature frequency distribution for 1 second data collection intervals. Vertical bars show the number of observed temperatures in each temperature range. For example, the bar associated with the range 387.5 to 412.5°C shows that this was observed just over 4000 times. The red points and line show the cumulative percentage of the observations. For example, approximately 20% of the observations are <375°C.

An example of a simple frequency distribution for these same temperature data are shown in Figure 21. This kind of frequency distribution, however, must be interpreted with much caution. One might be tempted to conclude, for example, that there is an extended amount of time (about 60% of the observations) when the exhaust temperature for this vehicle is above 400°C. This, in turn, could lead to a belief that a catalytic particulate filter material could be effectively regenerated by such temperatures. The flaw in reaching this conclusion is that the number of times the temperature is >400°C says nothing about the length of time the temperature stays above 400°C for each episode. That is, 4000 measurements in the range of 400°C ± 12.5°C could represent a single episode containing a continuous 4000 seconds or it could represent 4000 different episodes where >400°C occurred for only 1 second, or it could represent anything in between these two extremes. It is clear that proper regeneration of a catalyzed filter medium would require a significantly prolonged episode >400^{o}C to achieve a burn-off of the soot. This simple frequency distribution fails to give the necessary information to see if that is happening.

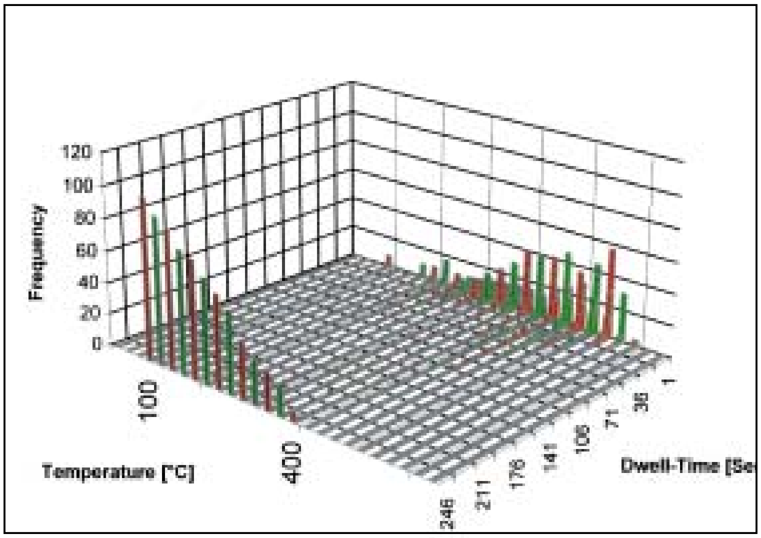


Figure 22: Temperature and dwell time frequency distribution for vehicle #445 using 1 second data collection interval.

To circumvent this problem, another approach was developed by A. Mayer during the VERT work. It involved an investigation into the dwell time at given temperatures. The dwell time frequency distribution is best presented as a three-dimensional diagram, where the third dimension is the dwell time added to the previous simple temperature frequency,as shown in Figure 22.

This graph allows one to see that the highest temperatures are usually associated with very short dwell times (on the order of tens of seconds) and that such dwell times would be insufficient to overcome the thermal inertia of the filter medium and to sustain these temperatures for the time necessary to burn the soot.

5.6 Results

The monitoring results recorded for the test vehicles during the duty cycle monitoring in the period of April-September 2000 are shown in Tables 5 and 6.

Table 5: Duty-cycle monitoring summary of test vehicles (1 sec. measuring time)

Vehicle #	Vehicle description	Hours	T1 °C Mean	T1 °C Max/Min	T2 °C Mean
735	26 T Truck	27.3	233	477/78	223
820	Scoop	183.3	313	498/51	313
2180	Tractor	294.0	159	543/57	147
621	Tractor	363.8	No data	No data	No data
362	Scoop	453.2	366	465/135	364
445	Scoop	592.1	341	468/66	338

Table 6: Duty-cycle monitoring of test vehicles (60 sec. measuring time; same column headings as above).

735			No data	No data	No data
820			329	615/54	328
2180			192	609/51	178
621			203	606/54	178
362			370	549/57	378
445			382	579/60	356

5.7 Conclusions

(1) The low hours on vehicle #735 was due to general maintenance problems with this truck. The truck was taken out of service by the mine in the summer of 2000 and no substitute vehicle was available.
(2) Scoops might be able to be used with catalytic PFSs, but temperature variation is large and dwell times are limited and these may be critical factors limiting the successful use of passive systems.
(3) Tractors definitely need active systems.
(4) Alarms on backpressure are highly recommended.

6. SELECTION OF FILTER SYSTEMS

The vehicles, on which test PFSs were to be placed, initially included 3 LHDs, 1 heavy duty truck and 2 light-duty tractors. More than 50 manufacturers worldwide offer PFSs capable of filtering DPM, but this number was reduced significantly by application of several service and performance criteria. In selecting PFSs for testing, consideration was given to each candidate PFS's expected reliability and the technical and operational viability under the duty cycle of the vehicle. Important also was reliability shown through experience elsewhere and technical support of the PFS manufacturer. In addition, the Stobie tests were able to take into consideration its companion project at Brunswick mine where testing using 2 LHDs and 2 trucks was already underway.

6.1 Criteria for initial selections of PFSs

Regeneration of PFSs was known to be a critical aspect of having a system work successfully over a long-term period of time. The probability of success of each regeneration system depended on the method used for regeneration and, therefore, the factors needed for success varied for each kind of system. These factors are shown in Table 7.

Table 7: Critical success factors of various regeneration methods.

Regeneration method	Implementation complexity	Fuel quality	Secondary Emissions (NO_2)	Regeneration Rate	Duty Cycle	Power supply	Additive dosage	Cost	Dependability	Operating logistics
Diesel burner	X							X		
Continuous Regeneration		X	X	X	X					
Fuel-Borne Cat.	X						X			
Catalytic coating				X	X					
Electric offboard						X			X	X
Burner standstill									X	X

The strategy employed for selecting PFSs for the Stobie project relied on two principal types of information:

- The experience gained during extensive testing of many systems in Europe by VERT.
- The types of PFSs under test at Brunswick mine because duplication of effort was to be avoided.

6.1.1 VERT Criteria

VERT published (VERT, 2004) results of PFS testing that met certain broadly accepted criteria. These criteria were:

- Filtration of >95% (new and at 2000 hours service) and elemental carbon in the exhaust reduced by >90% when averaged over four operating conditions of the ISO 8178 test cycle.
- No increase in CO, chained hydrocarbons, NOx, dioxins, furans, poly-aromatic hydrocarbons and nitro-poly-aromatic hydrocarbons during PFS operation and/or regeneration.
- Opacity of exhaust of 5% during free acceleration.
- At maximum exhaust flow at rpm limit, the backpressures to be maintained
    - For new filter: <50 mbar
    - For operating filter: maximum range of 125-150 mbar.
- For fuel additives, dosing should be automatic with interrupt if filter ruptures.
- Muffling capacity is to be equivalent to muffler that is being replaced by the PFS.
- The life expectancy of the PFS is >5000 hours. Useable hours until ash cleaning was expected to be > 2000 hours.
- Labelling of serial number and manufacturing data must be clearly visible and legible even after prolonged use. Also, flow direction through the filter must be indicated by an arrow and reverse mounting should be prevented by design.

The candidates meeting VERT criteria are listed in Table 8.

6.1.2 Criteria from duty cycle monitoring

For LHDs: Even though passive systems were initially perceived to be favored because of the lack of attention they required, the duty cycle information showed a high variation in the sustained (dwell time) temperatures achieved. Accordingly, it was felt that electrical heating back-up would be wise to employ.

For Tractors: The duty cycle data clearly showed that only active systems were to be candidates.

Table 8: Candidate PFSs meeting VERT criteria. Those marked with an (X) were under test at Brunswick mine.

Heavy Duty	Light Duty
Engine Control Systems (X)	Engine Control Systems-3M
Engelhard	Diesel Control Limited
Oberland-Mangold (X)	Greentop
Diesel Control Limited (X)	
Johnson-Matthey	
Deutz	
HJS	
HUSS	

6.2 The Chosen PFSs for testing at Stobie

Deutz — Chosen for the #735 Truck
Reasons: With the truck having a Deutz engine, it was thought that matching a Deutz PFS with a Deutz engine was wise. The Deutz PFS has been well-proven in Europe. Deutz PFSs were not tested in Brunswick. Of the various means of regeneration, the Deutz system used an exhaust manifold burner and it was felt this type of system should should be tested.

Johnson-Matthey — Chosen for the #820 LHD
Reasons: The JM PFS is based on a fuel additive to achieve regeneration. Other fuel additive systems were under test at Brunswick and the JM system was seen to be a competitive system in terms of reliability and operational viability. An active electrical heating system was added to back-up regeneration.

Oberland-Mangold — Chosen for the #445 LHD
Reasons: This system has a knitted glass fiber filtration medium, which is significantly different than the cordierite/silicon carbide ceramic media. It uses a fuel borne catalyst without an active back-up. A similar system was under test on a truck at Brunswick and it was thought beneficial to get a comparison on an LHD for the same kind of system.

Engelhard — Chosen for the #362 LHD
Reasons: This system uses a catalytic coating. It appeared to be competitive with certain catalytic coatings under test at Brunswick.

ECS-3M — Chosen for the #2180 Tractor
Reasons: This system was seen to be a leading candidate for active systems for light duty vehicles.

Greentop — Chosen for the #621 Tractor
Reasons: This system has proven to be reliable in Europe and is another leading candidate for active systems.

6.2.1. Vehicle problems

During the project a number of the initial vehicles became unavailable for the following reasons:

#735 Truck: was retired from the Stobie fleet prior to PFS installation; no suitable replacement truck was available.

#445 LHD: was retired by Stobie mine after 2 years of testing.

#621 Tractor: this tractor had little use; an identical tractor (#017) was substituted in order to gain more PFS service.

#2180 Tractor: after about 3 years of requiring higher than normal maintenance and concomitant low hours of operation, #3013 LHD was used as a substitute vehicle.

#213 LHD: this vehicle was buried by a run of ore on November 8, 2004, and was damaged.

#820 LHD: after 2.5 years of testing, the testing was completed and the two DPF were removed.

PFS second choices were made as a result of operational problems encountered with the first choices. These were:

ECS/Combifilter — Chosen for #445 LHD and #213 LHD
Reasons: to replace poorly performing Oberland-Mangold PFS. The ECS system employed for the Stobie test used an electrical heating system for regeneration instead of the catalytic coating and NO_2-based regeneration system used at Brunswick.

ECS/Combifilter — Chosen for #2180 Tractor and #3013 Tractor
Reasons: to replace ECS/3M Omega system after 3M announced its decision to stop production of the Omega line.

DCL-Titan — Chosen for #621 Tractor and #017 Tractor
Reason: to substitute for Greentop, which could not supply their PFS under the terms and conditions requested by Stobie.

Arvin-Meritor — Chosen for #111 LHD
Reason: to substitute for the Deutz burner regeneration system that was to be installed on #735 Truck. Since a truck was not available at Stobie, the Arvin-Meritor burner regeneration system was installed on an LHD.

6.2.2 PFS-vehicle combinations tested

The ultimate configurations of the particulate filter systems and the vehicles are given in Table 9.

Table 9: Ultimate PFS-vehicle pairings tested

PFS System Model	Johnson-Matthey DPF 201	Oberland Mangold	ECS-Unikat Combi S18	ECS-Unikat Combi S18	Engelhard DPX2	Arvin-Mer.	ECS-3M Omega	ECS-Unikat Combi S	DCL Titan
Vehicle #	#820	#445	#445	#213	#362	#111	#2180	#2180 → #3013	#621 → #017
Vehicle type Engine	LHD Deutz (dual)	LHD DDEC60	LHD DDEC60	LHD DDEC60	LHD DDEC60	LHD DDEC60	Tractor Kubota	Tractor Kubota	Tractor Kubota
Type of PFS	Pass.+act.	Passive	Active	Active	Passive	Active	Active	Active	Active
Filter medium	(a)SiC (b)cordierite	Knitted glass	SiC	SiC	Cordierite	Cordierite	Ceramic fiber	SiC	SiC
Catalyst	Fuel borne	Fuel borne	-----------	------------	Coated on filter	--------------	-----------------	-----------------	---------------
Act. Regen.	On board elec	-----------	On board elec	On board elec	------------	Fuel burner	On board elec	On board elec	Off board elec

7. PFSs: DESCRIPTIONS AND INSTALLATIONS

7.1 Oberland-Mangold

The filter medium of the Oberland-Mangold system is a mesh of ceramic micro-fibers, which act as a deep-bed filter for soot particulate. These fibers are compressed between two perforated tubes and canned in cartridges. All the cartridges are assembled into the filter assembly as shown in Figure 23. The number of cartridges to be included in the PFS was determined by Oberland-Mangold using information on the diesel engine type, age and duty cycle. The unit was mounted on LHD #445 as shown in Figure 24.

Figure 23: Oberland-Mangold casing containing eight filter cartridges.

Regeneration of the O-M system is passive by means of a fuel additive, which catalyzes the burning of the filtered soot. As part of the installation, a fuel additive run-in period of about 3-4 hours was performed, using 1.27 L of additive for 376-379 L of diesel fuel, to fully coat the engine internals with the platinum-based catalyst. Under normal operation the additive was dosed automatically from a 12 L addition tank by means of a dosing control module, components of which are shown in Figure 25. A metal frame and guard was used to secure the additive dosing system to the scoop's chassis.

Figure 24: O-M filter installed on LHD #445.

Figure 25: Oberland-Mangold fuel additive components. Left: overall system; Upper right: electronic additive control; Lower right: additive pump.

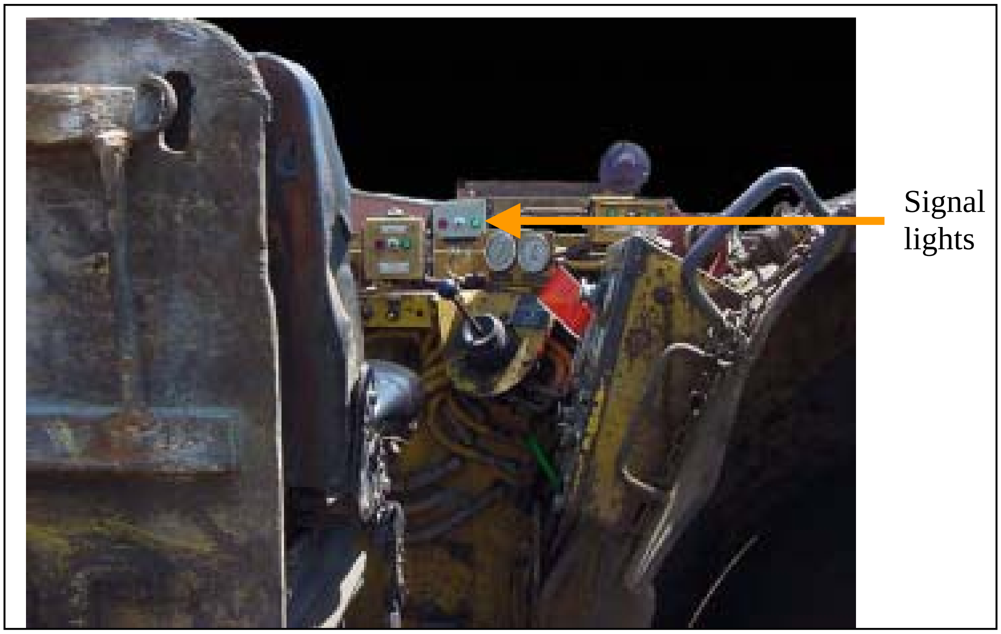


Figure 26: Operator's dash showing signal lights for Oberland-Mangold pump status.

Special additive pump status lights were added to the dash, as shown in Figure 26, so that action could be taken by the operator upon the additive pump stopping. Additional filter alert lights to signify filter plugging were hard-wired to the existing "engine problem" lights on the dash.

The O-M PFS installation, including the fuel additive dosing system, was started for LHD#445 on June 18/01 and completed on June 22/01. Training was carried out by Inco's Maintenance Dept. for the heavy-duty equipment mechanics. Manuals for the operation of the PFS were compiled by Inco's Training Dept.

7.2 Johnson Matthey (JM)

JM manufactures a variety of particulate filter systems that operate on different principles. The PFS chosen to be installed on LHD #820 was based on a combination of JM DPFiS (fuel additive) and DPFi (electrical heating) systems. It was felt that this particular LHD[α] might suffer incomplete regeneration if only a fuel catalyst was used and, therefore, an electrical heating backup was also provided.

Because the #820 LHD had a Deutz engine (dual exhaust system for 12 cylinders), two PFSs were installed on the vehicle. These units were initially identical filters (JM-DPFi201) having silicon carbide honeycomb filter media. After considerable testing one of the filters (the driver's side) showed some separation of the filter medium with the canister. This separation was initially not influencing the performance of the filtration and it continued in operation for quite a bit of additional time (another 723 hours). Eventually, however, the separation became more severe and it became necessary to replace this filter after 2138 hours of operation and the decision was made to replace it with a new cordierite filter. Following the special tests in the summer of 2004, the other silicon carbide filter (off-driver side) was also replaced with a cordierite honeycomb filter.

The canisters were stainless steel construction with modular design, having V-clamps and gaskets for easy assembly and servicing. Within the inlet stage, there existed a diffusion plate that provided even distribution of particulate-laden gases over the filter honeycomb. The heating element stage, Type EC-B/Ca, shown in Figure 27, consisted of electric heating elements with power and air supply connections. The air flow during regeneration assisted in obtaining the optimum heat distribution to the filter's mass.

Figure 27: Heating element at the bottom of the Johnson-Matthey filter.

[α] LHD #820 is used in a semi-production mode. Its duty cycle varies from high loads for short periods of time to light loads over extended periods of time.

The cylinders were installed vertically, using vibration-reducing mountings, on each side of the engine in place of the mufflers, as shown for one side in Figure 28.

Figure 28: One of two JM filters mounted on either side of the dual exhaust engine.

Figure 29: Automatic fuel additive equipment (left) and backpressure monitoring display on dash (right).

The fuel additive was cerium-based (EOLYS™) from Rhodia. The dosing of the additive was done from an on-board additive reservoir each time refueling was carried out using an automatic dosing system, DOSY 200, supplied by JM and shown in Figure 29 (left). The targeted amount of additive used aimed to reduce the soot ignition temperature to 400^{o}C.

Monitoring of backpressure was not only done using the normal dataloggers described in Chapter 5, but also using the JM PIO210 monitoring system, as shown in Figure 29 (right), which was mounted on the vehicle's dashboard. This unit had a series of LED displays from green to yellow to red indicating a progression of increasing backpressure. A "red" signal indicated that the unit had to be electrically regenerated.

The electrical regeneration station for the JM system was located outside the 2400 Level garage in Stobie mine. The vehicle was brought to the station and a specific procedure was followed each time. The components of the station are shown in Figure 30. The power was supplied at 230V (connector shown in Figure 31). Mine compressed air (see Figure 31) was connected to the air port and the control box provided a timed sequence for the heater coil to attain 600^{o}C with monitoring of the progress of regeneration by means of air pressure measurement. The system stopped itself automatically when the pressure reading against the filter showed a pre-set low value and a light was activated on the control panel. Regeneration typically lasted 1-2 hours.

Figure 30: Display panel (on left) and inside of panel (on right) for electrical regeneration of the JM system.

Figure 31: Air line with moisture removal and pressure gauge (left) and electrical connector (blue) and air line beside it on the right.

7.3 ECS/3M Omega

The ECS/3M Omega system was installed on Kubota tractor #2180 on Sept 4/01. The system consisted of 3M glass fiber cartridges located within a cylindrical housing, which was mounted horizontally on the left front fender of the tractor, as shown in Figure 32.

The system had its own monitoring of soot buildup based on backpressure measurements and this was displayed via two units mounted on the dash in front of the operator. As shown in Figure 33, one of these units displayed an LED progression of four steps of increasing backpressure. The other unit had a single LED (red) and an audible alarm for signaling system failure or plugging.

The regeneration station for the system was inside the 1800 Level garage shown in Figure 34. This station controlled the timed air flow and power to the heating element. The regeneration was to be conducted after each shift and was to last 60 minutes.

Figure 32: ECS/3M filter mounted on #2180 tractor. The yellow cage is to prevent operator contact with hot surfaces. The red box on the fender is a protective casing containing the power connector for electrical regeneration.

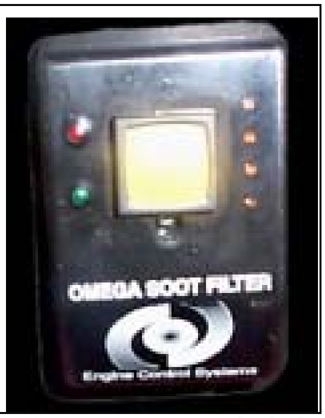


Figure 33: Omega dash display

Figure 34: ECS/3M Omega regeneration station.

7.4 ECS/Combifilter

Due to the fact that the ECS/3M Omega system on #2180 had become irrelevant because 3M had announced its decision to cease production of glass fiber filters, an ECS Combifilter was installed on tractor #2180 on May 6/02.

The unit, shown in Figure 35, was mounted horizontally on the front fender of the tractor. The main component of this system was an extruded SiC honeycomb filter. An auxiliary component was an electrical heating coil built into the intake end of the filter's housing. The filter was sized to collect soot during an 8-hour shift, immediately after which it was to be regenerated by connecting the unit to a regeneration station inside the 1800 Level garage (see earlier Figure 34). The regeneration period under these conditions was about 60 minutes.

Tractor #2180 continued to have general maintenance problems due to its age. In order to increase the rate of operating hours of the ECS Combifilter, it was transferred in the period July12-19/04 to a new Kubota tractor (#3013) and was installed in exactly the same manner it had been installed on the older tractor.

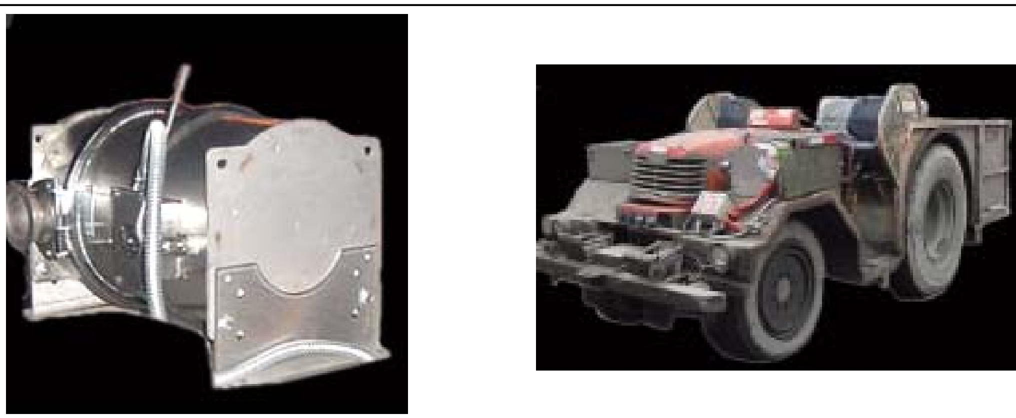


Figure 35: ECS Combifilter, left: as received; right: mounted on vehicle #2180.

7.5 Engelhard

The Engelhard DPX2 filter, shown in Figure 36, was installed on LHD #362 on June 10/01. This system was fully passive utilizing an extruded cordierite honeycomb filter medium, the internal surfaces of which were coated with a platinum-based catalyst.

The installed system is shown in Figure 37, which also shows the dash-mounted backpressure indicator with yellow (warning) and red light displays.

Figure 36: Engelhard filter

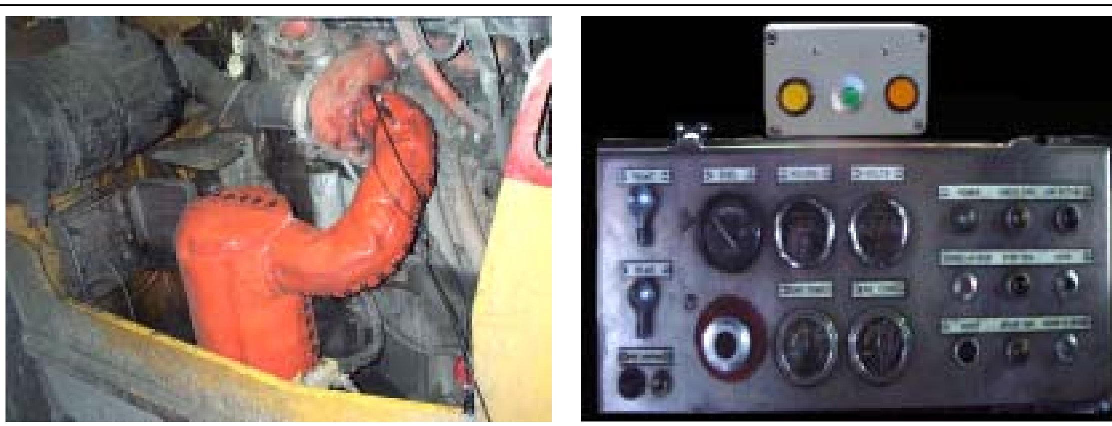


Figure 37: Installed filter (left) and backpressure monitor on dash (right).

7.6 DCL Titan

The DCL Titan system was installed on Kubota tractor #621 on February 3/02. It was subsequently moved in July/04 to an identical Kubota (#017) so that a more rapid pace of operating hours could be logged.

The filter, shown in Figure 38, was an extruded SiC honeycomb medium contained in a stainless steel cylinder. It was mounted between inlet and outlet caps. Quick disconnect clamps

Figure 38: DCL Titan filter, side view on the left and end view on the right. The side view shows the two end caps connected to the main canister by quick disconnect clamps.

were used for easy regeneration. The filter assembly was mounted in a horizontal position on the front fender (as shown in Figure 39) and covered with a metal box to prevent operators coming into contact with its hot surfaces.

Figure 39: Views of DCL Titan mounted on the Kubota fender. Lower photograph shows the protective box.

Figure 40: DCL backpressure monitor mounted on dash.

A monitoring unit (see Figure 40) for backpressure was supplied by DCL and was mounted on the dash of the vehicle. Normal operation was indicated by a green light. A yellow light indicated a backpressure of about 125 mbar as a warning that the filter was becoming loaded. A red light indicated that the filter needed to be regenerated.

The regeneration station was located inside the 1800 Level garage. Instead of plugging an on-board system into the power station, as was done for many other DPF systems being tested at Stobie, the DCL Titan filter was removed from the vehicle and was placed in a "cooker" (shown in Figure 41) having an heating coil. The cooker was permanently connected to a wall-mounted power control panel, shown in Figure 42. The control panel activated a timed regeneration cycle which typically lasted 1-2 hours. After the heating cycle was completed, the filter was allowed to cool to room temperature before removing it from the cooker and re- installing it on the tractor.

Two identical DCL Titan filters were used for this vehicle so that one filter could be used on the operating vehicle while its companion filter was being regenerated.

Figure 41: Regeneration "cooker" for DCL filters: side view on left and top view (showing heater elements) on right.

Figure 42: Regeneration station showing loaded filter in the cooker and the control panel at upper right.

7.7 ECS Dual Combifilters

ECS/Unikat dual S18 Combifilters were installed on LHD #213 on Feb 17/03. The dual units were mounted side by side in a vertical position. The filter medium was extruded SiC honeycomb. Each filter canister contained electrical heating elements at the bottom of its housing.

The filters were sized to collect soot over two working shifts with active electrical heating regeneration performed each day. The dual filters operated in parallel. Two cylinders were used instead of one cylinder due to spatial considerations (see Figure 43 and 44).

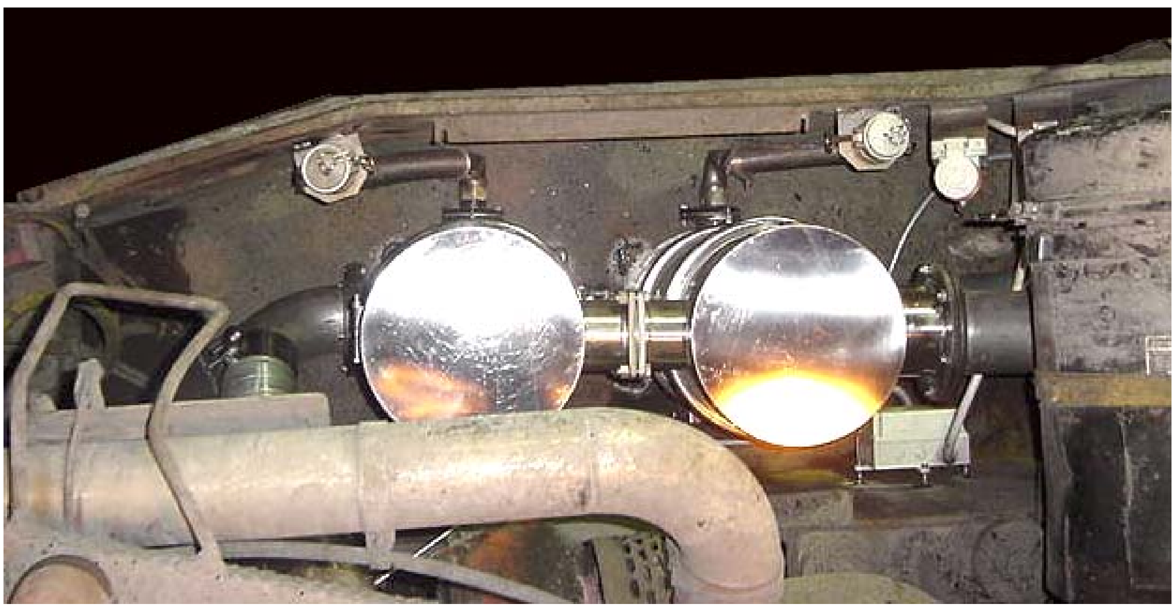


Figure 43: Top view of installed ECS Combifilters

Figure 44: Side view of Combifilters (left) and backpressure monitor on dash (right).

Monitoring of backpressure was carried out by the system and a signal indicating high pressure (regeneration needed) was mounted as a red LED on the vehicle's dash shown in Figure 44 (right). A green "test" button was located next to the LED.

The regeneration station, shown in Figure 45, was initially located at the 3000 Level garage. However, due to a lack of consistent regeneration, the cause of which appeared to be that Level 3000 was not very convenient, a concerted effort was made with the operators to improve regeneration operations by moving the station to Level 3400 truck bay. The regeneration unit consisted of dual control panels, dual power cables and connectors (Figure 46) and compressed air supplies (Figure 47) that were hooked up to each canister. A 70 minute heating cycle was generally used with the control panel showing amperes to each heating coil and timed countdown. Following the heating period, a 20 minute cooling period was allowed.

Figure 45: Regenerating station for ECS Combifilter

Figure 46: Regeneration control panel for one filter (left) and power cables (right).

Figure 47: Compressed air connection.

CombiClean Station

A CombiClean™ System was purchased by Inco outside the DEEP Stobie project because the company had decided to purchase an ECS CatTrap PFS for one of its LHDs. The CombiClean station was required for the CatTrap PFS. One should not be confused by the name "CombiClean" and the combifilter being used in the Stobie tests. The combifilter used a built-in electrical heater for regeneration and an external control station, whereas the CombiClean station has both the heater and the control station off-board.

However, due to periodic problems encountered with the ECS station used for the ECS PFS in the Stobie tests, it was decided to use the CombiClean unit as a substitute. This was found to be very effective in returning the PFS to a clean state and, accordingly, in the latter stages of the Stobie tests, the ECS Combifilter was periodically cleaned by the CombiClean station even if the on-board heaters were working. It was also decided to clean the DCL Titan PFS in the CombiClean system during the last few months of testing.

The CombiClean system consisted of rack mounted components: a heater canister, a vacuum system, a compressed air system, and a control panel. The system is shown in Figure 48.

Figure 48: The ECS CombiClean™ System, consisting of dual heating compartments. Outside the picture at the bottom is a ShopVac vacuum system (see view in Figure 50) employed at certain stages in the regeneration procedure.

The loaded filters were physically carried to the CombiClean station and were mounted (gasket sealed and clamped) to the top of a heater unit, as shown in Figure 49. Care was taken to align the filter so that the bottom to top direction corresponded to the direction of exhaust flow when the filter was in operation on the vehicle. The control panel, shown in Figure 50, was then used to activate the air flow through the filter (bottom to top) and the heater. Lights on the control panel signified when the regeneration was complete. It was also possible to clean the filter by blowing compressed air downward at the top of the filter, while simultaneously operating a vacuum system (removing air from top to bottom), so that residual soot and ash could be removed from the engine side of the filter.

Figure 49: Placement of used filter on the heater (left) and clamping it (right).

Figure 50: Control panel (left), vacuum system (right) and compressed air blowing (middle).

7.8 Arvin Meritor

Arvin Meritor manufacturers a cordierite filter medium with an active burner-assisted regeneration system. Such a unit is shown in Figure 51 (in a horizontal position). The need for filter regeneration was sensed by overpressure, the limit of which was set prior to operation of the vehicle. The regeneration burner regulated the diesel fuel and combustion air to raise the exhaust temperature to 650°C for typically eight minutes.

Figure 51: Arvin-Meritor PFS (horizontal position).

Two identical units were installed in parallel on Toro LHD #111 on Jun 4/04 as shown in Figure 52. These systems were mounted vertically because of special restrictions and extensive alteration of the exhaust manifold was necessary. The burners were located in the top sections of each canister (see Figure 52), with the bottom sections containing the cordierite filter medium. Compressed air was provided for the burners using an air compressor and air drier provided by A-M (shown in Figure 53).

Figure 52: Vertically mounted dual Arvin-Meritor PFSs on Toro #111 LHD.

Figure 53: Air drier for burner

The burner had its own diesel fuel tank, fuel filter, fuel pump (with shutoff valve), a fuel-air mixing unit and an atomizer. Flexible high pressure fuel lines (3/8 inches in diameter) were employed. The combustion air was supplied through flexible stainless steel (1 inch diameter) hose to the burner. The combustion air source was a compressed air tank located on the vehicle. Pressure sensors and pressure regulators controlled the combustion air, which was also filtered and pumped. Pumping of both air and fuel was carried out by DC (12 or 24 volt) motors.

Ignition of the fuel-air mixture was done by an igniter coil able to generate 40,000 volts from the on-board 12 or 24 volt battery.

A lamp was used to indicate if the regenerated filter overpressure remained unacceptably high due to non-soot ash build-up.

8. METHODS FOR TESTING PERFORMANCE

8.1 Special Emission Testing

Three special emission testing periods were carried out during the project:

- July 16-19, 2001
- May 25-31, 2002
- June 7-11, 2004

The work was performed as in-kind contributions by A. Bugarski and G.H.Schnakenberg of the U.S. National Institute for Occupational Health and Safety (Pittsburgh Research Laboratory) and D. Wilson for ECOM America (Gainsville, Georgia). The Stobie team acknowledges with gratitude the services provided by these individuals in all aspects of the performance measurements on the PFSs. All of the relevant data from these tests are given in this report; the reports from NIOSH on the special tests are available upon request.

The types of performance measurements remained the same over the three test periods so that direct comparisons of performances could be made as a function of the operating time of each PFS. The vehicles (engines) were operated during the special tests over several steady-state conditions and various types of instrumentation were used to measure:

- Particulate concentrations upstream and downstream of a filter;
- Filter efficiencies for removing diesel exhaust components;
- Particulate size distributions;
- Gaseous components (NO, NO_2, CO, CO_2, and O_2) upstream and downstream of a filter;
- Opacities;
- Smoke Numbers.

Each vehicle was subjected to the special testing within the Frood surface shop so that there would be convenient access to the instruments being used. Each vehicle had the service brake set and wheels chocked during the test period. Three repeatable steady-state conditions of engine operation were run:

- High idle: with the transmission in neutral, the highest rpm was obtained;
- Snap acceleration: with the transmission in neutral, the engine was suddenly taken from idle to full rpm and then brought back to idle. This condition was run once for exhaust opacity measurement (see below) and run ten times for obtaining smoke numbers.
- Torque converter stall (TSC): For LHDs: the engine was run at the maximum rpm in the highest gear. The TSC test is recognized to be a reliable way to load the engine. (Because the heat produced is mostly dissipated in the torque converter, the tests at this condition were necessarily short to prevent the converter fluid from reaching too high a temperature.)

For these engine conditions, engine rpms were measured using an AVL DiSpeed 490, which takes readings of structural-borne noise and airborne noise.

8.1.1 Filter Efficiency Measurements

The efficiency of a filter to remove elemental carbon particles or gaseous exhaust components was obtained by taking measurements upstream and downstream of the filter and calculating the efficiency by means of:

$$\text{Efficiency (in \%)} = \frac{(\text{Measurement})_{up} - (\text{Measurement})_{down}}{(\text{Measurement})_{up}} \qquad \text{[Equation 1]}$$

:

Using PAS 2000

Real time high idle and torque converter stall[β] concentrations were measured using a photoelectric aerosol analyzer (PAS 2000), shown in Figure 54, developed by Matter

Figure 54: PAS 2000 photoelectric aerosol analyzer (on the right) with the dilution equipment on the left.

Engineering (Wohlen, Switzerland) and marketed by EcoChem (League City, Texas). The PAS is based on the detection of ionized particles. Soot (elemental carbon) particles in diesel exhaust typically have a layer of polycyclic hydrocarbons adsorbed on their surfaces. When illuminated by ultra-violet light, these hydrocarbons become ionized and thus the soot particles become positively charged. The PAS detects the flow of these charged particles as an electric current, which is proportional to the number of particles present. Other work has shown a good correlation between the current measured and the concentration of elemental carbon. However, because particle size distributions affect the correlation between mass concentration of elemental carbon and the PAS current, and these distributions may be different upstream and downstream of a filter, the filter efficiencies so-measured are considered to be estimates of filter efficiencies.

[β] The PAS 2000 was unsuitable for measuring the transients produced during snap acceleration.

The raw exhaust contained too high a concentration of soot for measurement directly by the PAS 2000. The exhaust was therefore diluted using a spinning disk system from Matter Engineering, Model MD19-2E (shown in Figure 54). This was mounted to allow quick switching between upstream and downstream locations. The sampling lines were heated to 150^{o}F to prevent condensation of semi-volatile organics. The dilution ratios had to be adjusted occasionally for differences in soot concentrations over the various engine conditions being used, but all measurements were normalized.

Total aerosol concentration

The number concentration and size distribution of particles between 10-392 nanometers were measured using a Scanning Mobility Particle Sizer (SMPS) Model 3926 from TSI Inc. (St.Paul, Minnesota) and shown in Figure 55. These measurements also required the use of the dilution system described above.

Figure 55: Scanning Mobility Particle Sizer

The SMPS selectively passed aerosol in 10-300 nm mobility diameters and a particle counter optically counted each particle. Over about one minute the classifier scanned through the range of mobility diameters. Size distributions were collected for various engine conditions; an example of the display is shown in Figure 56. To obtain total aerosol, all sizes were summed and efficiencies were calculated by equation [1].

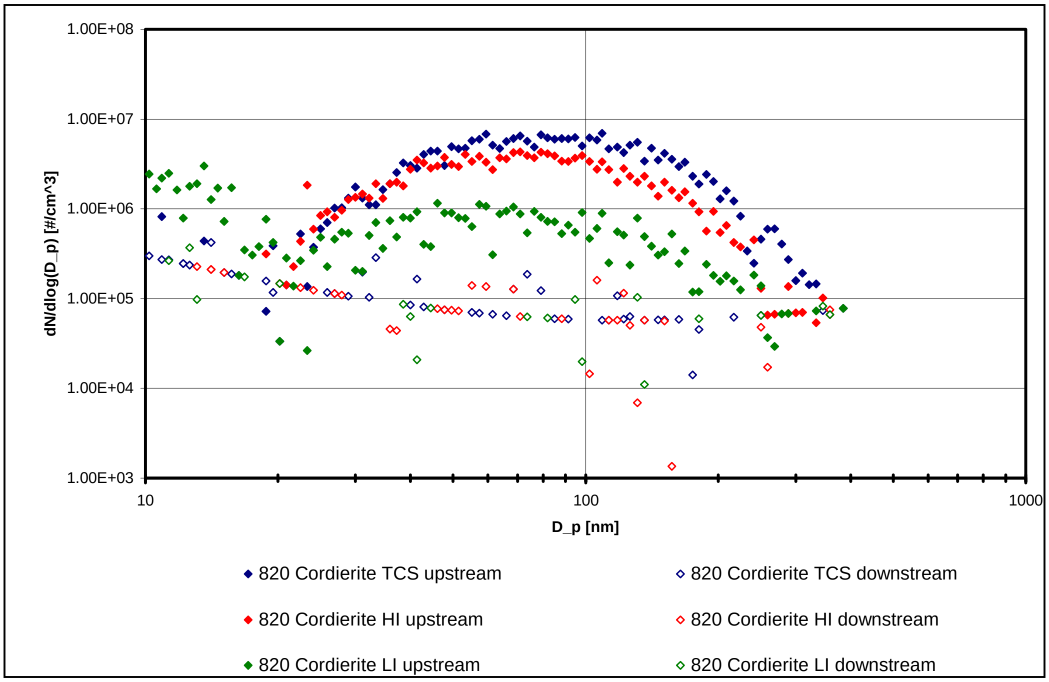


Figure 56: Example of size distributions collected over various engine conditions. Filled points are upstream of the filter and open points are downstream.

Gaseous Components

The concentrations of NO, NO_2, CO, CO_2 and O_2 were measured using ECOM KL and ECOM AC Plus portable analyzers from ECOM America (Gainsville, Georgia) shown in Figure 57.

Figure 57: ECOM gas analyzer (on the left) and the AVL Dicom 4000 (on the right)

Two ECOM units were employed for the special tests because of an interest by NIOSH in comparing the results. For the routine testing carried out by the Stobie personnel only the ECOM AC Plus unit was used and thus this report primarily focuses on measurements by that unit. Calibration of the ECOM unit was done periodically.

Special probes, examples of which are shown in Figure 58, were used for conducting ECOM measurements.

Figure 58: Probes for making ECOM measurements.

8.1.2 Smoke Numbers

Filter samples of the Bacharach smoke number were collected for the torque converter stall engine condition using the ECOM analyzers mentioned above. The filter samples were collected by flowing 1.6 liters of exhaust through a filter paper that was clamped in the sampling probe,

Figure 59: Probes for smoke numbers (left) and examples of filters upstream (middle) and downstream (right).

shown in Figure 59. A spot approximately 6mm in diameter was “exposed” to the exhaust (see Figure 59). Greyness of the spot on the paper was graded by comparing it to a grey scale supplied by ECOM from 0 (white) to 9 (black). Averages were obtained from several measurements.

8.1.3 Opacity

The AVL DiCom 4000 was used to measure opacity. The measurement is based on light transmission through the exhaust stream. The engine was ramped from idle to full throttle and the AVL instrument detected the rpm increase and started the measurement. Once the instrument had detected a maximum engine speed had been attained, the instrument displayed the peak rpm and the opacity. The following opacities are generally recognized:

- 0-5% good filter performance
- 5-10% marginal filter performance
- >15% unacceptable filter performance.

8.1.4 Engine backpressure

For some of the special testing, a Magnehelic™ differential pressure gauge from Dwyer Instruments (Michigan City, Indiana) was used to measure engine backpressure. The gauge was connected to a port located just upstream of the filter.

Figure 60: Equipment and crew in Stobie maintenance shed ready to do special testing during July/04.

Figure 61: Crew taking special measurements (Dr. Bugarski top left, Dr. Schnakenberg top right, vehicle operator bottom left, and Drs. Stachulak and Schnakenberg bottom right).

8.2 Routine Testing

All vehicles were periodically brought into the shop for routine maintenance. During the time when the vehicles were undergoing such examination, the Stobie DEEP team also performed testing on the filter systems. The plan was to conduct such routine tests at least every 250 hours. Due to convenience, often the routine testing was done more frequently.

The routine tests used the ECOM system described above for the special tests. The measurements obtained were smoke numbers and target gas analyses (CO, NO, NO_2 and O_2) both upstream and downstream of the filters.

8.3 Data Evaluation

All separate periods of data belonging to one PFS were joined together to make one complete data set for that PFS. For some of the longer tests, the complete data sets were split into calendar year periods. The procedures described in Chapter 5 for editing the data from duty cycle monitoring were also employed for the PFS testing periods. An example of such a data set is shown in Figure 62 for vehicle #820 (left side). In this figure the x axis is the operating time (not real time) and the small black crosses along the x axis indicate when each sub-set of the data file was started (the start dates for each sub-file are the only times for which a calendar time exists. For the operational data, however, the calendar time is not the preferred way of displaying data because there were many periods where the vehicle and PFS were not operating. Consequently, the operating time was selected as the most appropriate way to view the data as a function of time. These graphs are contained in Appendix C for each PFS under test.

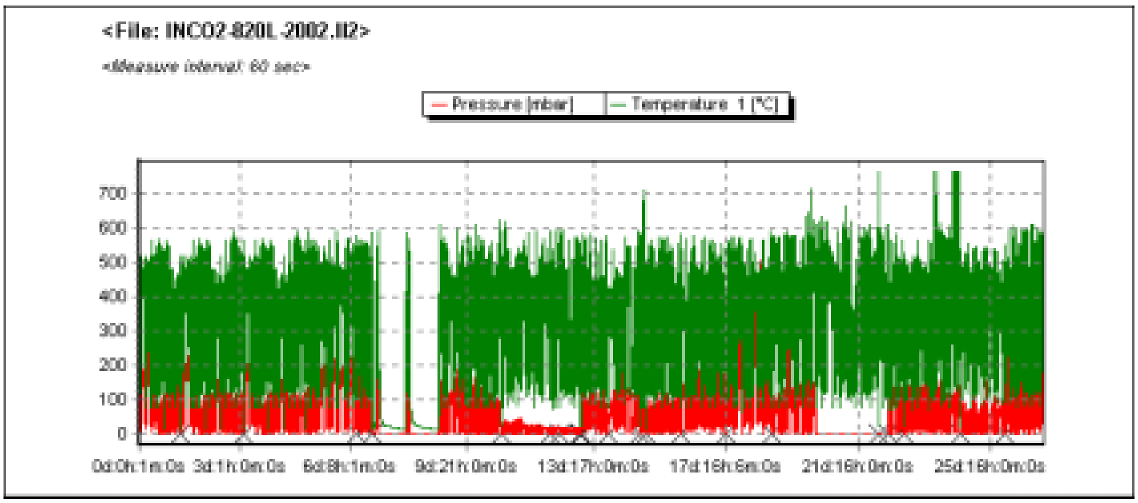


Figure 62: Example of the display of pressure and temperature data as a function of vehicle operating time.

In order to investigate details of events, data zoom files were created covering the entire time history. These zoom files are also contained in Appendix C. Events having significance or requiring commentary were marked on each zoom with a circle containing a number, as exemplified in Figure 63.

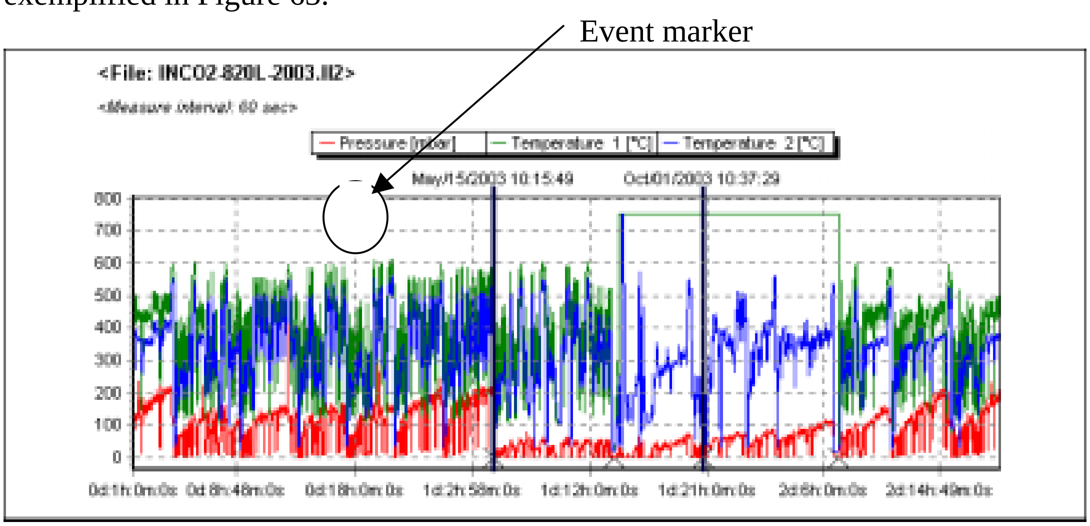


Figure 63: Example of an event marker (circled 1) on a data zoom

Each one of the zooms, marked with “event markers”, are also included in Appendix C and a list of comments for each event marker are given there as well. Each zoom for the complete cleaned data set was analyzed to give statistics on its selected parameters and these zoom files are located in Appendix C and are identified at the top right corner with the zoom identifier. (Note that the zooms covering the complete useable data are not to be confused with the two example zooms shown on each data “summary data page”.)

Graphical displays of critical parameters are given in Appendix C for each zoom covering the entire useable data for each PFS. These displays include a pie chart, such as that shown in Figure 64, that shows the percentage of pressure readings that were normal (green at < 150 mbar), alert mode (yellow at > 150< 200 mbar), and alarm mode (red at > 200 mbar).

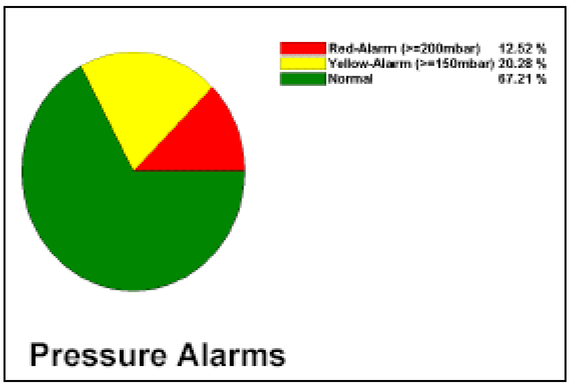


Figure 64: Example of pie chart showing percentage of pressures exceeding alert and alarm levels contained in Appendix C.

Two other graphical displays, such as shown in Figure 65, report frequency distributions of backpressure and exhaust temperature.

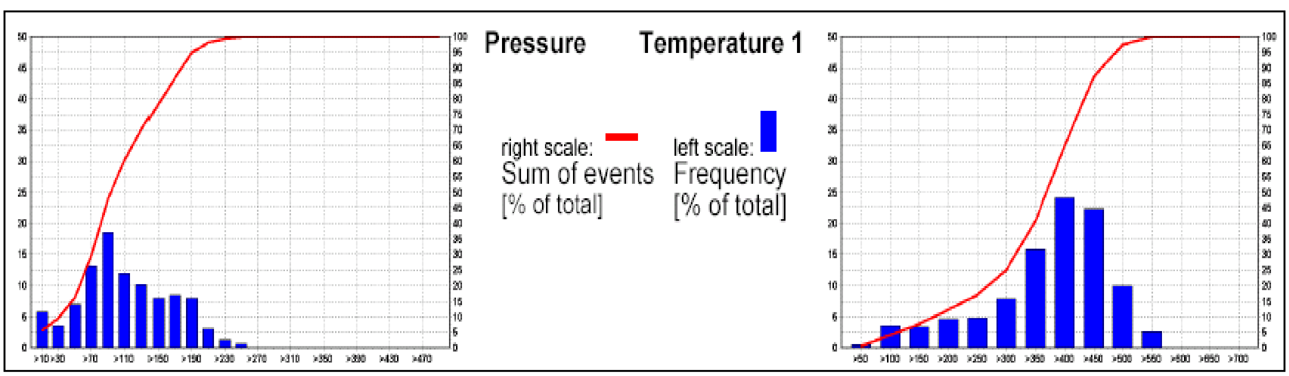


Figure 65: Examples of frequency distributions for pressure and temperature contained in Appendix C.

The final graph for each zoom data set is a “bubble diagram”, which was an alternative method of representing the 3-dimensional dwell time diagram described earlier in Chapter 5. The bubble diagrams were believed to be easier to understand in a qualitative manner. As can be seen by the example shown in Figure 66, the frequency of each data range is depicted by a circle, the diameter of which is related to the number of data occurring in that range. While the y-axis is easily understood by being split into increments of 100^{o}C of temperature, the x-axis requires additional explanation. The x-axis refers to the number of duration intervals used in measuring temperature. For example, if a data set has been collected using 60 sec intervals[φ], then the integers on the x-axis refer to the number of 60 sec intervals) over which the temperature was found to remain in the selected range on the y-axis. As a further explanation,

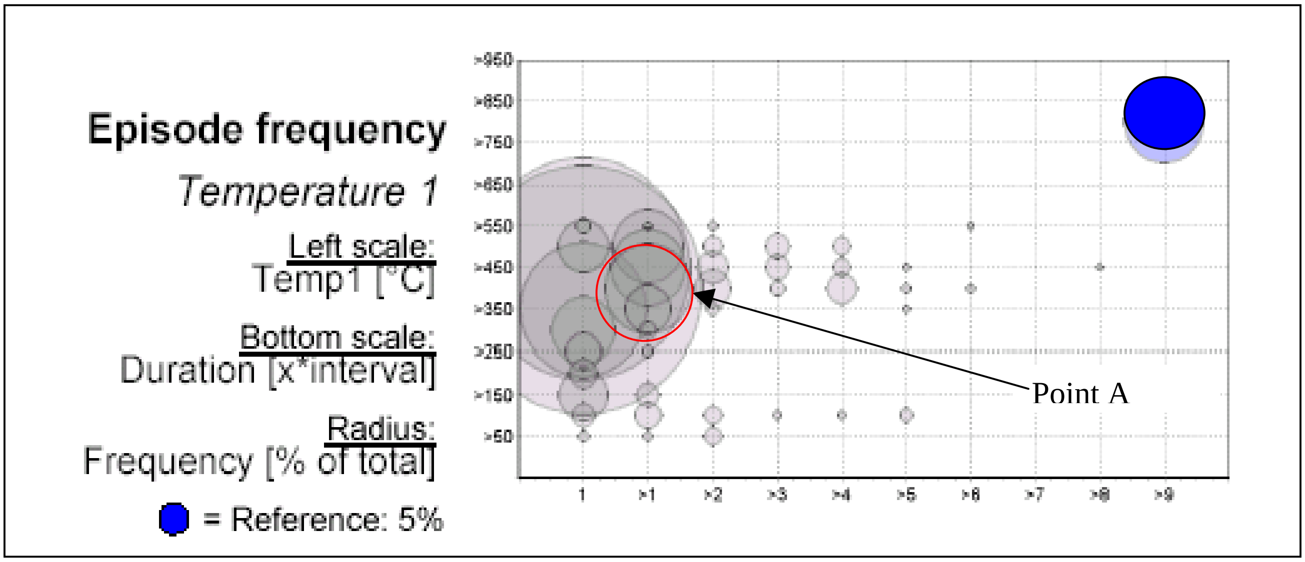


Figure 66: Example of a frequency distribution of temperature durations.

consider point A in Figure 66. This point refers to a temperature range of 350-450°C (y-axis) and >1 interval (x-axis). The >1 interval for this particular data set refers to >60<120 seconds of duration. The size of the shaded circle ("bubble") refers to the percentage of time the temperature was in that range for that duration. Since the reference circle (top right of the graph) defines 5%, and since the point A circle is roughly the same size as the reference circle, the temperature spent 5% of its time within this window of temperature and duration.

One can then appreciate that the more circles are to the left side of the diagram, the shorter are the durations at temperature. The larger the circles the larger fraction of data occurs at that point. In Figure 66 it is fairly easy to see that the major duration of time temperatures remain in a window is <120 seconds. There are a few points at greater than 120 seconds duration, but the circles are relatively small.

At the bottom of each summary data page in Appendix C is a table of statistics for critical parameters (often backpressure and inlet exhaust temperatures were the only reliable measurements). Because each complete set of useable data is completely covered by a sequence of zoom files, the statistics for the zooms can be graphed to reveal trends over time for each PFS being tested. Examples of such trend plots are shown for vehicle #820 (left side PFS) in Figure 67. All trend plots are included in Appendix C; selected trend plots are shown for specific PFSs in Chapter 9.

[φ] Note that the data collection interval for each data set is defined at the top right corner of each summary data page in Appendix C.

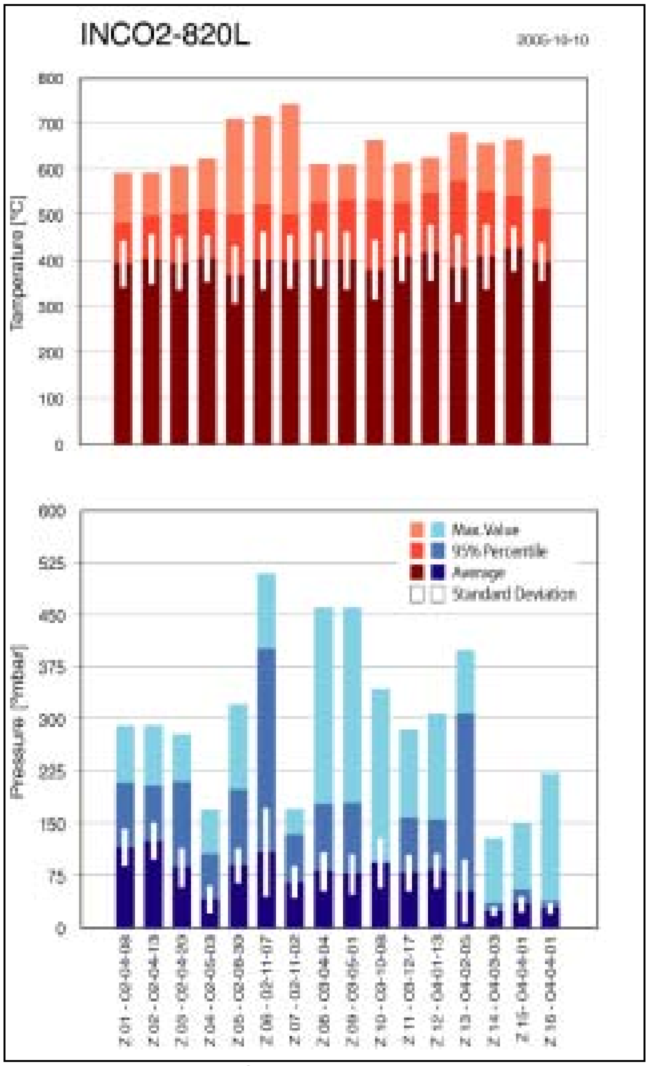


Figure 67: Example of trend plots. These plot are constructed from the statistics of the zoom data covering the entire useable data set. In this case the data from vehicle #820 (left side) is represented by 16 zoom data files covering the PFS operation from April 2002 to April 2004. Each zoom is plotted in sequence from left to right on the x-axis. The vertical white lines in each zoom represent ±1σ standard deviation. The colour code is shown at the top right of the bottom diagram.

9. PERFORMANCES OF PFSs

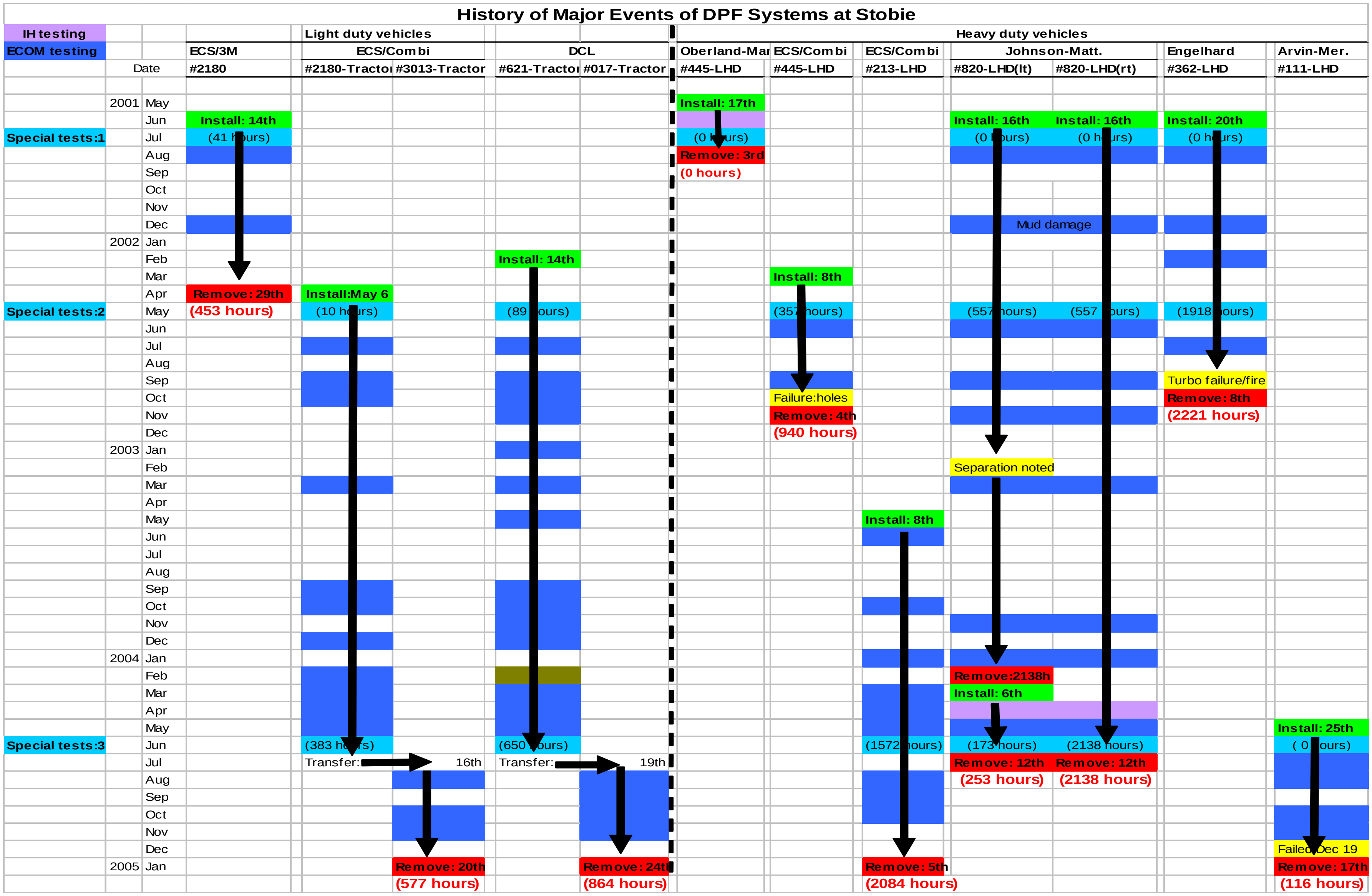
The performance of each PFS will be discussed separately in the initial portion of this Chapter and then relevant comparisons between certain systems will be made in Chapter 10. A number of performance criteria were evaluated for the PFSs, namely: special tests in which detailed information about filter efficiencies and particle size distributions were obtained; routine testing carried out about every 250 hours (as part of routine vehicle maintenance activities) to analyze exhaust gases and obtain smoke numbers; issues related to ease of installation and maintenance of a system; and issues related to effective operation of a system. Each of these criteria will be discussed under each PFS tested.

In a small number of cases the weekly data downloads, which were forwarded to Switzerland for statistical analyses by A. Mayer, were misplaced. These missing downloads have therefore not been included in the statistics reported in the Appendix. The effect of missing these downloads is not believed to be significant. However, an attempt is being made to locate these missing files and to revise the statistics accordingly. If these statistics differ significantly from those reported herein and in the Appendix, then an addendum to this report will be issued at some time in the future. There also may be some small inconsistencies between the tabular information and the graphical information. Additional work is being conducted to harmonize all files and will be reported in the addendum described above.

An overall history of the testing at Stobie is shown in Figure 68, where the PFSs and their respective vehicles are listed across the top and time in months is listed in rows from May 2001 to January 2005. Green indicates installation; red indicates PFS removal. Yellow indicates that a potential problem was noted. The special tests (three in total) are shown in light blue. The routine ECOM testing is shown in dark blue. The industrial hygiene soot monitoring is shown in purple. This display allows one to see in a general way what happened with each trap being tested. Details are provided below.

THIS PAGE INTENTIONALLY LEFT BLANK

Figure 68: History of major events in the Stobie project (overleaf)


History of Major Events of DPF Systems at Stobie
IH testing
ECOM testing
Date
Light duty vehicles
Heavy duty vehicles
ECS/3M
#2180
ECS/Combi
#2180-Tractor
#3013-Tractor
DCL
#621-Tractor
#017-Tractor
Oberland-Mar
#445-LHD
ECS/Combi
#445-LHD
ECS/Combi
#213-LHD
Johnson-Matt.
#820-LHD(lt)
#820-LHD(rt)
Engelhard
#362-LHD
Arvin-Mer.
#111-LHD
2001 May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2002 Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2003 Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2004 Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2005 Jan
Special tests:1
Special tests:2
Special tests:3
Install: 14th
(41 hours)
Remove: 29th
(453 hours)
Install:May 6
(10 hours)
(383 hours)
Transfer:
16th
Remove: 20th
(577 hours)
Install: 14th
(89 hours)
(650 hours)
Transfer:
19th
Remove: 24th
(864 hours)
Install: 17th
(0 hours)
Remove: 3rd
(0 hours)
Install: 8th
(357 hours)
Failure:holes
Remove: 4th
(940 hours)
Install: 8th
(1572 hours)
Remove: 5th
(2084 hours)
Install: 16th
Install: 16th
(0 hours)
(0 hours)
Mud damage
(557 hours)
(557 hours)
Separation noted
Remove:2138h
Install: 6th
(173 hours)
(2138 hours)
Remove: 12th
Remove: 12th
(253 hours)
(2138 hours)
Install: 20th
(0 hours)
(1918 hours)
Turbo failure/fire
Remove: 8th
(2221 hours)
Install: 25th
(0 hours)
Failed Dec 19
Remove: 17th
(116 hours)

9.1 Oberland-Mangold System
(on LHD #445)

Special Emission Tests

Shortly after the O-M system was installed, special tests were carried out in July 2001. Table 10 contains the very disappointing findings.

Table 10: Results of special testing Oberland-Mangold filter after 0 hours of operation.

Engine		Efficiency (%), eq [1]		Smoke No.	%Opacity	Downstream				
Temp.	Speed[b]	PAS	EC			%		ppm		
						O_2	CO_2	CO	NO	NO_2
warm	HI	13.6								
warm	TCS	2.8		7/5.5[a]						
warm	TCS	19.3	39.8		15.2					
warm	TCS	44.5	58.4		14.2					
warm	TCS	17.5			18.2					
warm	Snap A		69.5							
cold	LI					15.7	3.8	85	810	39
cold	TCS					9.2	8.6	337	603	17

a: upstream/downstream

b: HI=High idle; LI= Low idle; TCS= Torque converter stall; Snap A= Snap acceleration

No upstream measurements, other than a smoke number, were made because of the extremely poor filtration efficiencies, which ranged from 2.8% to 69.5%. The downstream smoke number was very high at 5.5, which showed significant soot was coming through the filter.

This system was deemed to have failed and was removed from service and returned to Oberland-Mangold. No statistical analyses of the data collected were performed.

9.2 ECS/ 3M Omega System
(on Tractor #2180)

The ECS/3M system was installed on June 14/01 and was removed on April 29/02 after compiling 453 hours of operation.

Routine Tests

Two periods of routine testing were carried out on the ECS/3M Omega system (see the dark blue months shown in July and December/01 in Figure 68) with results shown in Table 11.

Table 11: Routine smoke numbers and gas analyses for ECS/3M Omega system.

Date	Meter (h)	Upstream						Downstream				
		Sm No.	CO (ppm)	NO (ppm)	NO_2 (ppm)	O_2 (%)	T (^oF)	Sm No.	CO (ppm)	NO (ppm)	NO_2 (ppm)	O_2 (%)
8/17/01	2540	9	193	173	44	16.1		3.5	233	165		15.7
12/7/01	2805	6	232	166	58	15.3	218	2.0	238	154	43	15.5

The filter showed marginal performance in that the downstream smoke numbers were not as low as desired. No significant increases in target gases downstream were observed.

Special Tests

The system was tested for filtration efficiency shortly after its start up; results are shown in Table12.

Table 12: Special tests on ECS/3M Omega system at 41 hours operation.

									Downstream					
Engine	Efficiency (%), eq [1]						Smoke No.	%Opacity	%		ppm		
Speed[b]	PAS	EC	O_2	CO	NO	NO_2			O_2	CO_2	CO	NO	NO_2
HI	77	94.4	2	-21	5	32	9/3.5		15.7		233	165	30
HI	88.3												
HI	84.3												
HI	83.5	91.4											
Snap A								4.2-5.8					

a:upstream/downstream

b: HI=High idle; LI= Low idle; TCS= Torque converter stall; Snap A= Snap acceleration

Note: a negative number in efficiency means downstream was greater than upstream.

The filter had marginal filtration efficiency ranging from 77-94% of the soot. The downstream smoke number was fairly high at 3.5 and the opacity was marginal at about 5%. Surprisingly, the CO showed an increase of 21% across the filter and the NO_2 showed a decrease of 32% across the filter. As these results were the opposite of what would be expected from a catalyzed trap, the results were double-checked and were verified as correct.

Even though this filter had marginal performance, it remained in service for nearly a year and compiled 453 hours of operation. It was removed in April/02 only because 3M had announced its business decision to cease manufacturing the glass fibers employed in the filter. As this PFS became obsolete, it was removed so that another relevant candidate PFS could be tested on tractor #2180.

Other comments

The operators of tractor #2180 were inconsistent in their regeneration practices due likely to a lack of habit of plugging it in.

Some problems were experienced with the transformer for electrical regeneration and the Omega controller required a wiring harness replacement, but the PFS was not employed long enough for definitive predictions to be made about the robustness of this system. These issues, however, become irrelevant because the system is no longer manufactured.

Statistical analyses of data for the ECS/3M filter are given in Appendix C, but are not discussed here because this system has become obsolete.

9.3 ECS/Combifilter
(on #2180 and #3013 Tractors)

The ECS/Combifilter was installed on Tractor #2180 in April/02, following the removal of the ECS/3M system (see above). This filter operated for more than two years on Tractor #2180 and then was transferred to Tractor #3013 (identical tractor) to try and get more operating hours. The system remained on #3013 until the end of the project in January 2005. Nearly three calendar years and 577 operating hours were tested.

Table 13: Smoke numbers and gas analyses for ECS Combifilter

Date	Meter (h)	Upstream						Downstream				
Date	Meter	Sm No.	CO (ppm)	NO (ppm)	NO2 (ppm)	O2 (%)	T (^oF)	Sm No.	CO (ppm)	NO (ppm)	NO2 (ppm)	O2 (%)
7/4/02	2976	4	299	127	39	15.6	428	1				
7/11/02	2979	8	268	136	39	15.6	408	2	290	145	24	16
7/25/02	2988	6	105	346	11	13.2	177	0	330	143	61	15.6
9/4/02	3011	6	296	123	54	16	454	0	320	112	54	16.1
10/4/02	3039	5	306	131	44	15.8	489	1	309	134	31	16
10/31/02	3044	7	303	161	48	16	293	1	235	185	46	16.6
3/20/03	3114	6	346	141	53	15.4	441	1	340	150	36	15.8
9/26/03	3172	7	365	102	54	15.4	469	1	362	120	38	16
10/29/03	3198	7	407	87	50	15.9	423	1	363	92	47	16.2
12/4/03	3228	7	360	133	46	15.9	465	1	332	119	52	16.6
12/27/03	3235	8	328	158	56	15.2	451	0	310	160	43	15.6
2/5/04	3256	7	297	158	50	15.4	439	1	304	170	35	15.9
3/11/04	3275	7	277	155	45	15.3	291	1	286	145	42	15.7
4/2/04	3282	6	270	107	51	16.1	445	1	272	121	32	16.4
5/5/04	3294	7	319	62	39	17.2	378	2	323	82	39	16.4
8/10/04	10	9	402	103	63	15.9	218	2	408	181	13	16.
10/6/04	95	6	268	166	50	15.6	480	0.5	269	150	46	16.4
11/5/04	134	6	273	181	54	15.4	584	1	293	150	55	16.4
average		6.6	305	143	47		407	1	314	139	41	

<u>Routine tests</u>

Eighteen periods of routine testing of the system were carried out. The smoke numbers and target gas analyses for each period are shown in Table 13. The smoke numbers showed reasonable filter efficiency: upstream averaged 6.6 and downstream averaged 1.0. As shown in gure 70, no trends in smoke numbers were observed. There appeared to be no significant change in the target gases between upstream and downstream values. As can also be seen in Figure 69, which plots gas analyses as a function of operating time, no trends were observed.

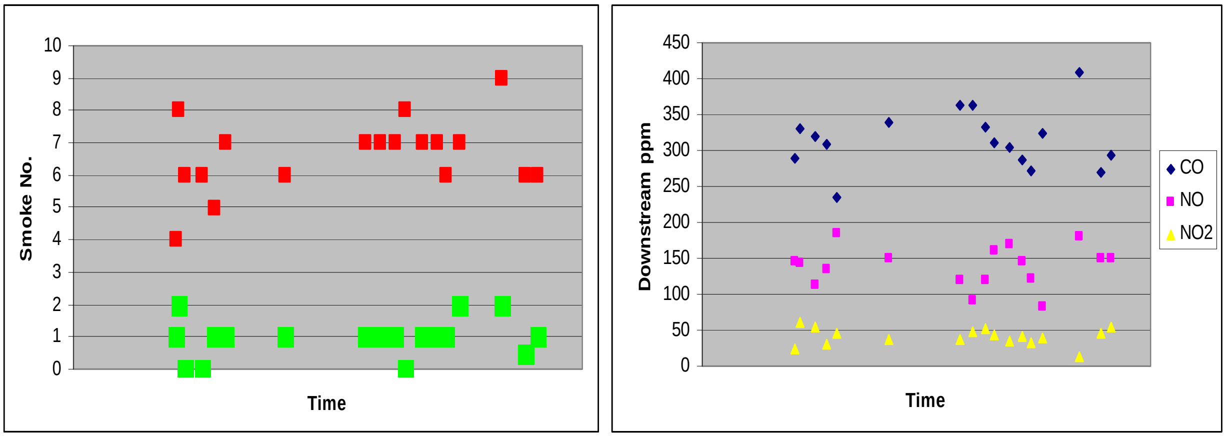


Figure 69: Results of routine testing of ECS/Combifilter on tractors #2180 and #3013. Left: Smoke numbers as a function of time (red data are upstream and green data are downstream). Right: Target gas analyses (in ppm) downstream of the ECS/Combifilter.

<u>Special tests</u>

Two special tests were carried out on the ECS/Combifilter installed on Tractor #2180, one in May 2002 and the other in June 2004. These two tests bracket the routine testing done on this system while it was installed on Tractor #2180. Just after the June 2004 special tests, the system was transferred on Tractor #3013 to get more operating hours.

The May 2002 and June 2004 results are shown in Table 14.

Table 14: Special test on ECS/Combifilter done in May 2002 with 6 hours service and in Jun 2004 with 366 hours service.

									Downstream					
Engine Speed[b]	Efficiency (%), eq [1]						Smoke No.[a]	Upstream %Opacity	%Opacity	%		ppm		
	PAS	EC	O_2	CO	NO	NO_2				O_2	CO_2	CO	NO	NO_2
May/02														
HI	99.9	99.7	2	-1	12	22	6.5/0			15.9	3.7	390	103	52
LI	99.9	99.7		3	1	22				18.0	2.2	135	200	46
Snap A								40.0	0.23					
Jun/04														
HI	99.9	99.9		14	-105	47	8.5/0				4.0	375	315	38
LI				-3	-44	73					2.3	153	204	18
Snap A								44.7	0.0					

a:upstream/downstream

b: HI=High idle; LI= Low idle; TCS= Torque converter stall; Snap A= Snap acceleration

Note: a negative number in efficiency means downstream was greater than upstream.

These results showed excellent efficiencies, very low % opacity in downstream exhaust, and marginal changes in target gas concentrations between upstream and downstream. The largest change was observed for NO and NO_2. NO_2 decreased between upstream and downstream and NO increased. This is due to conversion of NO_2 to NO by the filter medium.

Size distribution

The size distributions measured in May 2002 and shown in Figure 70 were carried out for high idle and low idle.

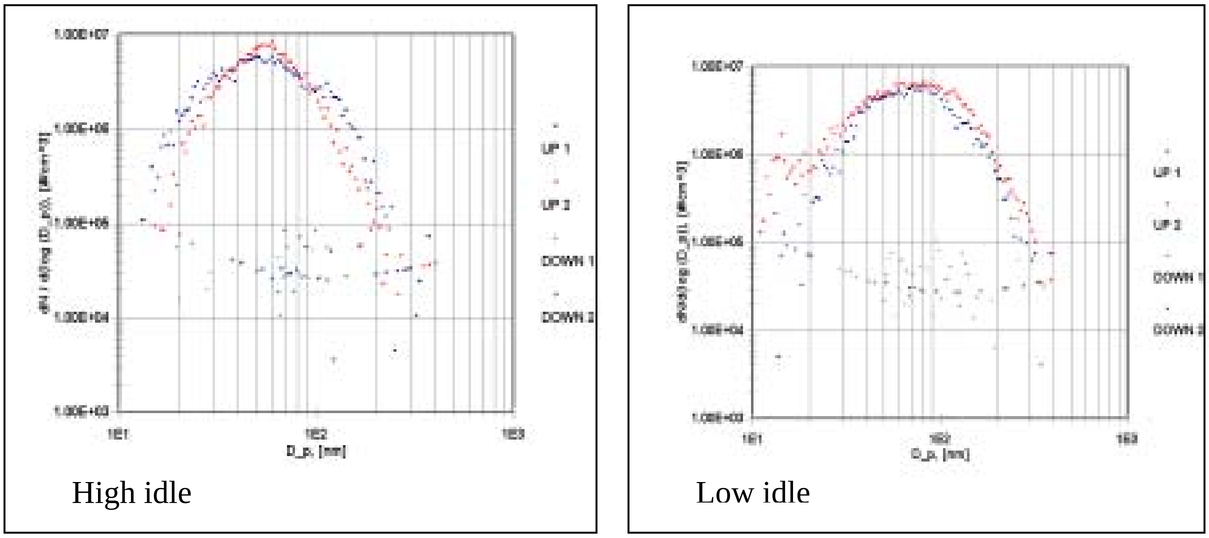
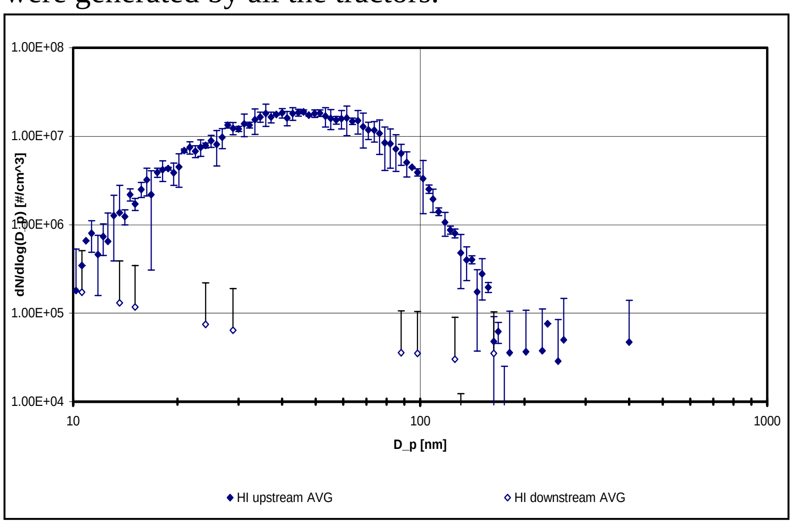


Figure 70: Size distributions of high and low idle conditions.

These distributions are both single modal, but differ between the high idle and low idle conditions. The low idle conditions generated particles with larger mean electrical mobility diameters and somewhat smaller concentrations. As would be expected due to all test tractors (#2180, #3013, #621, and #017) being virtually identical, very similar upstream distributions were generated by all the tractors.



The size distribution measured in Jun 2004 for the high idle condition is shown in Figure 71, where average particle counts are obtained from several scans.

Figure 71: Average size distributions for ECS/Combifilter on tractor #2180.

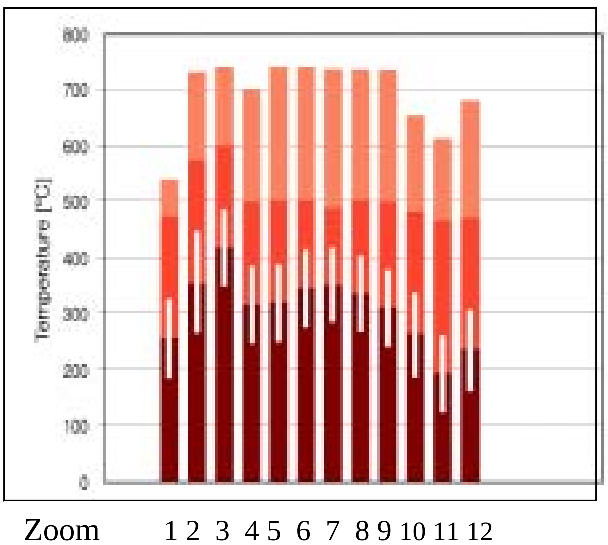
Statistical analyses

The temperature and pressure data collected for tractor #2180 (Jan 2002 to May 2004) are contained in Appendix C (identified as INCO3-2180). This entire period was split into 12 sections (called zooms) and the statistics for each zoom period are given in Table 15. The trend of temperature over the 12 zooms is given in Figure 72 and the trend in backpressure is given in Figure 73.

Table 15: Statistical data for ECS/Combifilter on tractor #2180

		Pressure (mbar)				Temperature (°C)			
Zoom No.	Calendar start	Min.	Ave.	Max.	95%ile	Min.	Ave.	Max.	95%ile
1	a	10	76	258	190	87	263	531	478
2	a	12	109	322	257	96	361	729	578
3	Aug 9/2002	10	46	88	50	156	414	735	598
4	Sep 27/2002	12	59	110	70	78	316	699	498
5	Apr 30/2003	10	46	98	56	48	265	765	413
6	Sep 19/2003	10	71	170	120	45	266	765	400
7	Oct 10/2003	10	55	96	62	63	349	747	486
8	Oct 30/2003	10	59	142	77	84	340	747	500
9	Nov 28/2003	10	56	142	75	84	320	747	496
10	Jan 15/2004	10	57	154	90	54	267	654	481
11	Jan 22/2004	10	37	124	81	69	185	615	466
12	Apr 2/2004	10	54	278	83	51	234	681	475

a: Zooms 1 and 2 were for data when the ECS/3M filter was on tractor #2180.



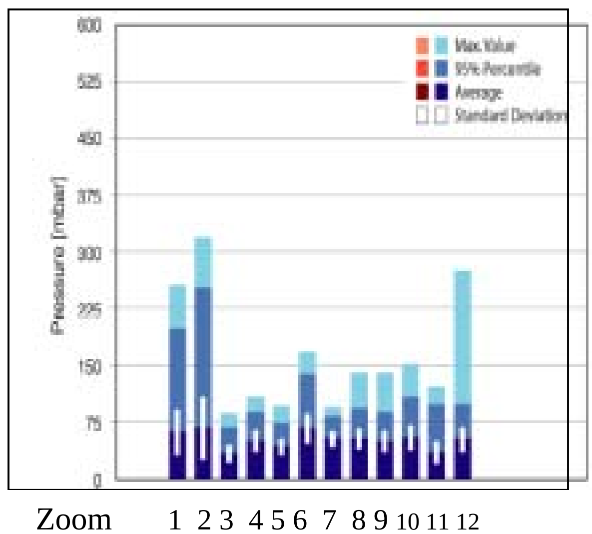


Figure 72: Temperature trend over 12 zooms (see legend in Figure 73.)

Figure 73: Backpressure trend over 12 zooms

The best integral period upon which to judge the statistics of the ECS/Combifilter on tractor #2180 covers the calendar period from Apr 30 2003 to Jun 2004 (263 hours of the total 383 hours to total operating time). This integral period, covering zooms 5 to 12, had overpressure and temperature statistics shown in Table 16.

The frequency distributions for pressure and temperature over this integral period are shown in Figure 74. The episodic temperature (temperature durations) frequency distribution is shown in Figure 75. For the nearly 15,000 useable pressure data collected (60 sec intervals), Figure 76 shows the fractions of the backpressure that were normal, alert mode (yellow), and alarm mode (red). It can be seen that the backpressure on this filter was generally well behaved.

Table 16: Integral performance data of ECS/Combifilter on #2180 (Apr 30/03 to Jun/04)

	Pressure (mbar)				Temperature (°C)			
	Min.	Ave.	Max.	95%ile	Min.	Ave.	Max.	95%ile
inlet side	10	55	510	87	51	293	750	485
outlet side					3	270	765	400

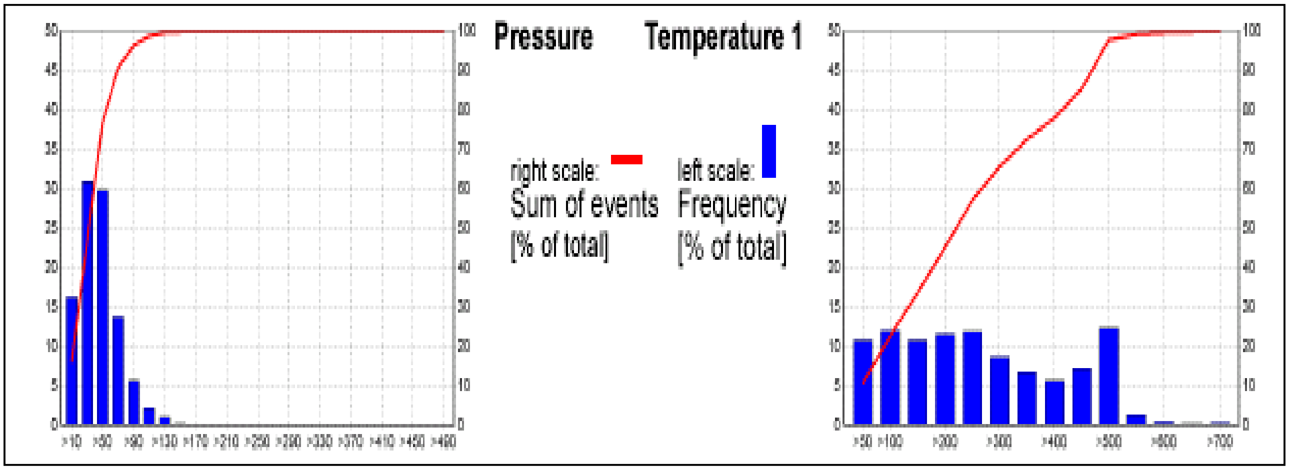


Figure 74: Frequency distributions of backpressure and temperature for ECS/Combifilter on tractor #2180.

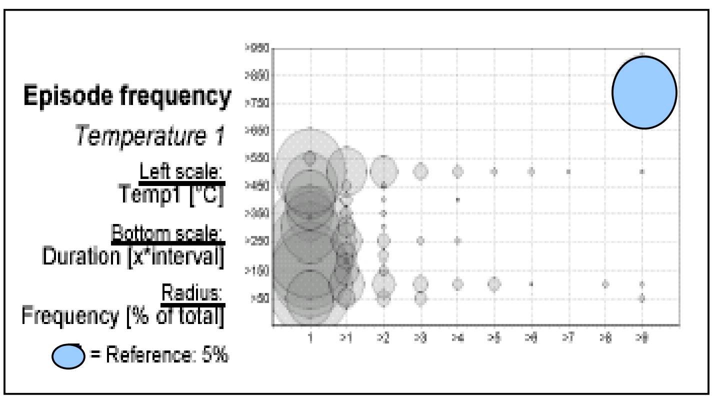


Figure 75: Episodic temperature-duration frequency.

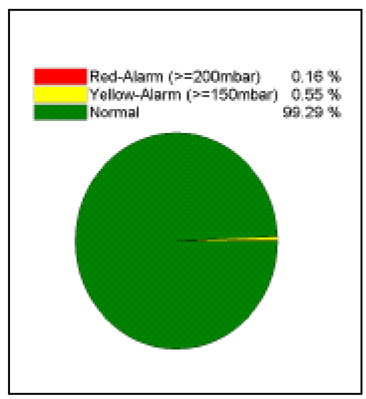


Figure 76: Backpressure pie chart.

9.4 DCL/Titan
(on #621 and #017 Tractors)

The DCL/Titan system was installed on Tractor #621 in February 2002 and operated for more than two calendar years (see Figure 68). Because of the limited use #621 was getting, the system was transferred to an identical Kubota Tractor, #017, where it remained for the remainder of the project. Overall, the DCL/Titan system had almost three years of testing.

It must be noted, as previously explained in Chapter 7, that the system consisted of a single filter unit, but that two identical filters were used alternately. That is, when one filter was being regenerated off-board, the sister filter was being used on the vehicle. The filters were switched after every shift.

<u>Routine tests</u>

The two sister filters used for this system during the project were individually identified for routine testing of smoke numbers and gas analyses. Results are given in Table 17.

Table 17: Routine testing of DCL/Titan filters

Filter1594

Date	Meter(h)	Upstream					Downstream			
		SmNo.	CO(ppm)	NO(ppm)	NO2(ppm)	T(^{o}F)	SmNo.	CO(ppm)	NO(ppm)	NO2(ppm)
7/31/02	578	7	271	124	26	159	1	323	127	60
9/4/02	603	6	271	140	56	452	1	280	147	46
10/3/02	642	8	226	194	34	491	3	235	181	33
11/1/02	690	8	194	254	40	487	1	209	195	37
5/2/03	866	7	252	192	43	495	1	261	178	39
9/26/03	935	7	288	176	50	477	1	219	136	35
11/25/03	952	7	260	194	40	549	1	265	169	42
2/5/04	1006	7	162	243	31	653	1	170	191	33
4/2/04	1025	7	218	175	39	511	1	197	141	15
5/7/04	1044	6	195	175	36	484	1	216	185	21
8/10/04	119	7	269	148	54	1303	1	265	149	39
10/6/04	175	6	246	167	54	454	1	244	158	42
11/4/04	226	7	279	154	54	536	1	252	141	40
sum		90	3131	2336	557	7051	13	3136	2098	482
ave.		7	241	180	43	542	1.0	241	161	37

Filter1593

Date	Meter(h)	SmNo.	CO(ppm)	NO(ppm)	NO2(ppm)	T(^{o}F)	SmNo.	CO(ppm)	NO(ppm)	NO2(ppm)
9/4/02	604	2	286	140	52	460	0	268	143	45
1/30/03	794	7	117	141	41	483	1	195	202	34
3/12/03	826	6	228	225	40	465	1	243	190	31
10/27/03	944	6	210	204	43	355	1	209	191	41
12/27/03	976	6	212	219	41	541	1	220	199	41
3/1/04	1015	7	199	218	37	946	1	218	191	29
9/17/04	172	6	220	167	48	504	2	207	154	44
sum		40	1472	1314	302	3754	7	1560	1270	265
ave.		6	210	188	43	536	1.0	223	181	38

Filter 1594 had 13 periods of testing, while Filter 1593 had 7 periods. Of the 13 tests performed on Filter 1594, 10 of the tests were done while the filter was on #621 Tractor and 3 of the tests (the three last rows in the Table) were done while the filter was on #017 Tractor. Similarly, for the 7 tests done on Filter 1593, 6 tests were done while the filter was on #621 and 1 test (the last row in the table) was done while the filter was on #017 Tractor.

There did not appear to be significant differences in smoke numbers or target gas analyses between the two filters (as judged by the similarity of average values). Also, when smoke numbers were plotted as a function of time, as shown in Figure 77, no significant trends were apparent.

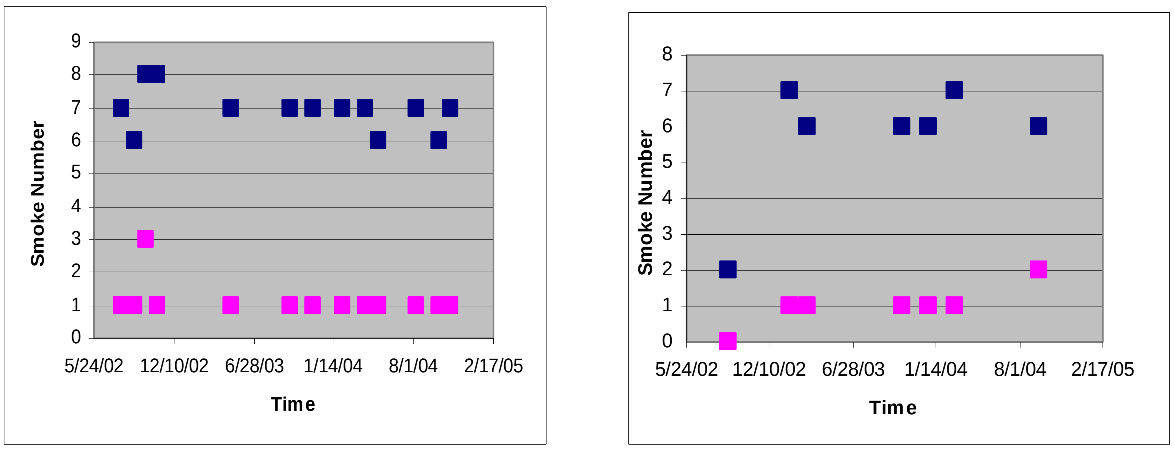


Figure 77: Smoke numbers for DCL filter #1594 (left) and #1593 (right) from mid-2002 to the end of 2004.

The plots of downstream gas concentrations for both DCL filters are shown in Figure 78. No trends are apparent. An apparently higher average NO concentration for filter #1593 is likely within analytical uncertainty.

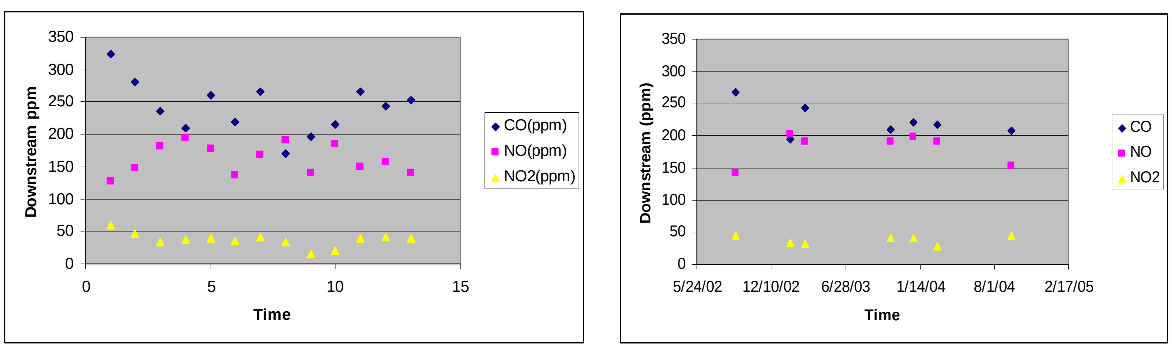


Figure 78: Target gas concentrations downstream of DCL filter #1594 (left) and #1593 (right).

<u>Special tests</u>

Two periods of special tests were conducted: the first in May 2002; the second in June 2004. Results of these tests are given in Table 18. Excellent soot filtration efficiencies were found in both periods. Likewise, downstream smoke numbers and opacities were also good. Some marginally higher NO was observed downstream (relative to upstream) in the 2004 tests and this is due to some small amount of conversion of NO_2 to NO by the filter medium.

Table 18: Special tests on DCL system on tractor #621.

Engine Speed[b]	Efficiency (%), eq [1] PAS	EC	O_2	CO	NO	NO_2	Smoke No.[a]	Upstream %Opacity	Downstream % Opacity	Downstream % O_2	Downstream % CO_2	Downstream ppm CO	Downstream ppm NO	Downstream ppm NO_2
May 2002 (89 h)														
LI	99.9	99.3		4	13	9				18	2.2	122	211	70
HI	99.8	99.8		-1	8	7				16.2	3.6	312	116	84
Snap A								33.5	0.3					
Jun 2004 (650 h)														
LI				0	-13	42					2.2	153	154	43
HI	99.9	97.5		11	-15	19	5.5	1			4.6	375	101	48
Snap A								37.9	0.0					

a:upstream/downstream

b: HI=High idle; LI= Low idle; TCS= Torque converter stall; Snap A= Snap acceleration

Note: a negative number in efficiency means downstream was greater than upstream.

Size distribution

The size distributions of particles measured during June 2004 both upstream and downstream of the DCL/Titan filter during high idle are shown in Figure 79. Each point on the distribution was the result of many measurements and the average values are represented as points with uncertainty bars being ± 1 standard deviation. The upstream distribution is representative of particulate coming from a light duty engine. Effective removal of particulate by the filter is seen across all particle sizes.

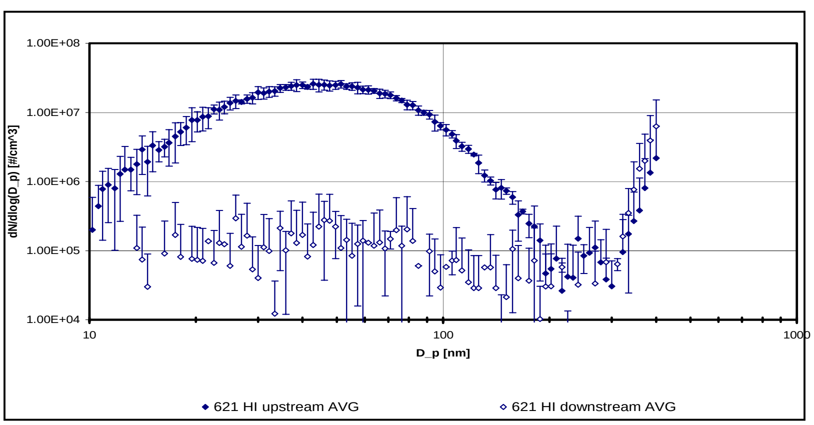


Figure 79: Size distribution of upstream and downstream particles during high idle of Tractor #621. The measurements >200 nanometer size have spurious electronic signals and are to be neglected.

Statistical analyses

Temperature and backpressure data for the DCL Titan filter on tractor #621 for the period Mar 2002 to June 2004 are contained in Appendix C (identified as INCO5-621). This period was split into 8 zooms, the statistics for which are given in Table 19. The DCL Titan filter was transferred to tractor #017 in Jul 2004 to get a faster accumulation of hours. The data collected on #017 for 4 zoom periods are given in Table 20. Tables 19 and 20 give the entire history.

Table 19: Statistical data for DCL Titan on tractor #621

		Pressure (mbar)				Temperature (°C)			
Zoom No.	Calendar start	Min.	Ave.	Max.	95%ile	Min.	Ave.	Max.	95%ile
1	Apr 8/2002	10	47	106	55	78	299	480	438
2	Apr 13/2002	10	49	264	64	75	280	504	430
3	Apr 27/2002	10	64	170	105	78	297	558	450
4	Nov 14/2002	10	65	486	85	90	324	729	444
5	Jan 31/2003	10	62	158	96	54	279	591	480
6	Dec 4/2003	10	68	162	107	66	296	564	485
7	Feb 12/2003	10	69	188	111	54	274	561	470
8	May 7/2004	10	69	220	135	69	260	726	486

Table 20: Statistical data for DCL Titan on tractor #017

		Pressure (mbar)				Temperature (°C)			
Zoom No.	Calendar start	Min.	Ave.	Max.	95%ile	Min.	Ave.	Max.	95%ile
1	Aug 10/2004	10	171	416	288	96	317	618	445
2	Aug 10/2004	40	341	504	488	111	320	684	556
3	Aug 11/2004	10	137	406	230	102	300	618	510
4	Aug 19/2004	18	145	402	270	51	228	600	431

Trends of temperature and backpressure with time for this filter are shown in Figures 80 and 81, respectively. Both of these figures contain the statistics over the 8 zooms of #621 and the 4 zooms of #017. It can be seen that the pressures were generally well-behaved while on #621 (except for a maximum value of over 500 mbar, which indicates that regeneration was necessary), but the backpressures were somewhat higher when the filter was installed on #017. An explanation of the higher backpressures on #017 may be due to a combination of:

- During the week of July 17/04 when the DCL unit was installed on #017, most of the DEEP team was on vacation and training about regeneration was very limited;
- During early Aug/04 it was found that the DCL regeneration station was not completing its cycle. It was sent to DCL for repair.
- A major rock burst on the main ramp for level 3400 prevented LHD #017 from returning to be regenerated.

During these periods it was requested that the DCL filter be regenerated on the CombiClean unit located on the surface. It is highly likely that the DCL filter experienced poorer regeneration during this period and the higher backpressure may have resulted.

The best integral performance data for the DCL Titan filter is on tractor #621 from Jan 31/03 until its transfer. For this integral period the statistics are given in Table 21. The pressure and temperature frequency distributions are shown in Figure 82. The episodic temperature-duration frequency is shown in Figure 83. The fraction of time the backpressure was normal is shown in Figure 84.

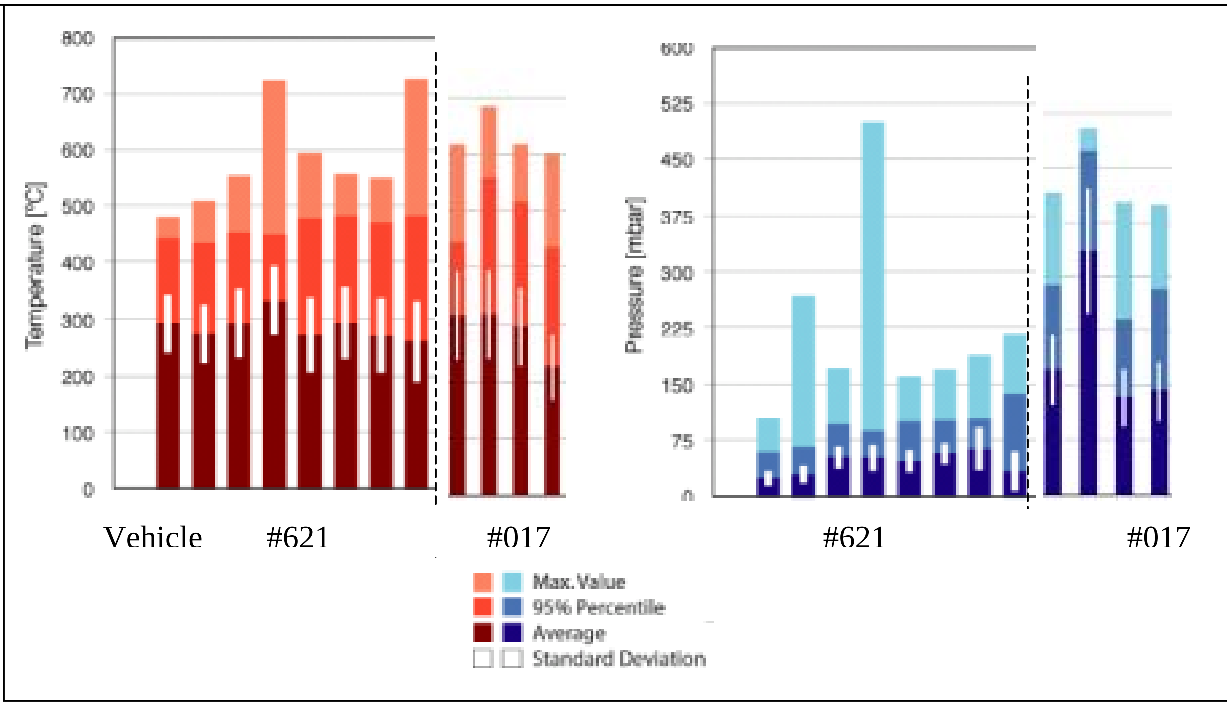


Figure 80: Trend of temperature **Figure 81: Trend of backpressure**

Table 21: Integral statistics for DCL Titan on tractor #621 (Jan 21/03-Jul 19/04)

	Pressure (mbar)				Temperature (°C)			
	Min.	Ave.	Max.	95%ile	Min.	Ave.	Max.	95%ile
inlet side	10	68	510	110	54	276	726	481
outlet side					3	251	765	392

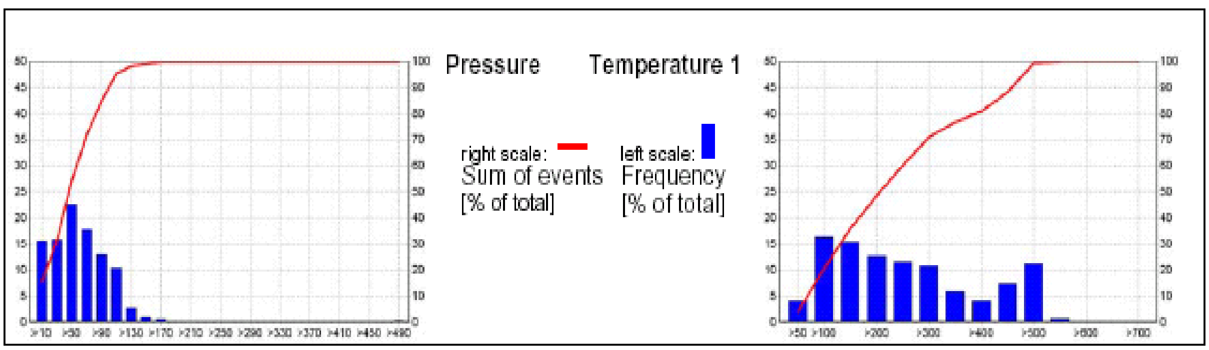


Figure 82: Pressure and temperature frequency distributions for DCL Titan filter.

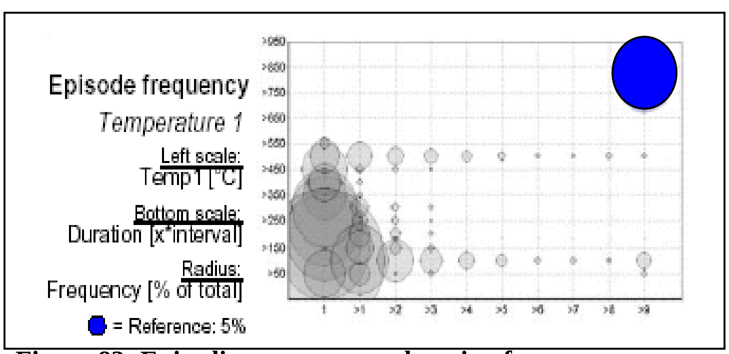


Figure 83: Episodic temperature-duration frequency.

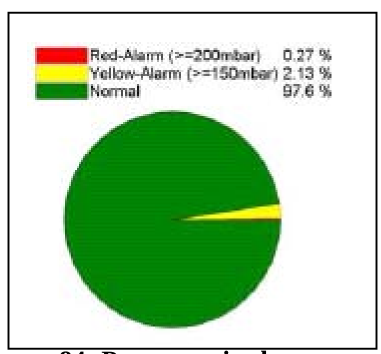


Figure 84: Pressure pie chart.

9.5 ECS/Combifilter (first)
(on #445 LHD)

After the failure of the Oberland-Mangold system on LHD #445 it was decided to put an ECS/Combifilter on vehicle #445. This was accomplished in April 2002. Three routine ECOM periods were conducted to measure smoke numbers and target gases and one special test was carried out on the system in May 2002 shortly after its installation.

Special test (May 2002)

Table 22: Results of special test for ECS/Combifilter on an LHD.

Engine Speed[b]	Efficiency (%), eq [1]						Smoke No.[a]	Upstream %Opacity	Downstream					
									% Opacity	%		ppm		
	PAS	EC	O_2	CO	NO	NO_2				O_2	CO_2	CO	NO	NO_2
TCS	94.8	99.6		-104	-41	63				9.4	8.6	224	688	13
LI	93.0	93.6		-9	-8	75				16.3	3.9	93	858	34
HI	92.9	--		22	-30	60	7.8/5.7	35.3	1.6	13.4	5.6	98	553	12

a:upstream/downstream

b: HI=High idle; LI= Low idle; TCS= Torque converter stall; Snap A= Snap acceleration

Note: a negative number in efficiency means downstream was greater than upstream.

The notable points about the results in Table 22 were:

(a) the highest PAS/EC and highest counts of particles were observed upstream from this engine. This is because #445 has a very high fuelling rate and higher power output compared to other LHDs being tested.

(b) Downstream particulate concentrations were higher than expected with PAS measured efficiencies of between 92-94%.

(c) Smoke numbers were very poor and higher than expected downstream opacity was observed.

(d) The unusual increase in downstream CO (as denoted by the negative efficiency number) was likely caused by some filtered soot burning during the test.

(e) Backpressure was noted to exceed 150 mbar under the TCS condition.

The special test indicated that this system was not performing as it was expected, even after only a short operational life. Concerns about vehicle operator attention to regular active regeneration (plugging the unit into the regeneration station power supply) were discussed (see below).

Routine tests

Three routine testing periods were carried out on this system and the results are shown in Table 23. By September 2002 the system was showing extremely poor smoke numbers and it was obvious that regeneration was not working.

Table 23: Smoke numbers and gas analyses for ECS/Combifilter on LHD #445.

Date	Meter(h)	Upstream					Downstream			
		SmNo.	CO(ppm)	NO(ppm)	NO2(ppm)	T(^{o}F)	SmNo.	CO(ppm)	NO(ppm)	NO2(ppm)
6/27/02	281	7	154	542	12	851	1			
9/11/02	540	8	70	558	11	805	6	89	562	7
9/15/02	444	7	90	606	14	939	7	114	648	6

Regeneration problems

Investigations were launched into why regenerations were not being performed routinely. It was learned that the regeneration station, located on level 3000, was not the best location for regeneration because of the distance between it and where the LHD #445 was being operated. This situation created extra effort in conducting the regeneration with the result that the filter was becoming more and more blocked with soot. Backpressure readings became unacceptably high and the decision was made to manually clean the filter.

Damage to the ECS/Combifilter

When the filter was cleaned of the built up soot, it became obvious that significant damage to the filter medium had occurred and that the integrity of the filter was compromised.

The failure of the ECS/Combifilter on LHD #445 was due to a number of reasons. The first obvious reason was the logistical difficulties the operators experienced in doing routine regeneration of the system. If systems that rely on active regeneration are not provided with a good and easily conducted regeneration program, then it should not be surprising when such a system fails. While the Stobie team thought it had adequately communicated the need for regeneration to the vehicle operators, an unforeseen problem associated with ease of access to the regeneration station prevented the vehicle operators from fulfilling regeneration in a regular fashion.

The second reason for failure of this system was caused by the regeneration system itself. This was only clearly established after another ECS/Combifilter was installed (this one on LHD #213). At the beginning of operation on #213 the ECS filter also showed some indications of less than adequate regeneration (e.g., higher than expected backpressure). After consultation with ECS engineers it was determined that adjustments to the regeneration station were required, namely, that the air flow had to be decreased because of excessive cooling of the filter during regeneration and that the amount of heat delivered had to be increased and the time at temperature had to be increased. Upon making these adjustments the ECS regeneration system performed well.

Statistical analyses

Statistical data on this filter is identified in Appendix C as INCO4-445. Due to its failure due to poor regeneration practice, no further analyses of these data are given here.

9.6 ECS/Combifilter (second)
(on #213 LHD)

An ECS/Combifilter was installed on LHD #213 on Feb 14, 2003. Because of the previous failure of routine regeneration of the same type of filter on LHD #445, the Stobie team took extra effort to educate vehicle operators into the importance of their actions regarding regeneration. In addition, the off-board ECS regeneration station was moved from Level 3000 to Level 3400 so that its location was more convenient for vehicle #213. All of the efforts were rewarded with excellent service of the unit over more than 1.5 years until unit #213 was buried by a run of ore and was removed from further testing near the end of 2004.

Routine tests

Fourteen periods of routine testing of this system were carried out and results are shown in Table 24. The smoke numbers showed good filter efficiency with an average upstream value of 7.1 and an average downstream number of 1.0 (see also Figure 85).

Table 24: Smoke numbers and gas analyses for ECS Combifilter on LHD #213.

		Upstream						Downstream				
Date	Meter (h)	Sm No.	CO (ppm)	NO (ppm)	NO_2 (ppm)	O_2 (%)	T (^oF)	Sm No.	CO (ppm)	NO (ppm)	NO_2 (ppm)	O_2 (%)
5/7/03	390	7	135	634	19	10.5	790	0.5	110	525	10	11.3
5/25/03	546.8	7	108	1269	48	10.3	764	1	107	473	9	11.2
10/30/03	721.3	6	98	581	26	14.3	593	0.5	88	586	12	14.4
1/5/04	970.6	8	116	1375	48	10.8	739	2	106	642	14	11.7
1/29/04	1173.1	8	131	1253	32	10.4	764	0	143	815	18	11.4
3/6/04	1376.8	7	113	1037	28	10.7	492	1	120	698	21	11.9
3/17/04	1462	7						1				
4/8/04	1661.5	7	77	1043	30	11.6	707	1	86	466	7	12.2
4/15/04	1688	7	83	463	12	11.7	639	2	77	443	6	12.3
5/4/05	1855	8	87	518	16	11.2	740	1	90	497	6	12
6/7/04	1968	8	107	467	26	14.7	501	0	117	445	3	11.2
8/19/04	274	7	84	477	26	14.8	903	3	75	474	4	14.8
9/13/04	314	7	57	639	24	13.8	634	1	62	460	9	15.1
10/1/04	425.3	6	84	502	27	14.6	700	1	71	501	10	15.4
sum		100	1280	10258	362	159.4	8966	15	1252	7025	129	164.9
ave.		7.1	98	789	28	12.3	690	1	96	540	10	13

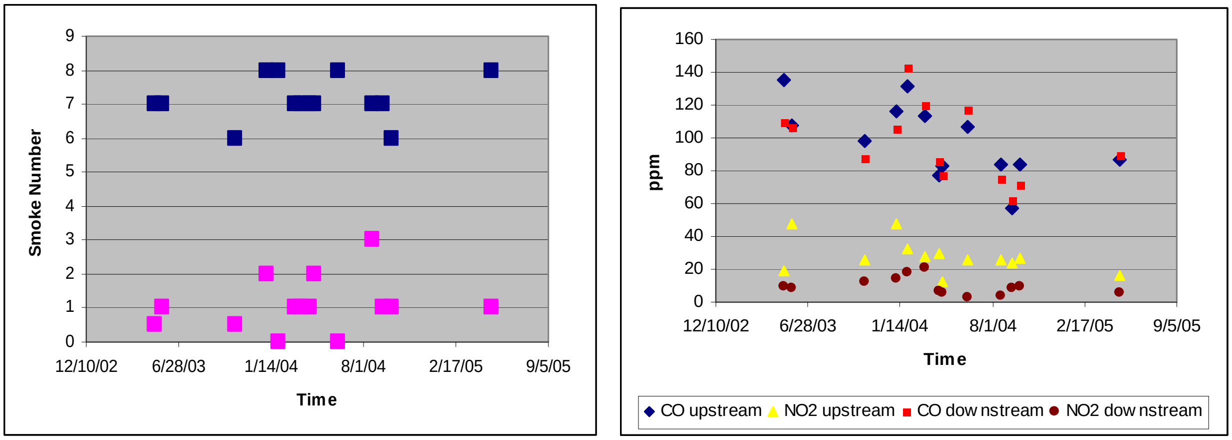


Figure 85: Left: Smoke numbers as a function of time downstream of ECS on #213; Right: Target gas analyses for ECS on #213.

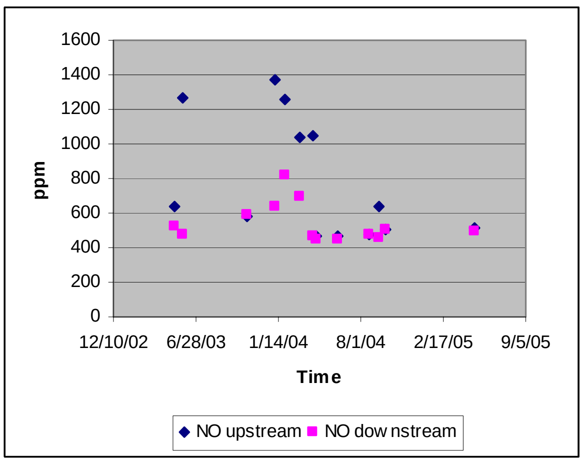


Figure 86: NO analyses for ECS on #213.

CO analyses (see Figure 85) may be have trended down with time both upstream and downstream and this may have been related to engine conditions. NO_2 concentrations are relatively low. The NO analyses are shown separately in Figure 86 because the ppm scale is different. The NO concentrations were much higher upstream and downstream than those seen for the light duty vehicle (see ECS/Combifilter on #2180). Although considerable scatter exists, the data may also reflect a decreasing trend upstream.

An example of routine operation of this system is shown in Figure 87, The horizontal axis is time and covers about 52 hours between April 30, 11:40AM, and May 2, 3:40PM. The green line shows the upstream temperature, blue shows the downstream temperature, and red shows the backpressure. During the period shown, the backpressure slowly increased from about 60 to about 100 mbar.

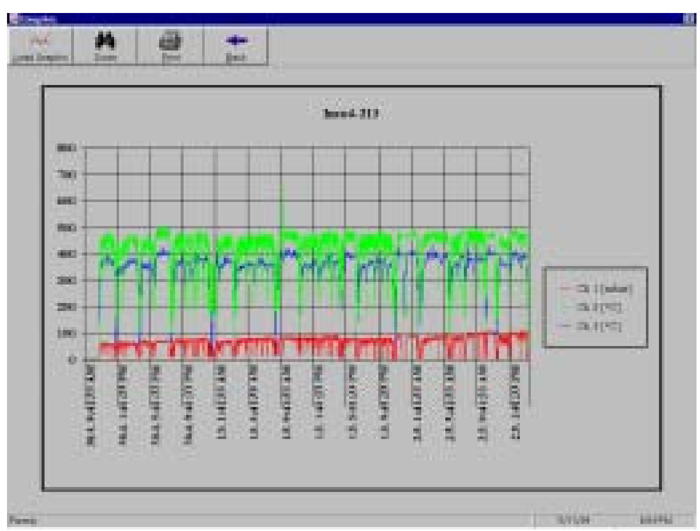


Figure 87: Routine datalogging for vehicle #213 over a 52 hour period April 30-May 2, 2004.

Special test

One special test was conducted on this system in June 2004. Results are given in Table 25. In general, excellent soot removal efficiencies were observed with high idle smoke numbers being 8.5 and 0 upstream and downstream, respectively. The only numbers that are worth noting in this table are the significant reductions in downstream NO_2 under all engine conditions tested.

Table 25: Special test on ECS on LHD #213.

Engine	Efficiency (%), eq [1]						Smoke No.[a]	Upstream %Opacity	Downstream					
									%Opacity	%		ppm		
Speed[b]	PAS	EC	O_2	CO	NO	NO_2				O_2	CO_2	CO	NO	NO_2
HI	99.8	98.9		3	3	61	8.5/0				4.6	112	369	5
LI				4	4	81					2.1	116	355	7
TCS	99.9	91.2		-23	12	36					7.7	169	376	7
Snap A								45	0.4					

a:upstream/downstream

b: HI=High idle; LI= Low idle; TCS= Torque converter stall; Snap A= Snap acceleration

Note: a negative number in efficiency means downstream was greater than upstream.

Size distribution

Particle size distribution was measured for this system under torque converter stall and high idle conditions and results are shown in Figure 88.

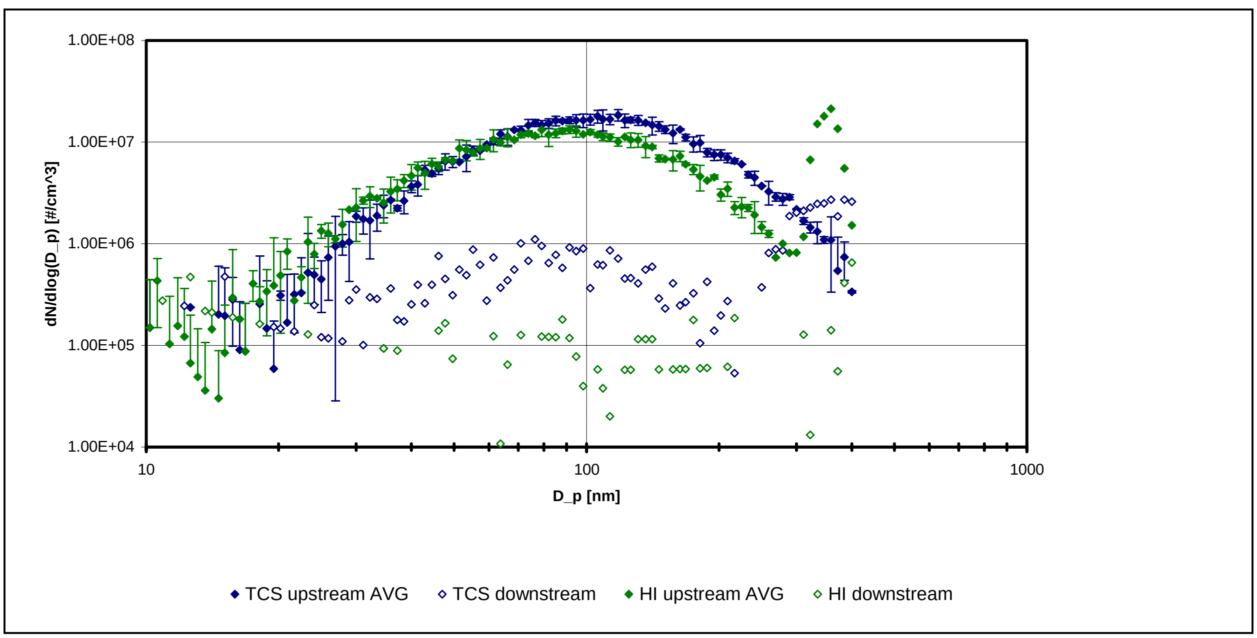


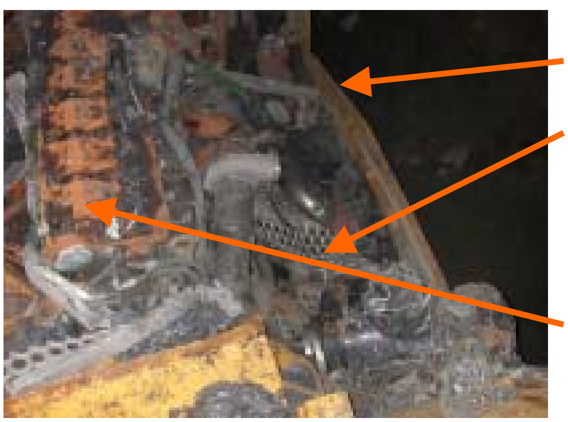
Figure 88: Size distributions for the ECS/Combifilter on an LHD; upstream TCS (solid blue) and high idle (solid green) are compared to the downstream distributions (open blue and open green, respectively). The high readings in the coarsest particle region for the solid green and open blue points are due to spurious electronic signals and should be neglected.

Accident with LHD #213

On November 8, 2004, LHD #213 was partially buried in a muck pile. The vehicle sustained significant damage when it rolled onto its right side and had to be pulled out of the muck. Photos showing the damaged unit after it had been towed to the garage at 2400 Level are shown in Figure 89. The ECS system and the datalogger on LHD #213 still worked, but the system was not put back into operation because #213 was too damaged and it was impractical to relocate the filter system to another LHD because the project testing was due to end within months.

Showing damaged vehicle electrical box.

Showing cracked and open top of engine block.



Showing position of ECS Combifilters.

Figure 89: Damage to vehicle #213 from mucking accident. Refer to Figures 43 and 44 to see the installed positions of the dual ECS/Combifilters on this vehicle.

Statistical analyses

Temperature and pressure data for th ECS/Combifilter on LHD #213 are given in Appendix C under INCO4-213. A total of 15 zoom periods covered the entire history of this filter on LHD #213. The statistical analyses for these 15 periods are given in Table 26. Trends of temperature and backpressure are shown in Figures 90 and 91, respectively. One can see that the average backpressure was much improved from the earlier ECS/Combifilter due to increased attention to regeneration. In fact, the trend is downward over the 15 periods showing improved regeneration practice with time. The temperature trend is fairly stable with averages over the 15 periods of about 400°C. This relatively low temperature on an LHD points out the need for active regeneration.

Table 26: Statistical data for the ECS/Combifilter on LHD #213 over 15 zoom periods.

		Pressure (mbar)				Temperature (°C)			
Zoom No.	Calendar start	Min.	Ave.	Max.	95%ile	Min.	Ave.	Max.	95%ile
1	Feb 14/02	10	76	258	190	87	263	531	475
2	Oct 10/03	10	90	160	105	105	424	543	436
3	Oct 30/03	10	105	214	133	96	402	645	440
4	Dec 12/03	10	101	202	130	99	402	564	438
5	Dec 22/03	10	100	158	108	99	408	555	434
6	Jan 29/04	10	91	162	110	99	399	516	438
7	Feb 14/04	10	94	220	119	99	394	531	436
8	Feb 27/04	10	86	154	105	102	402	717	441
9	Mar 17/04	10	60	140	68	102	420	516	440
10	Mar 27/04	10	57	124	48	102	426	636	442
11	Apr 8/04	10	68	132	86	123	433	573	444
12	Apr 18/04	10	53	92	48	117	425	516	442
13	May 12/04	10	57	112	60	132	434	711	445
14	May 23/04	10	55	118	48	132	433	711	446
15	Jun 25/04	10	56	118	53	72	458	750	525

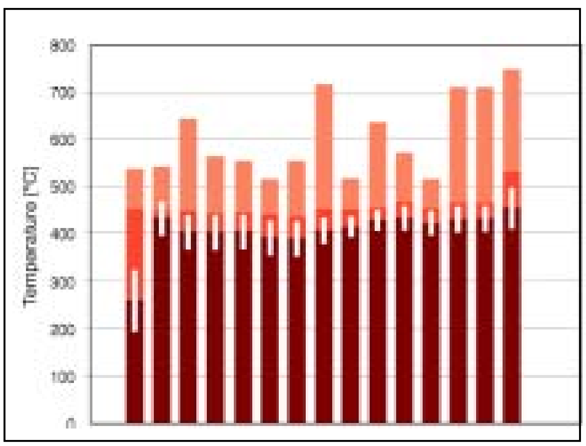


Figure 90: Trend of temperature for LHD #213

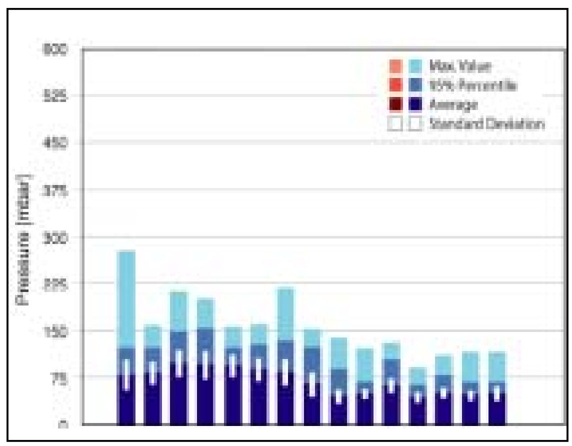


Figure 91: Trend of backpressure for LHD #213.

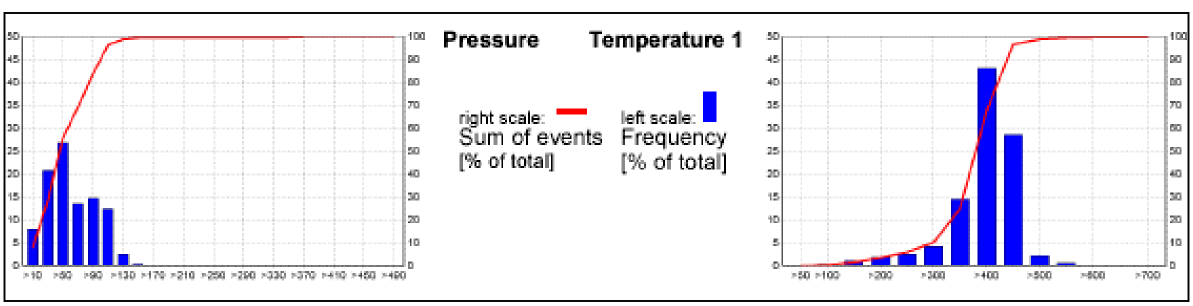


Figure 92: Frequency distributions of temperature and backpressure for LHD #213.

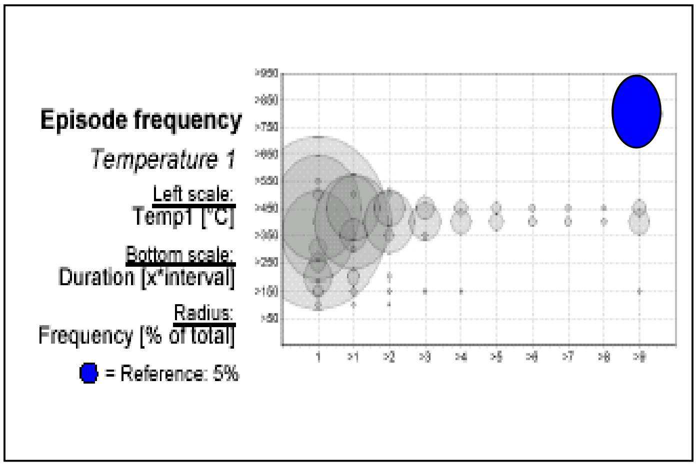


Figure 93: Episodic temperature-duration frequency for LHD #213

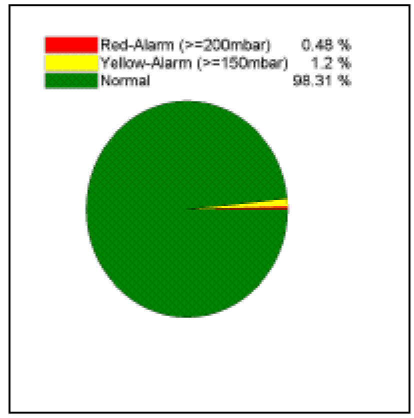


Figure 94: Pressure pie chart.

Table 27: Integral statistics for ECS/Combifilter on LHD #213.

	Pressure (mbar)				Temperature (^oC)			
	Min.	Ave.	Max.	95%ile	Min.	Ave.	Max.	95%ile
inlet side	10	80	510	109	72	419	750	448
outlet side					3	345	567	380

The integral statistics, covering Apr 30/03 to Aug 19/04, are given in Table 27.

The frequency distributions of both temperature and backpressure over the filter's life are shown in Figure 92 and the episodic frequencies at temperature are shown in Figure 93. These data clearly show that the temperature-durations were limited to <450^{o}C, < 2 minutes; this temperature-duration would not be adequate by itself to passively ignite and burn the soot on the filter. Recognition of this fact is an important finding for LHD-filter application.

As would be expected from the improved regeneration practice, the fraction of normal backpressure, shown in Figure 94, was very good.

Concluding comments on ECS/Combifilter

The ECS/Combifilter active (electrical heating regeneration) system performed very well for heavy duty LHD service. It was gratifying for the Stobie team to see this system perform well after the poor experience the same system showed when regeneration was not carried out routinely. This experience shows the importance of training operators and having an operational system that assures regeneration. Without such attention, active systems like this one are bound to fail. With good attention to regeneration, this system worked well.

9.7 Engelhard
(on #362 LHD)

The Engelhard system, a fully passive system utilizing a catalyst coating on a cordierite honeycomb, was installed on LHD #362 on June 20, 2001. The system operated for more than a year with good performance, including surviving an accident where mud penetrated into the filter from the discharge side. In September 2002 a fire occurred on the vehicle. The fire was associated with failure of the engine's turbo, which caused oil to be sprayed over engine and adjacent surfaces that ignited. This incident caused the Engelhard system to be removed with 2221 hours of operation.

<u>Routine tests</u>

Ten periods of routine testing of this system were carried out and the data are displayed in Table 28. The smoke numbers showed reasonable filter soot removal efficiency, averaging about 7 upstream and <1 downstream. Smoke numbers as a function of time are shown in Figure 95.

Table 28: Smoke numbers and target gas analyses for Engelhard on an LHD.

	Meter	Upstream						Downstream				
			CO	NO	NO2	O2	T		CO	NO	NO2	O2
	(h)	Sm No.	(ppm)	(ppm)	(ppm)	(%)	(^oF)	Sm No.	(ppm)	(ppm)	(ppm)	(%)
7/18/01	7892	8	82	572	26	7.8		0.5	10	470	60	7.9
12/6/01	8670	7.5	76	526	16	11.2	691	1	0	521	66	11.5
12/30/01	93	7.5	73	973	54	11.2	578	1	0	524	60	11.9
2/1/02	345	7	75	630	22	11.2	470	0	22	1099	40	11.7
5/23/02	1011	7	93	1313	61	10.7	628	1	0	1154	77	11.6
7/4/02	1156	9	98	479	13	10.8		0				
7/18/02	1191	3	79	557	30	14.2	526	1	11	541	22	14.4
8/7/02	1268	7	69	584	32	14.8	517	0	0	596	18	15.3
9/14/02	1581	7	99	542	11	10.7	520	1	16	630	16	11.3
9/18/02	1585	7.5	91	553	19	10.8	733	0	0	490	29	11.4
sum		70.5	835	6729	284	113.4	4663	5.5	59	6025	388	107
ave.		7.1	84	673	28	11.3	583	0.6	7	669	43	11.9

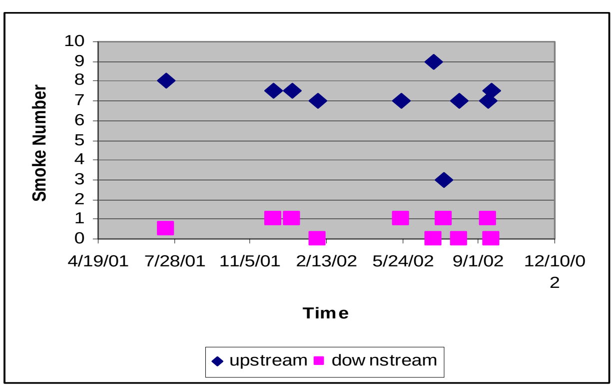
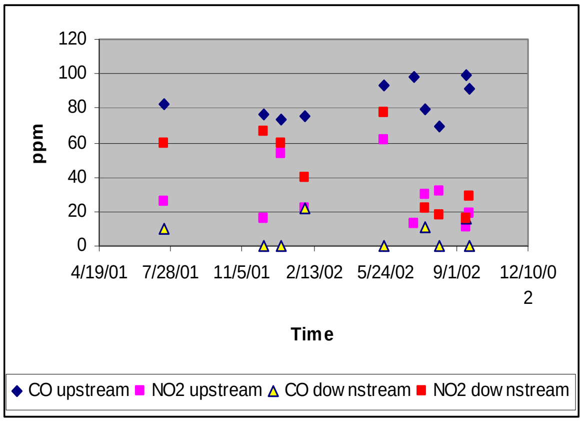


Figure 95: Smoke numbers for the Engelhard system.

One smoke number of 3 (upstream) appears to be anomalous. It is suspected that the measurement may have been conducted prior to the engine condition having been stable. If this number is removed, the upstream average smoke number becomes 7.5.

Gas analyses are shown in Figure 96. Two separate figures are necessary because of the ppm scale difference. CO downstream of the Engelhard filter was very low, which is consistent with the filter having a catalytic coating that assists in oxidizing CO to CO_2. It also appears that the NO_2 was somewhat lower during the latter periods of testing, but no reason exists for this behaviour. Likewise, there seems to be considerable scatter among the NO results for both upstream and downstream.



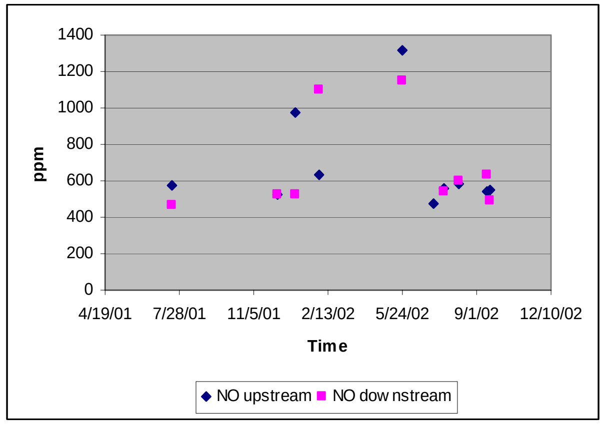


Figure 96: CO, NO_2 and NO (right) analyses for the Engelhard system.

<u>Special tests</u>

Two special tests were carried out on this system, one in July/01 shortly after the system was installed, and the other in May/02 when the system had compiled 1918 hours of operation. Results of these two tests are given in Table 29. Of note is the high removal of CO by the Engelhard filter. This was expected because of the catalytic coating present. Also of note is the high amount of NO and NO_2 downstream for certain engine conditions.

Table 29: Results of special tests on the Engelhard system on an LHD.

Engine Speed[b]	Efficiency (%), eq [1] PAS	EC	O_2	CO	NO	NO_2	Smoke No.[a]	Upstream %Opacity	Downstream %Opacity	Downstream % O_2	Downstream % CO_2	Downstream ppm CO	Downstream ppm NO	Downstream ppm NO_2
July/01 (0 hours)														
HI	99.7			98	-800	-81				9.9		2	421	58
TCS	99.6						8/0.5		0.2	7.9		10	470	60
TCS		98.8		80	18	-130								
TCS		100												
TCS		99.5												
Snap A		99.4												
May/02 (1918 h)														
TCSI	100	97		90	-1	-55	9/0	35.9	0.4	10.7	7.7	12	495	53
LI	99.6	95.1		91	2	1				14.2	5.1	9	506	50
HI	100			1	83	10				17.6	2.5	25	492	85

a:upstream/downstream

b: HI=High idle; LI= Low idle; TCS= Torque converter stall; Snap A= Snap acceleration

Note: a negative number in efficiency means downstream was greater than upstream.

Size distribution

Information on size distributions collected upstream during three different engine conditions are shown in Figure 97 (left). Torque converter stall and high idle showed similar upstream distribution; low idle showed particle counts more than an order of magnitude lower. Figure 97 (right) shows upstream and downstream distributions for torque converter stalls. Two replicate upstream distributions are shown in red and blue, while three replicate downstream distributions are shown in yellow, green and black.

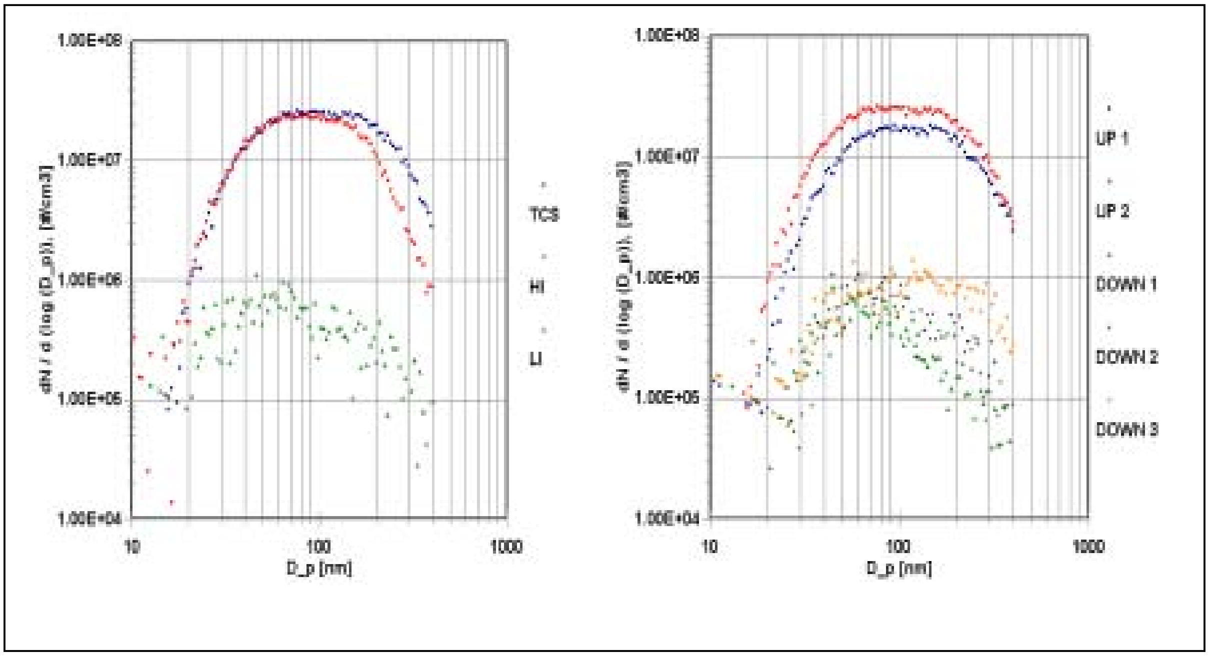


Figure 97: Size distributions upstream of the Engelhard filter for three engine conditions (left); upstream and downstream distributions for torque converter stalls (right).

Statistical analyses

The data for the Engelhard filter on LHD #362 are contained in Appendix C under INCO6-362. A total of 15 zoom periods covered the entire history of this filter (from Aug/01 to its removal in Oct/02 when the engine's turbo failed). Statistics for each of the 15 zooms are given in Table 30 an integral statistics for the complete history are given in Table 31. The trends of temperature and backpressure are shown in Figures 98 and 99, respectively.

Frequency distributions of pressure and temperature are shown in Figure 100. As observed with other LHDs, the temperature distribution clearly shows temperatures <500^{o}C. The episodic temperature duration frequencies are shown in Figure 101 and look very similar to other LHDs in this project.

As shown in Figure 102, which is a pie chart showing the fraction of normal backpressure, it is clear that this filter suffered relatively high backpressures for sustained periods, but its filtration efficiency (see above) remained excellent.

Table 30: Statistics for Engelhard on LHD #362 over 15 zoom periods.

		Pressure (mbar)				Temperature (°C)			
Zoom No.	Calendar start	Min.	Ave.	Max.	95%ile	Min.	Ave.	Max.	95%ile
1									
2	Nov 12/01	10	155	230	183	144	442	738	450
3	Dec 4/01	10	159	244	190	168	443	543	456
4	Dec 17/01	10	173	466	206	165	441	582	450
5	Jan 11/02	10	152	222	178	198	440	531	450
6	Jan 19/02	10	154	230	181	189	445	534	463
7	Feb 1/02	10	155	250	191	195	448	603	485
8	Feb 5/02	10	131	200	159	138	436	570	481
9	Feb 9/02	10	149	372	202	147	466	573	498
10	Feb 14/02	10	154	250	191	156	452	603	485
11	Feb 18/02	10	147	252	195	174	437	573	460
12	Apr 13/02	10	190	308	241	174	451	567	488
13	Apr 17/02	10	203	328	261	114	451	603	494
14	Jul 18/02	10	203	324	256	117	462	714	498
15	Aug 10/02	10	198	510	230	102	482	576	500

Table 31: Integral statistics for Engelhard on LHD #362.

	Pressure (mbar)				Temperature (°C)			
	Min.	Ave.	Max.	95%ile	Min.	Ave.	Max.	95%ile
inlet side	10	168	510	229	102	449	738	488

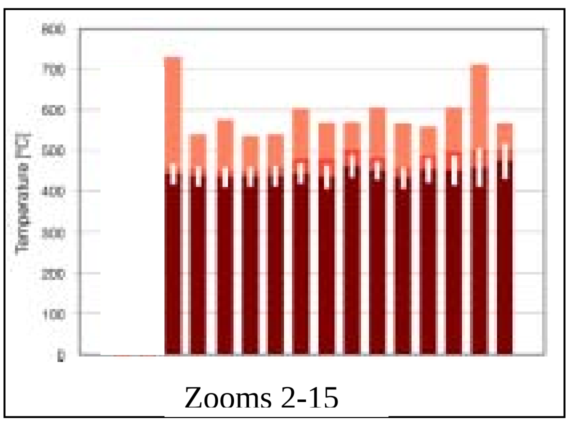


Figure 98: Trend of temperature for Engelhard.

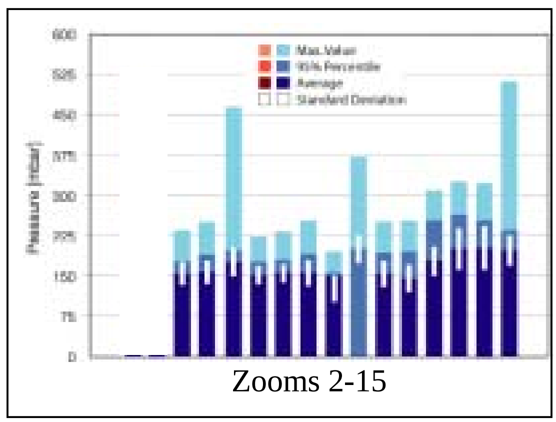


Figure 99: Trend of pressure for Engelhard.

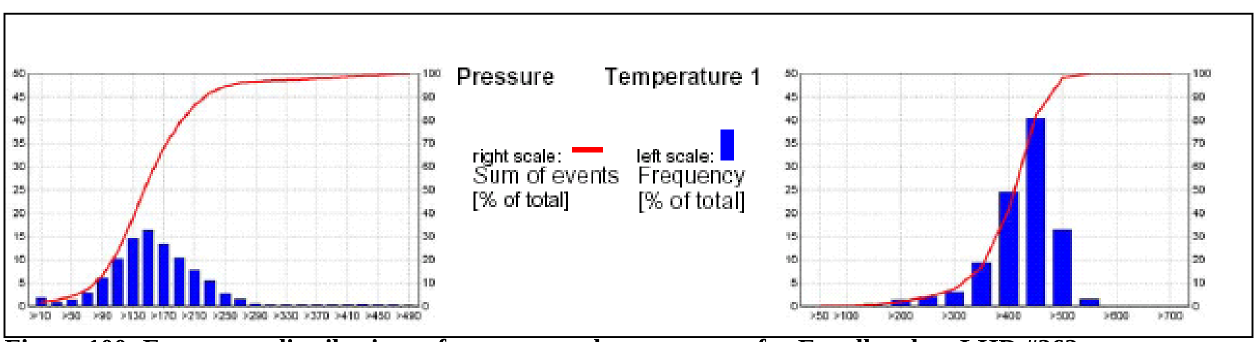


Figure 100: Frequency distributions of pressure and temperature for Engelhard on LHD #362.

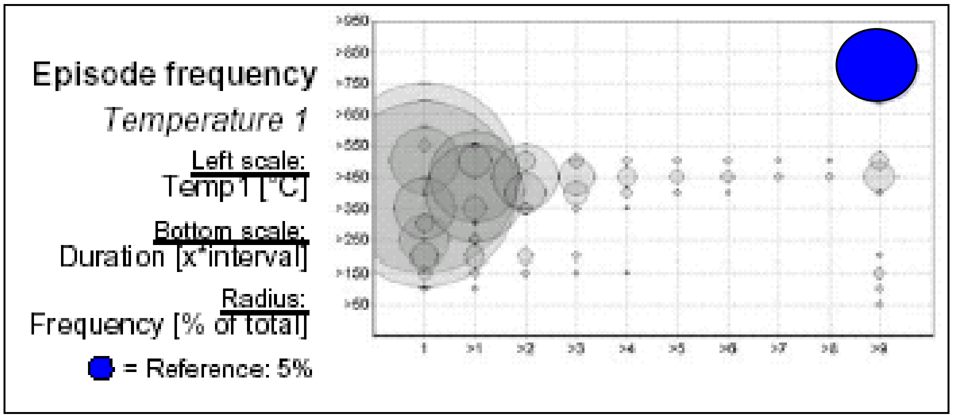


Figure 101: Episodic temperature duration frequencies.

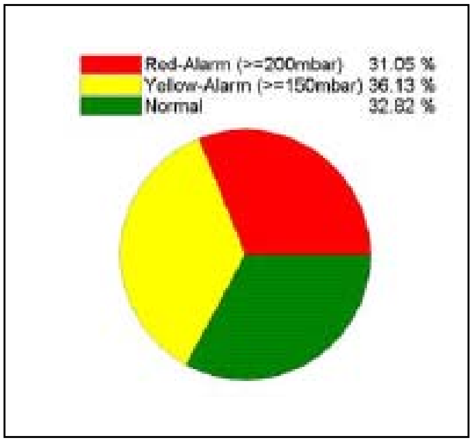


Figure 102: Backpressure pie chart

9.8 Johnson Matthey System
(on LHD #820)

LHD #820 had a Deutz engine with dual exhausts and therefore two Johnson Matthey filters were installed on June 16/01: the two filters are referred to as “left side” and “right side” from the vantage point of the driver. Alternatively, the left side could be termed the “driver’s side” while the right side could be termed the “off-driver’s side”. Both routine tests and special tests were carried out on each filter. Since the filters perform independently of each other, the performances are presented and discussed separately.

9.8.1 Johnson Matthey
(left side)

Routine tests

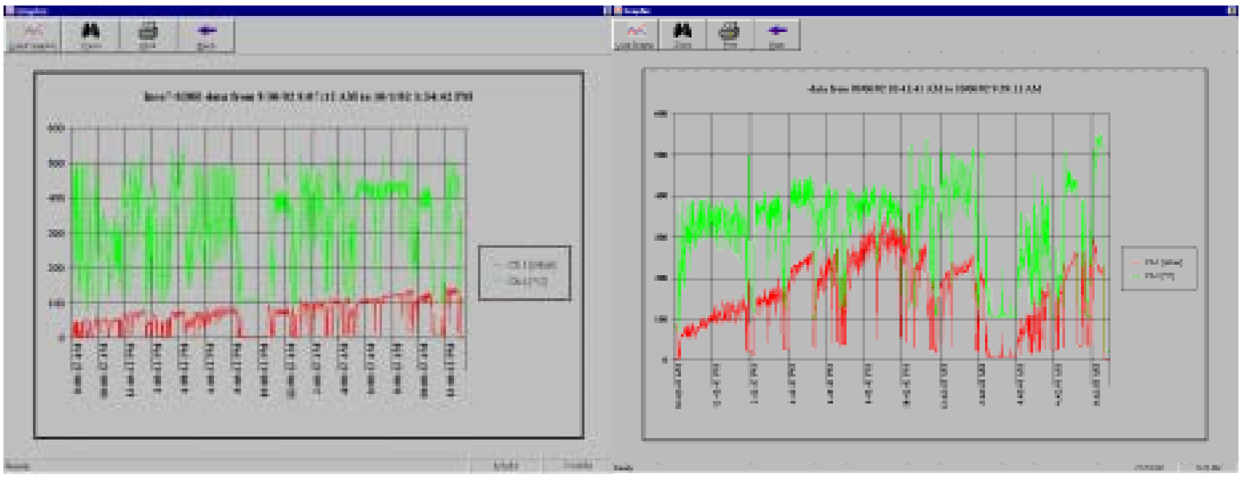
There were 13 routine test periods for this filter. Results are given in Table 32. While this filter generally showed acceptable smoke numbers downstream (averaging 1.5) compared to upstream (averaging 7.0), there were several periods of high backpressure caused by lack of proper regeneration. Since this filter operated first as a passive system, having a fuel-borne catalyst, the periods of high backpressure indicated lower than expected upstream gas temperatures (averaging 566 ^{o}F), which were insufficient to ignite and completely burn the soot on the filter. As the amount of catalyst added to the fuel was targeted to achieve ignition of the

Table 32: Smoke numbers and target gas analyses for Johnson Matthey (left) on an LHD.

Date	Meter	Upstream						Downstream				
	(h)	Sm No.	CO	NO	NO2	O2	T	Sm. No.	CO	NO	NO2	O2
			(ppm)	(ppm)	(ppm)	(%)	(^{o}F)		(ppm)	(ppm)	(ppm)	(%)
7/17/01	6086	6.5	115	480	15	9.3		0	115	534	10	9.1
1/3/02	6292						689	9+	0	517	20	9.6
6/28/02	6748	4	162	493	10	9.4		0				
9/30/02	6887	7	111	609	10	8.3	925	1	111	609	10	8.3
11/27/02	7097	8	153	337	33	14.7	351	1	134	354	24	14.8
2/3/03	7322	7	169	580	9	9	414	4	131	601	6	9
2/20/03	7390	9	112	440	11	8.1	479	4	84	485	6	8.5
3/26/03	7578	8	134	557	9	8.5	542	1	103	546	3	8.9
11/27/03	7916	6	128	610	6	7.8	687	1	107	589	3	8.8
1/26/04	8105	7	174	555	22	10.3	487	4	128	610	11	10.9
3/11/04	138	7	116	522	20	10.8	584	2	107	548	13	11
4/14/04	234	7	159	487	27	11.1	445	1	141	528	10	11.2
6/14/04	385		46	194	2	16.2	621	--	26	170	2	17.2
sum		76.5	1579	5864	174	123.5	6224		1187	6091	118	127.3
Ave.		7.0	132	489	15	10.3	566	1.5	99	508	10	10.6

Please disregard the red highlight in this table.

soot at 750^{o}F (400 ^{o}C), it is clear that this temperature was not attained for considerable periods of time during the test. As this possibility had been forecast, the Johnson Matthey filter also had the capability of being regenerated by electrical heating. The fact that periods of high backpressure occurred indicates that electrical regeneration was not practiced as routinely as was necessary. One such period is shown in Figure 103, where temperature (green) and backpressure traces(red) are shown over a 17 hour period in late Sep/02. It can be seen that the red backpressure on the right side filter continues to increase over this time, despite the downtime of the vehicle in the middle of the period.



(a) (b)

Figure 103: Temperature (green) and backpressure (red) traces over (a) a 17 hour period in late Sep/02 and (b) a one month period in late Sep/02 on vehicle #820 (right side).

It should be noted that specific high downstream smoke numbers in early 2003 were associated with the appearance of a noticeable crack between the filter honeycomb structure and its metal canister. This separation is shown in Figure 104. After consultation with Johnson Matthey technicians, it was decided to continue operation of the left side filter, but to watch it closely. In early 2004 it became apparent that the crack was growing and it then was decided to remove the left side filter (at 2138 total operating hours). It was replaced with a new cordierite filter from Johnson Matthey (installed on the left side onMar 31/04) and the LHD #820 was returned to production until the test was stopped in July 2004.

Figure 104: Separation of the Johnson Matthey filter (left side,a) in February, 2003. This filter remained in service until March, 2004, when the separation had worsened and filter efficiency was decreasing.

Smoke numbers as a function of time for the routine tests are shown in Figure 105. CO, NO and NO_2 gas analyses from the routine tests are shown in Figure 106. Considerable scatter in these data exist, but no discernable trends with time are evident.

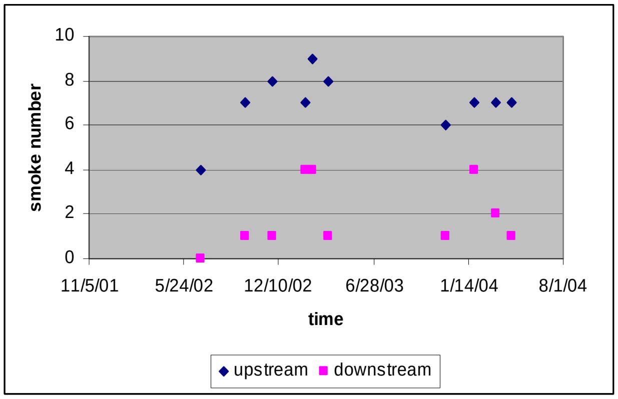
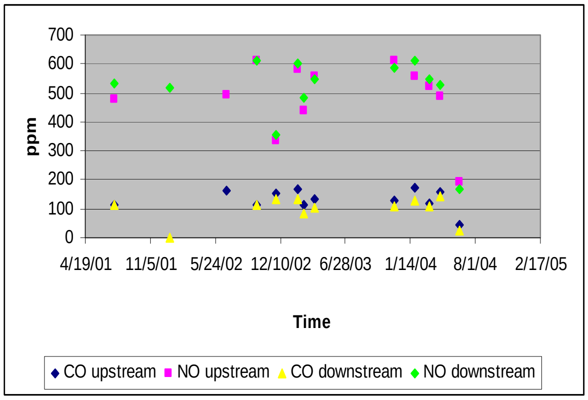


Figure 105: Smoke numbers for Johnson Matthey (left) on an LHD.



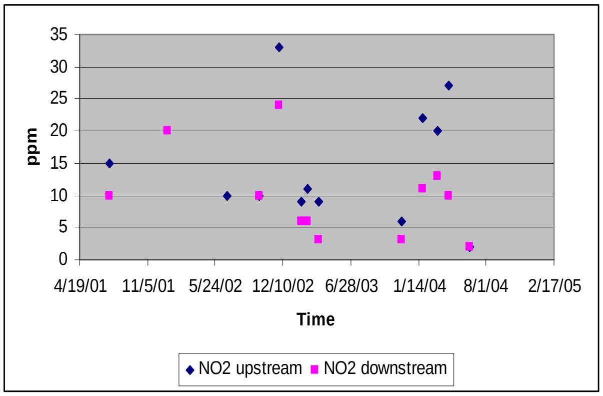


Figure 106: Gas analyses for Johnson Matthey (left) on an LHD.

Special tests

The Johnson Matthey filter on the left side of the vehicle was tested in July 2001 just after it was installed and again in May 2002 with 424 hours of operation. The original SiC filter was removed from the left side after 2057 hours of operation because of a noticeable separation between the honeycomb structure and the canister. A replacement Johnson Matthey filter made of cordierite was installed on March 31, 2004, and this filter underwent special tests in June 2004 after 173 hours of operation.

The special test results (see Table 33) show very good soot filtration efficiencies under all engine conditions. Both CO and NO_2 reductions were significant and the downstream NO_2 concentrations were low.

Size distribution

The size distributions for the torque converter stall, high idle and low idle conditions are shown in Figure 107. All distributions appear to be bi-modal with increasing amounts of the smaller size fractions occurring as one goes from TCS to HI to LI.

Table 33: Special test results for Johnson Matthey (left) filter.

									Downstream					
Engine	Efficiency (%), eq [1]						Smoke No.[a]	Upstream %Opacity	%Opacity	%		ppm		
Speed[b]	PAS	EC	O_2	CO	NO	NO_2				O_2	CO_2	CO	NO	NO_2
July/01 (0 hours)														
HI	99.9			0	-20	75				15.6		99	300	5
LI				13	-10	47				18.6		62	207	8
TCS	100	97.6			-11	33	6.5/0			9.1		115	534	10
Snap A		95.1												
May/02 (424 h)														
TCS	100	99.1		50	-2	50	8.8/0	7.8	0.1	6.5	7.7	185	364	6
LI	99.8	97.2		92	-1	79				17.5		5	199	6
HI	99.8	98.8		30	8	65				13.9		50	297	6
June/04 (173 h)														
TCS	99.9	98.7		-25	1		-/0.5	8.9	0			178	460	
HI	99.8	96.3		8	-4							84	315	
LI		84.5		4	-6							56	204	

a:upstream/downstream

b: HI=High idle; LI= Low idle; TCS= Torque converter stall; Snap A= Snap acceleration

Note: a negative number in efficiency means downstream was greater than upstream.

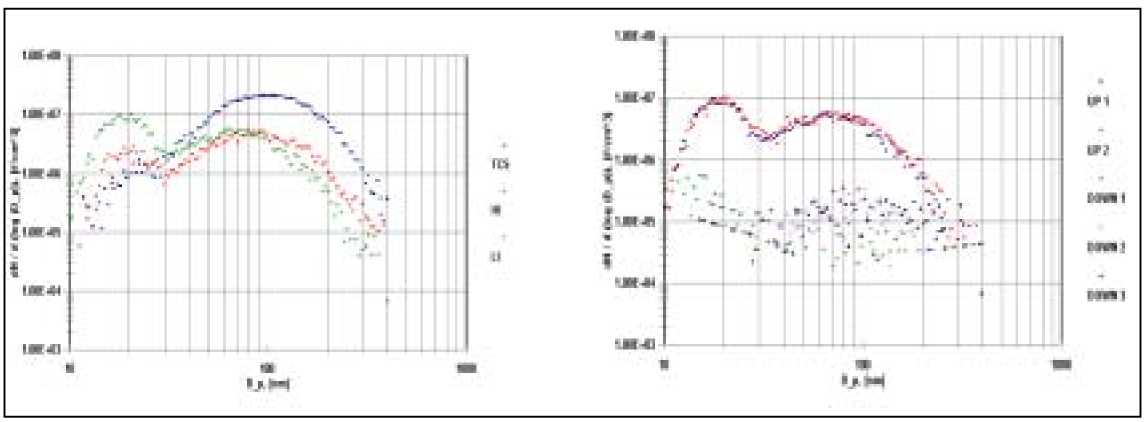


Figure 107: Size distributions from Johnson Matthey. Left: Downstream for various engine conditions. Right: Upstream and downstream distributions under low idle.

The inlet end and the discharge end of the Johnson Matthey filter before regeneration is shown in Figure 108. Clearly the inlet end is blackened with soot, as expected. The discharge end of the same filter is clean.

Figure 108: Johnson Matthey filter inlet side (left) and discharge side (right).

Statistical analyses

Appendix C contains the data from the JM filter on LHD #820 (left=driver's side), identified as INCO2-820L. The entire history of this filter is given in 16 zoom periods, as summarized in Table 34. Trends of temperature and backpressure for the 16 zoom periods are shown in Figures 109 and 110, respectively. It can be seen that the average temperature was fairly constant at around 400^{o}C. The pressure trend was more variable, but the average was generally well-behaved. There were high pressures observed regularly and these indicate more attention to regeneration was necessary.

Table 34: Statistics for JM filter on LHD #820(left) over 16 zoom periods.

		Pressure (mbar)				Temperature (^{o}C)			
Zoom No.	Calendar start	Min.	Ave.	Max.	95%ile	Min.	Ave.	Max.	95%ile
1	Apr 8/02	10	124	292	190	78	395	594	487
2	Apr 13/02	10	128	292	187	63	406	594	497
3	Apr 20/02	10	131	280	199	93	395	509	500
4	May 3/02	10	52	170	108	87	405	624	510
5	Aug 30/02	10	99	322	196	78	370	711	500
6	Nov 7/02	10	175	510	400	78	400	717	524
7	Nov 30/02	10	91	172	119	99	399	750	499
8	Apr 4/03	10	107	462	170	111	402	612	526
9	May 1/03	10	103	462	170	111	402	612	535
10	Oct 8/03	10	107	344	--	84	384	666	536
11	Dec 17/03	10	92	286	156	84	409	615	526
12	Jan 1/04	10	98	310	153	84	418	627	547
13	Feb 5/04	10	132	400	308	51	387	681	570
14	Mar 3/04	10	32	130	27	51	411	657	548
15	Apr 1/04	10	47	152	50	138	432	669	540
16	Apr 16/04	10	39	224	35	138	397	633	512

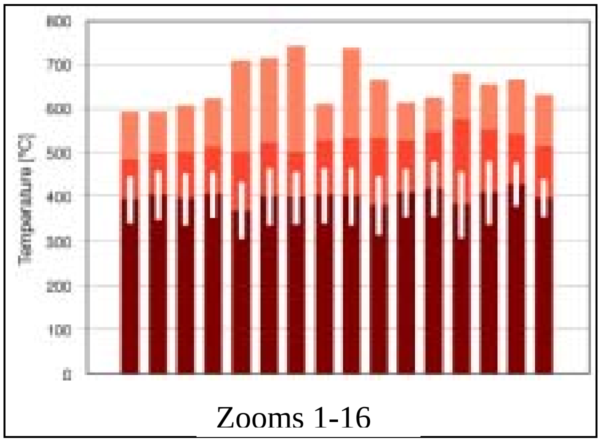


Figure 109: Trend of temperature for JM

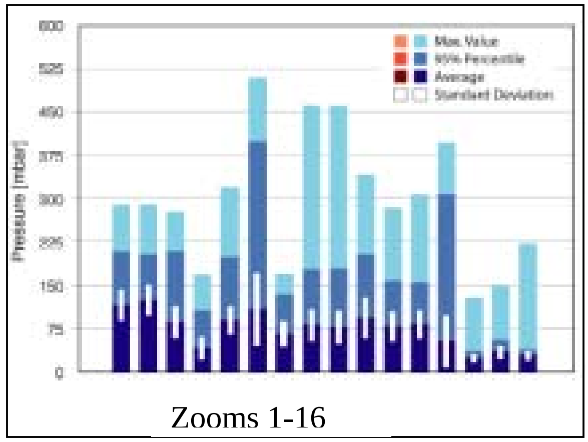


Figure 110: Trend of pressure for JM

Integral statistics across calendar years 2003-2004 are given in Table 35. The pressure and temperature frequencies for this integral period are shown in Figure 111. The episodic temperature duration frequencies are shown in Figure 112 and the fraction of normal pressure is shown in the pie chart in Figure 113.

Table 35: Integral statistics for the year 2003 for JM on LHD #820 (left side).

	Pressure (mbar)				Temperature (^oC)			
	Min.	Ave.	Max.	95%ile	Min.	Ave.	Max.	95%ile
inlet side	10	80	510	172	51	406	681	538
outlet side					3	333	765	474

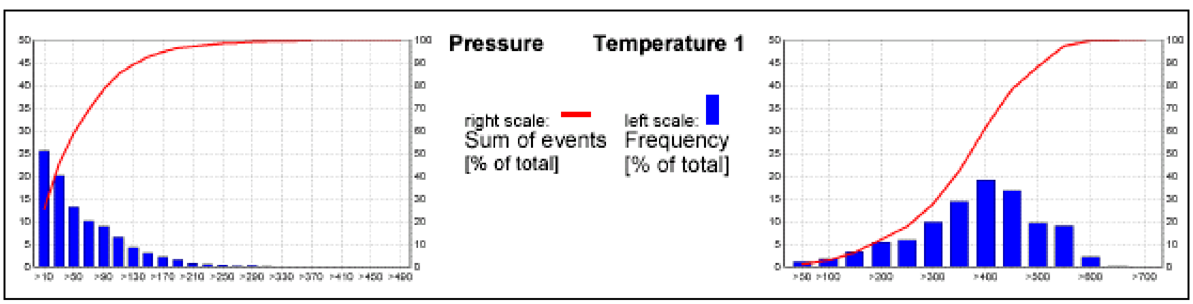


Figure 111: Pressure and temperature frequency distributions for JM on LHD #820 (left).

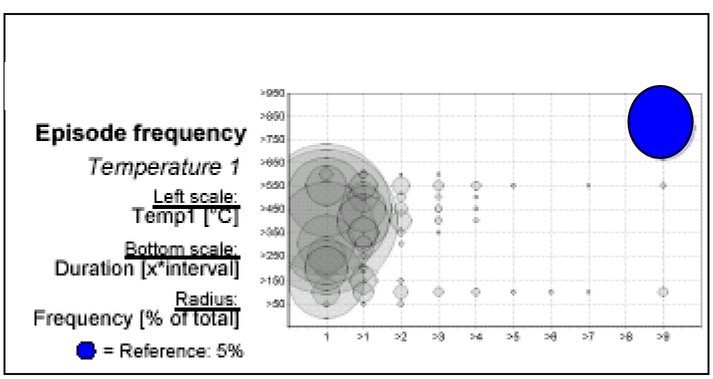


Figure 112: Temperature duration frequency distribution.

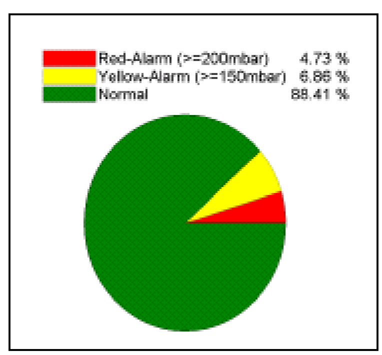


Figure 113: Pressure pie chart

9.8.2 Johnson Matthey (right side)

The Johnson Matthey filter, installed on the right side (off driver side) of LHD #820 on June 16/01, operated a total of 2343 hours until its removal on Jul 12/04. It was one of the most successful systems tested.

Routine tests

Thirteen routine tests were conducted on the right side and results are given in Table 36. The upstream and downstream smoke numbers averaged 6.3 and 1.6, respectively. However, if the 9+ downstream number is considered anomalous, then the average downstream is reduced to 0.9.

Table 36: Smoke numbers and target gas analyses for Johnson Matthey (right side) on an LHD.

		Upstream						Downstream				
Date	Meter	Sm No.	CO	NO	NO2	O2	T	Sm No.	CO	NO	NO2	O2
	(h)		(ppm)	(ppm)	(ppm)	(%)	(°F)		(ppm)	(ppm)	(ppm)	(%)
7/17/01	6086	6	133	398	22	9.3		0	130	435	10	9.4
1/3/02	6292						654	9+	8	485	47	9.5
6/28/02	6748	5	63	549	11	9.6		0				
9/30/02	6887	6	96	599	7	8.5	565	2	79	600	5	9
11/27/02	7097	7	135	308	27	14.5	329	2	122	313	22	14.9
2/3/03	7322	7	77	564	10	9.2	584	1	72	578	6	9.1
2/20/03	7390	7	110	373	15	9.1	433	1	87	396	5	8.5
3/26/03	7578	8	80	524	8	8.5	535	1	71	560	3	9
11/27/03	7916	6	148	498	6	9	512	0	84	499	4	10
1/26/04	8105	7	71	550	22	11.2	479	1	69	540	15	11.5
3/11/04	138	6	129	500	19	10.8	452	1	99	511	9	11.6
4/14/04	234	7	96	501	13	11.2	517	2	103	517	6	11.4
6/14/04	385	4	20	144	0	17.6	664	1	10	155	0	17.8
Ave.		6.3	96	459	13	10.7	520	1.6	78	466	11	11.0

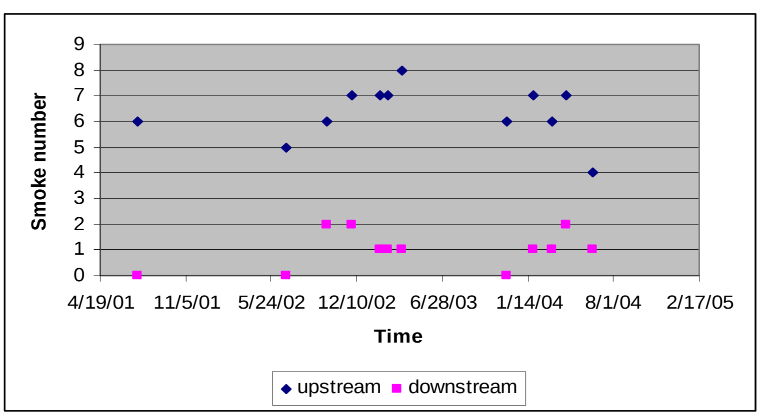


Figure 114: Smoke numbers as a function of time for Johnson Matthey (right side).

.

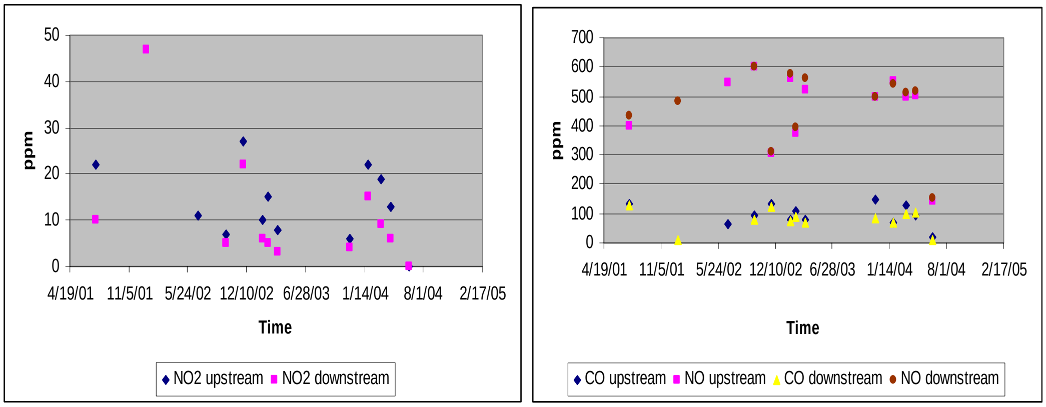


Figure 115: CO, NO, and NO_2 analyses for JM (right side)

Smoke numbers as a function of time are shown in Figure 114 (the 9+ anomalous downstream reading is not shown). No trends are evident. Target gas analyses are shown in Figure 115. No trends are evident.

Special tests

Three special tests were conducted on the JM (right side) filter and results are summarized in Table 37.

Table 37: Results of special tests on Johnson-Matthey (right side).

									Downstream					
Engine Speed[b]	Efficiency (%), eq [1] PAS	EC	O_2	CO	NO	NO_2	Smoke No.[a]	Upstream %Opacity	%Opacity	% O_2	CO_2	ppm CO	NO	NO_2
July/01 (0 hours)														
HI										15.9		110	263	10
LI				12	-37	92				18.8		75	240	2
TCS	99.9	98.3		2	-9	55	6.0/0			9.4		130	435	10
Snap A		97.8		17	-27	88								
May/02 (424 h)														
TCS	99.9	98.1		7	-8	71	7.0/0			8.9	9.0	92	457	9
LI	99.9	97.2		16	-27	56				18.3	2.0	137	149	31
HI	99.9	98.7		15	-21	82				15.4		120	235	8
June/04 (173 h)														
TCS	99.9	97.8				55					10.1			6.7
HI	99.8	98.1				65					4.5			7.7
LI		96.9				67					2.1			9.7

a:upstream/downstream

b: HI=High idle; LI= Low idle; TCS= Torque converter stall; Snap A= Snap acceleration

Note: a negative number in efficiency means downstream was greater than upstream.

The soot removal efficiencies were very good for all periods. Good NO_2 reductions were achieved.

Size distributions

Both upstream and downstream size distributions for the JM right side were similar to those reported above for the JM left side.

Statistical analyses

Data for the JM filter on LHD #820 (right=off-driver's side) are in Appendix C under INCO7-820R. This filter behaved very similarly to the JM filter on the left side (see above). The reader is referred to Appendix C for more details.

9.9 Arvin-Meritor System
(on LHD #111)

The Arvin-Meritor system was installed late in the Stobie project (May 7/04) in order to study the performance of a system using an active burner-assisted regeneration. Such a system was originally planned by the project team to be placed on a truck, but these plans were aborted because the truck was retired from service just prior to installation. Consequently, when it became possible to test a burner-activated system through Arvin-Meritor, the Stobie team decided to proceed with it on an LHD.

Considerable effort was expended by the Stobie team and by Arvin-Meritor personnel in doing the necessary safety checks before this system would be permitted underground. Additional effort was expended in installing the various components of the system, as described earlier in Chapter 7. It was with great optimism that the system was put into operation. It was very disappointing that the system did not perform well and in November/04 was removed from operation.

Routine tests

Four periods of routine testing were carried out on this system and results are summarized in Table 38. Results even in mid-August/04 showed relatively high smoke numbers in the downstream exhaust, indicating that filter efficiency for soot removal was being adversely

Table 38: Smoke numbers and target gas analyses for Arvin-Meritor on an LHD.

		Upstream						Downstream				
Date	Meter	Sm No.	CO	NO	NO2	O2	T	Sm No.	CO	NO	NO2	O2
	(h)		(ppm)	(ppm)	(ppm)	(%)	(^oF)		(ppm)	(ppm)	(ppm)	(%)
2/6/04	1478	5	21	1333	66	11.7	646	1	25	1232	39	12.5
8/12/04	3382	7	51	481	18	14.8	602	3	53	407	49	15.4
11/5/04	4148	7	54	492	27	14.9	624	3	10	437	30	15.4

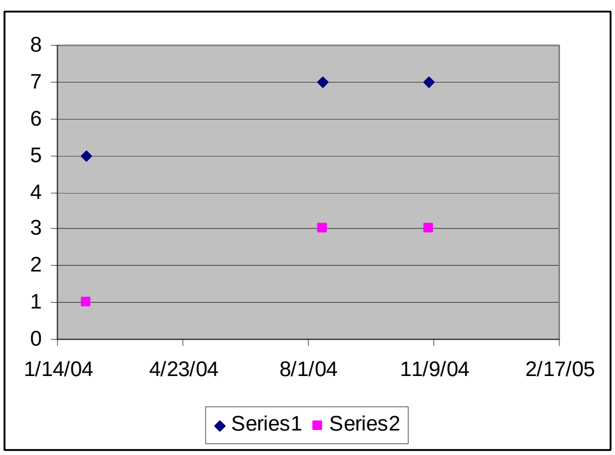


Figure 116: Smoke numbers as a function of time for the Arvin-Meritor system on an LHD. Series 1 is upstream; series 2 is downstream.

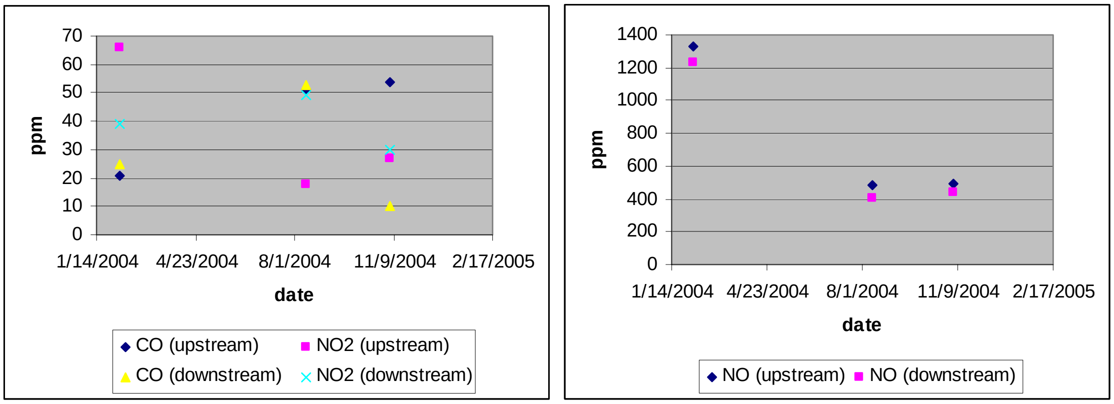


Figure 117: CO, NO and NO2 analyses as a function or time for the Arvin Meritor system.

affected. Trends as a function of time of these tests are given in Figures 116 and 117. The cause of the high readings of NO in Feb/04 is not known. If those readings are anomalous, then no trend of NO was evident. In the case of CO upstream, there appears to be an increasing trend, while NO_2 upstream shows a decreasing trend. These data show a likely poisoning of the Diesel Oxidation Catalyst placed downstream of the soot filter in Arvin-Meritor's system (see further discussion below).

<u>Special test</u>

One special test in June/04 was conducted soon after the system was installed. Results are shown in Table 39. It is clear that soot filtration efficiencies were good immediately after installation. The high CO reduction efficiency is due to Arvin-Meritor's use of a Diesel Oxidation Catalyst downstream of the filter. The DOC is designed to control CO and hydrocarbon emissions during the regeneration using the manifold burner. This DOC, which oxidizes NO to NO_2, is also responsible for the reduction of NO and the increase in NO_2 between upstream and downstream.

Table 39: Removal efficiencies of the Arvin-Meritor system on an LHD at 0 hours of operation.

									Downstream					
Engine Speed[b]	Efficiency (%), eq [1]						Smoke No.[a]	Upstream %Opacity	%Opacity	%		ppm		
	PAS	EC	O_2	CO	NO	NO_2				O_2	CO_2	CO	NO	NO_2
HI	99.8	96.8		98	50	-432					4.4	1	211	147
LI		95.6		100	74	-496					2.3	0	120	273
TCS	99.9	98.1		92	21	-324	6.2/1				6.6	4	386	95
Snap A								23.6	0.4					

<u>Size distribution</u>

As this system was removed from service after a short time of operation, size distributions are not given.

<u>Statistical analyses</u>

Data collected for this system is located in Appendix C under INCO3-111. Since the period of operation was short, no details are presented here.

Overall conclusion

The Arvin-Meritor system experienced considerable problems with the software used to control the burner cycling. This problem caused the system to be removed from further testing.

10. Comparisons of PFSs

It may be convenient to compare the various PFS performances with one another. To do this, the measurements reported above in this Chapter for each PFS performance are graphically presented for ease of comparison.

Particle concentrations

Special testing results for particle concentrations as measured by the PAS 2000 in the summer of 2002 are shown in Figure 118 and particle count measurements by the SMPS are shown in Figure 119.

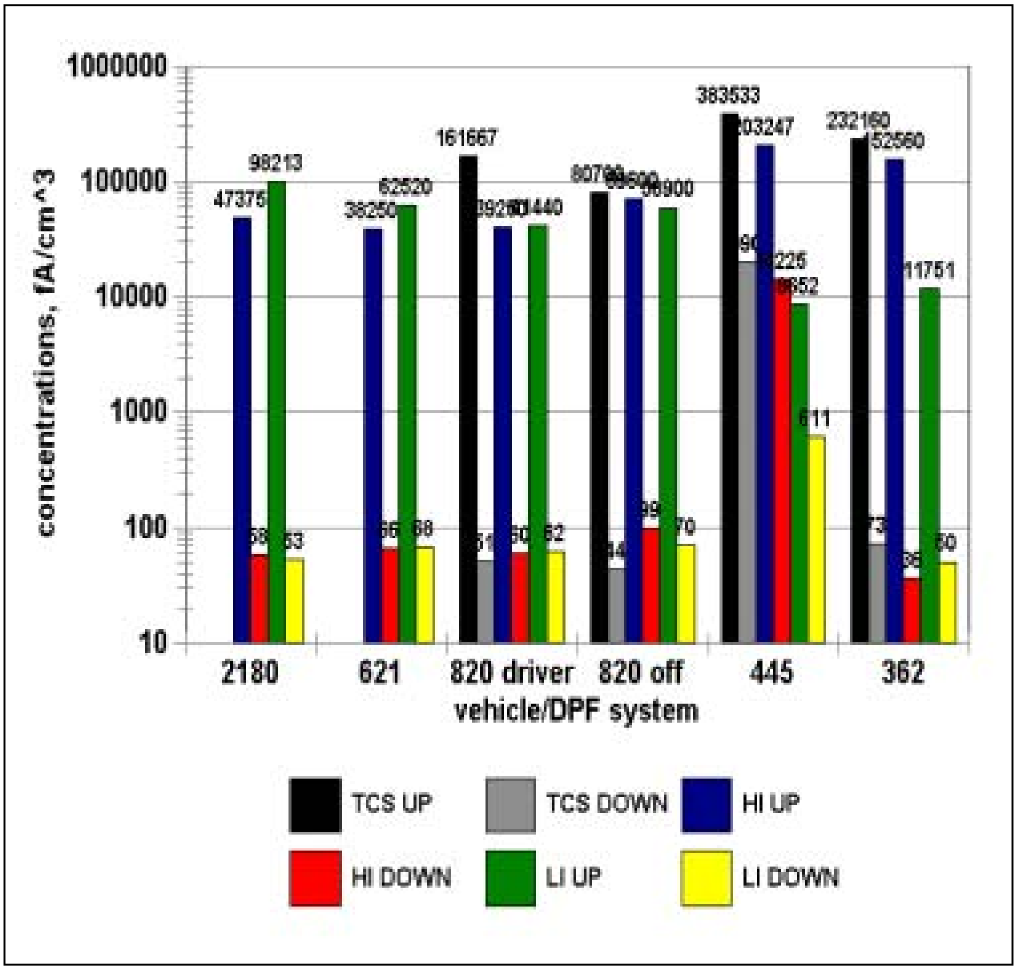


Figure 118: Average concentrations of polyaromatic hydrocarbons/elemental carbon particles measured via the PAS 2000 upstream and downstream of several engine conditions.

For PAS measurements, it can be seen that the highest concentrations of elemental carbon particles were observed in the exhaust of LHD #445 and LHD #362, which were powered by 11.1 liter DDEC engines. Under TSC the soot concentration for LHD #445 was considerably higher than for LHD #362 and this can be attributed to the higher fueling rate and power output of the LHD #445 engine. The concentrations of elemental carbon downstream of filters were comparable to each other, except for the ECS filter on LHD #445, which was somewhat higher.

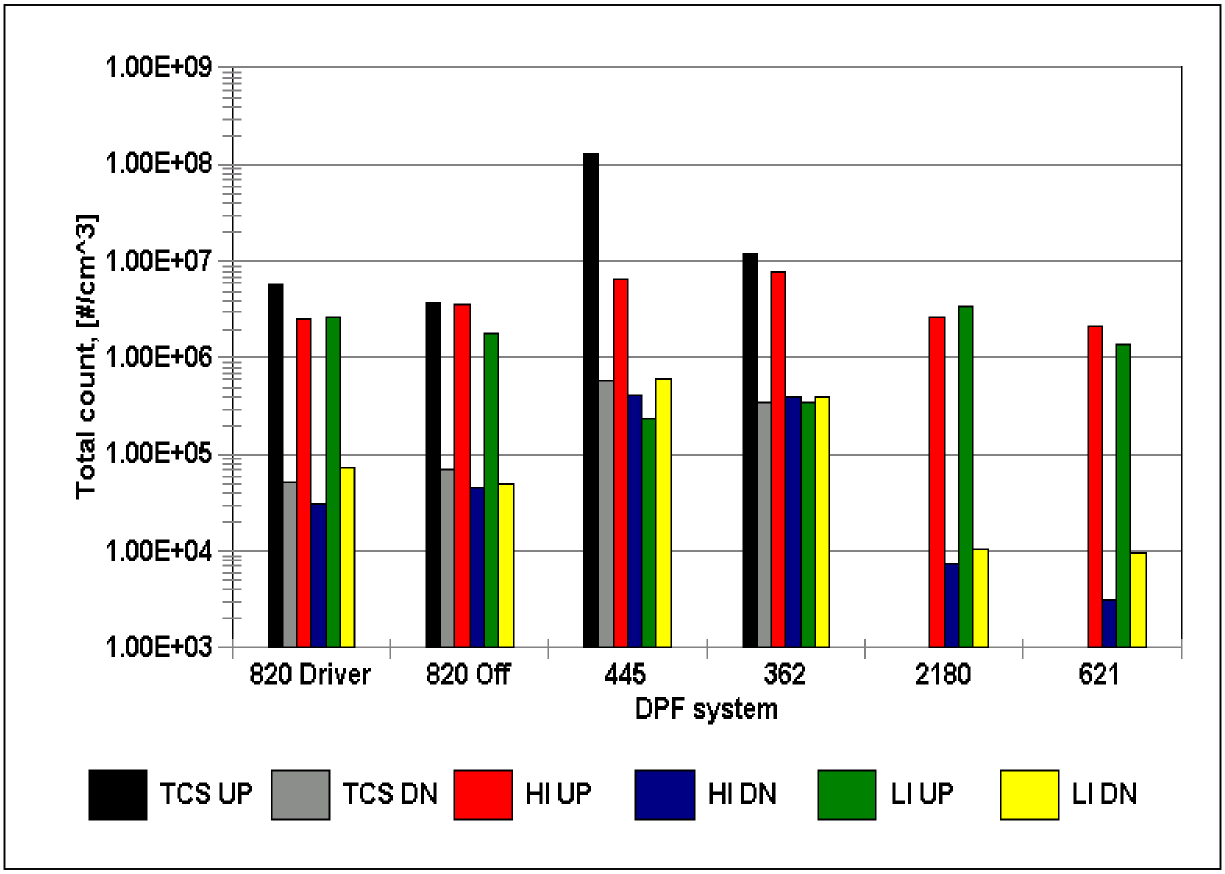


Figure 119: Particle counts measured in summer 2002 via the SMPS upstream and downstream of various engine conditions.

For the SMPS measurements shown in Figure 119, it is clear that the highest count concentration of particles upstream occurred for LHD #445 and #362 under the TSC and high idle conditions. Under low idle, however, the LHD #820 resulted in higher upstream counts. The low idle downstream particle counts for LHD#820 (JohnsonMatthey filter) were lower than the downstream counts for low idle for either the LHD#445 (ECS filter) or LHD #362 (Engelhard filter).

Comparison of the light duty vehicle (#2180 and #621) showed exceptionally low concentrations downstream of the ECS and DCL filters.

Target gases

Figure 120 shows CO concentrations under three different engine conditions. It should be noted that two different ECOM analyzers were used.

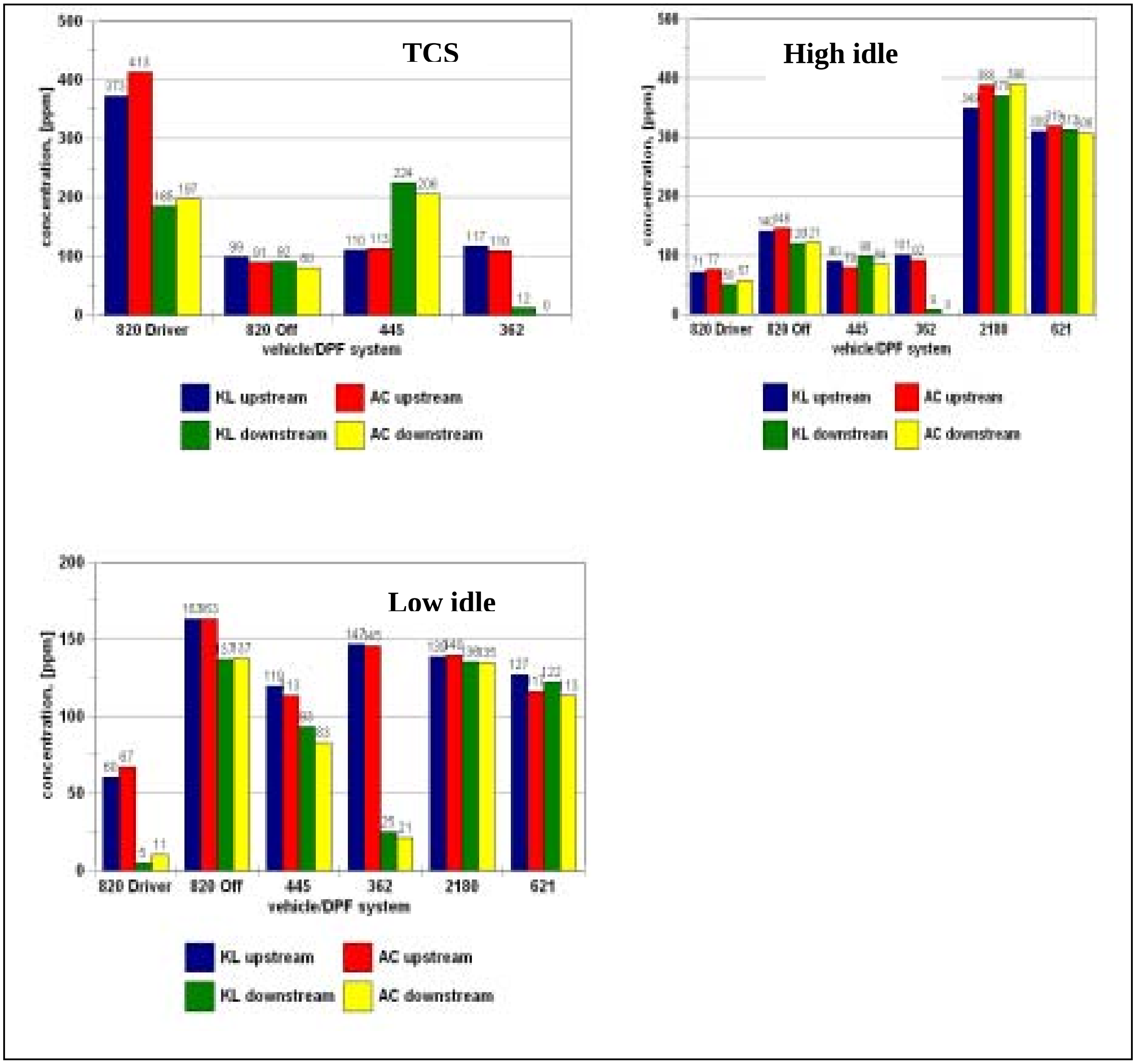


Figure 120: CO concentrations upstream and downstream of filters under TCS (left) and HI (right)

The measurements showed that concentrations of CO downstream of the Engelhard filter installed on LHD #362 were reduced by more than 89.5 percent at TCS and HI conditions. The results showed an unexpected increase in CO concentration downstream of ECS filter at TCS condition. It can be speculated that DPF regeneration during measurements caused this increase. The JM filter installed on the driver side of Deutz engine on LHD #820 reduced the exhaust CO concentrations by up to 91.7 percent depending on engine operating conditions. Surprisingly, JM unit installed on the off side of Deutz engine was not nearly as efficient as the one on driver side in removal of CO. The other DPFs did not exhibit significant effects on the CO concentrations.

NO concentrations for TSC, HI and LI conditions are compared in Figure 121. Only the ECS filter on LHD #445 was significantly affected, showing an increase of approximately 40% between upstream and downstream.

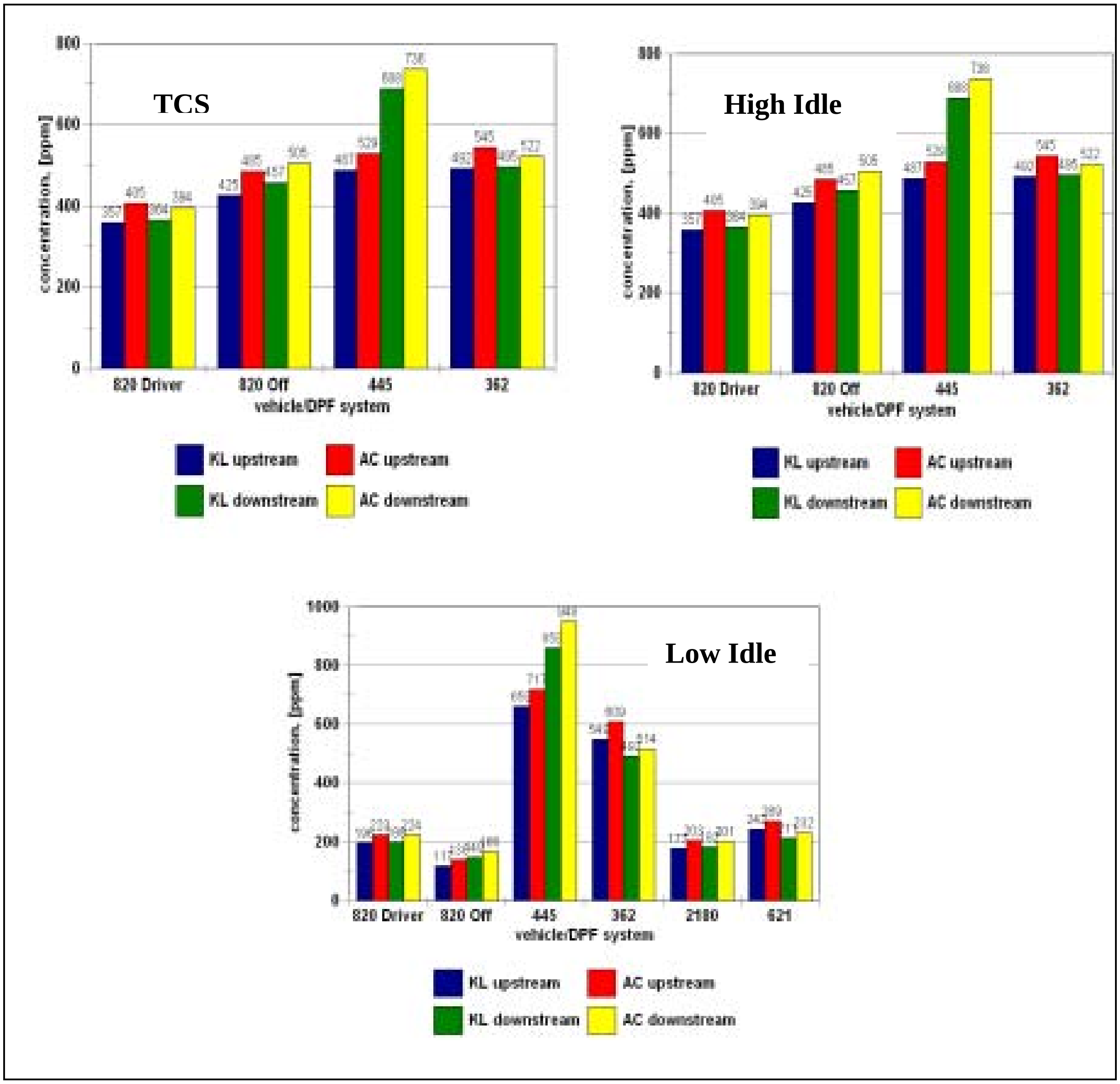


Figure 121: Concentrations of NO upstream and downstream for various engine conditions.

NO_2 concentrations for various engine conditions are shown in Figure 122. Only the Engelhard filter on LHD #362 showed increases in downstream NO_2 under TCS and low idle conditions.

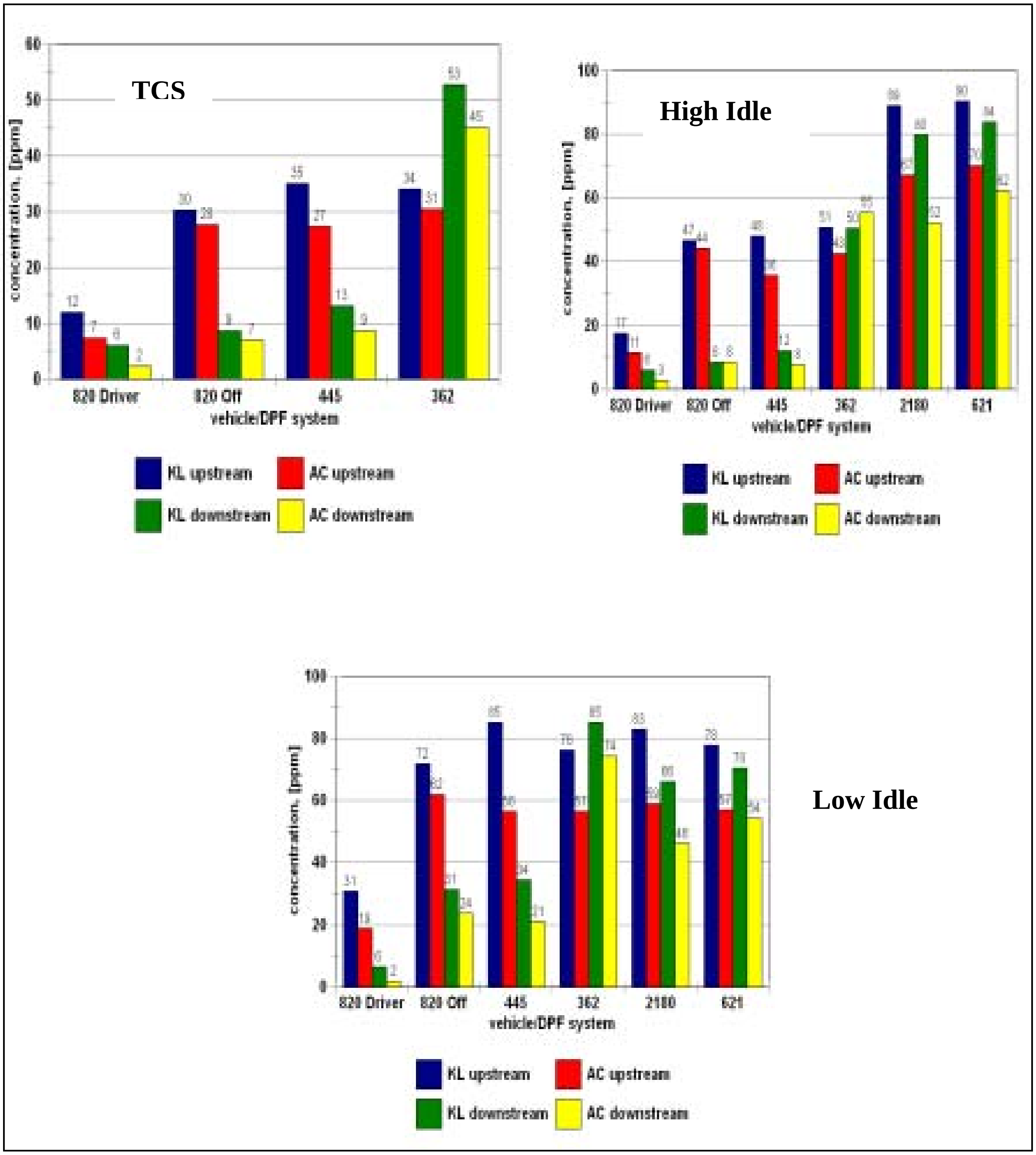


Figure 122: Comparisons of NO_2 concentrations for various engine conditions.

11. INDUSTRIAL HYGIENE MEASUREMENTS

11.1 Introduction

In the case of the Stobie Project, performing and interpreting industrial hygiene measurements were compromised by the fact that the diesel units and particulate filter systems being tested were being used in normal mine operation. Other non-test vehicles without PFSs were usually operating around the test vehicles. Accordingly, even though IH measurements were conducted and neighbouring vehicles were noted, the results obtained must be interpreted as having the possibility of interference from non-filtered diesel vehicles.

The procedures were carried out by personnel trained in performing IH measurements as part of ventilation monitoring. Certain test vehicles were operated without the PFS installed to give a baseline; these vehicles were then subjected to similar tests with the PFS installed. Generally the IH work was conducted during day shift (some also on afternoon shift) with the samples being representative of conditions on that shift.

11.2 Analysis of soot in mine air

There exist several methods to analyze for DPM in mine air. The two methods relevant to the Stobie project were the RCD method and the Thermal-optical method, the essentials of which are given below.

11.2.1 The RCD method

The Respirable Combustible Dust (RCD) method was developed in Canada (Hews and Rutherford, 1973; Rutherford and Elliot, 1977; Maskery, 1978) and has been routinely used by the mining industry in Canada to estimate DPM. Respirable dust in mining operations can come from mineral dusts, oil mists from pneumatic equipment and diesels. This is schematically shown in Figure 123.

All of the respirable aerosol is collected by passing mine air at a controlled and known flowrate through a cyclone to reject coarse aerosol and then through a 25 or 37 mm diameter silver membrane having a 0.8 µm pore size (alternatively, a pre-fired glass fiber filter can be used),which collects the respirable particulate. The amount of this material is determined by weighing the membrane before and after collection.

The silver membrane is then subjected to a controlled combustion at 400^{o}C for up to two hours. The amount of mass lost is taken to be the respirable combustible dust. A factor is available to correct for the expected loss of the membrane itself.

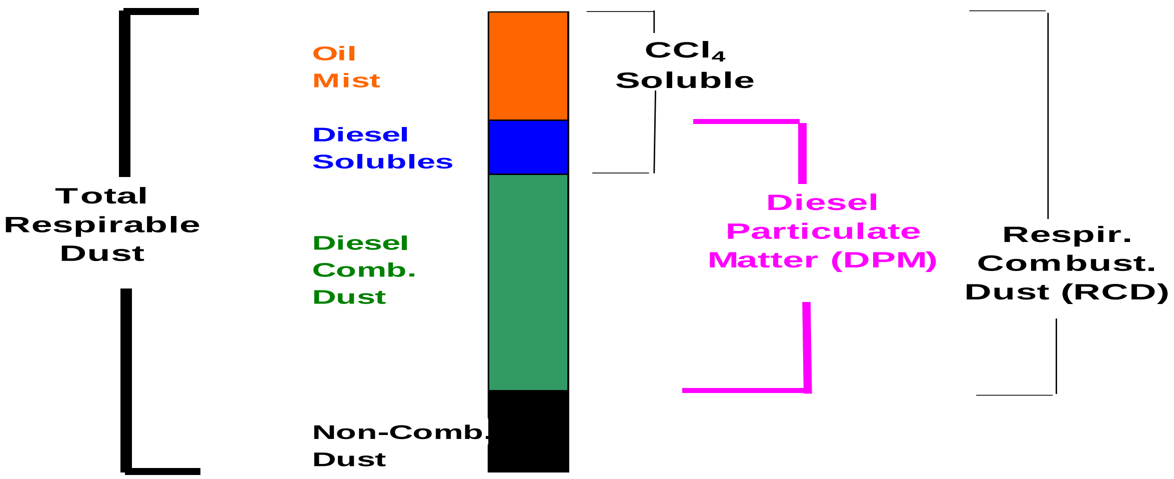


Figure 123: Schematic diagram showing the relationships between components of total respirable dust.

It is important to recognize that the RCD method analyzes respirable material that may arise from diesels and pneumatic equipment. Generally DPM is assumed to be approximately two-thirds of the RCD under typical mining conditions.

11.2.2 The Thermal-Optical Method

Unlike the RCD method, the thermal optical method distinguishes between hydrocarbons and elemental carbon. While also not able to analyze DPM per se (because hydrocarbons from diesels cannot be easily separated from hydrocarbons from oils), the elemental carbon portion of the analysis is a very good indicator of the major portion of DPM. Because the method is able to detect very small amounts of elemental carbon with high precision, this method is likely going to be the basis for new occupational exposure limits.

The method, termed the elemental carbon method, was pioneered by the U.S. NIOSH and is reported as method 5040 (Birch and Cary, 1996; NIOSH, 1999). The sampling of air is conducted using a similar technique as used in the RCD method, except that the filter material is pre-combusted ultra-pure quartz. A specific sized portion of the loaded filter is punched for analysis and inserted into a special oven.

As a preliminary step, the sample is oriented so that a laser beam shines through it and the filter's transmittance is monitored by photodiode detector. The first stage of analysis is done in an oxygen free helium atmosphere by increasing the oven temperature in four steps to 900^{o}C. During this heating, mineral carbonates will decompose to evolve carbon dioxide and the hydrocarbons (from diesels or from oils) will volatilize and are oxidized to carbon dioxide by granular manganese dioxide at 870^oC. All of the carbon dioxide is then converted to methane, which is subsequently analyzed by a flame ionization detector. A small portion of the hydrocarbons present in the sample may pyrolyze to form a carbon “char”. This char can be detected by a reduction in the transmittance of the laser beam shining through the sample.

The temperature is then reduced to 525^oC and a 2% oxygen-helium mixture is introduced to the sample, which again in heated in four steps to 900^oC. In the presence of oxygen the elemental carbon burns to form carbon dioxide. Any char that was formed in the first stage hydrocarbon removal is corrected for by allowing the laser transmittance to regain its pre-first-stage value before beginning to integrate the elemental carbon signal. As before, the CO_2 is converted to methane for quantitative detection.

The method is usually calibrated by injecting a known amount of methane into the oven assembly. Excellent reproducibility has been obtained by NIOSH. CANMET now has the capability to analyze samples according to this method.

11.3 Specific procedures

Typically a total of 10 air samples were taken for a test vehicle on an IH day. The distribution of samplers were:

- 3 for RCD analysis using a 25mm silver membrane and a pumping rate of 1.7 liters/min with a cyclone ahead of the sampler. These samplers were located in a basket just behind the vehicle operator;
- 3 for EC analysis using a 37mm filter and a pumping rate of 2 liters/min with a cyclone ahead of the sampler. These samplers were also located in a basket (the same as the one for the RCD samplers) just behind the vehicle operator;
- 2 for EC analysis located at the fresh air supply;
- 2 for EC analysis located at the exhaust air outtake.

Flowrates on the pumps were set at the beginning of the shift and were checked for the same setting at the end of the sampling period. The flows were calibrated with a Gillian Flow Calibrator. All results reported had constant flowrates over the sampling periods.

Generally the samplers and pumps were started at the vehicle location at 8:30AM, then the air supply samplers and pumps were started at 9:15AM, the samplers at the exhaust air outtake were started at 9:25AM. The IH personnel recorded the work being performed by the vehicle and the occurrence of any other diesel vehicles nearby. The exhaust air and fresh air supply samplers were typically stopped at a little before 3PM and the vehicle basket samplers stopped just after 3PM.

Air flow measurements in the stope were also taken.

11.4 Results

Table 40: IH sampling results for Tractor #2180 without and with ECS filter.

#2180 & ECS	Date	Duty	Sampling time (h)	mg/m^3			
				Supply Air (EC)	At vehicle (RCD)	(EC)	Exhaust Air (EC)
WITHOUT							
58810 CFM	6/25/01	Per.Car	4.2	0.02	<0.13	0.07	0.09
	6/25/01	Per.Car	4.2	0.01	<0.13	0.11	0.08
	6/25/01	Per.Car	4.2	0.01	<0.13	0.07	0.08
WITH ECS							
94000 CFM	3/31/04	Per.Car	3.3	0.01	<0.14	0.04	0.02
"	3/31/04	Per.Car	3.3	0.04	<0.12	0.06	0.007
"	3/31/04	Per.Car	3.3	--	<0.15	0.06	--
99500 CFM	4/1/04	Per.Car	3.0	0.008	<0.15	0.05	0.08
"	4/1/04	Per.Car	3.0	0.00	<0.15	0.04	0.08
"	4/1/04	Per.Car	3.0	--	<0.15	0.05	--

Note: Per.Car means Personnel Carrier

The first comment that can be made about the data in Table 40 is that the supply air was very low in EC for all times sampled. The EC samples taken at the vehicle without the filter installed averaged 0.08 mg/m^3 and with the ECS filter installed averaged 0.05 mg/m^3. This showed a reduction in EC for the filter, even at very low soot levels being produced by the engine in this service. As expected, the exhaust air showed a minor increase in soot over the supply air. The RCD measurements showed a lack of detection when the soot (dust) levels were very low.

These results show good performance of the ECS filter on the #2180 Tractor.

Table 41: IH sampling results for #621 Tractor with and without DCL filter.

#621 & DCL	Date	Duty	Sampling time (h)	mg/m^3			
				Supply Air (EC)	At vehicle (RCD)	(EC)	Exhaust Air (EC)
WITHOUT							
39700 CFM	2/25/02	Per.Car	2.3	0.00	<0.3	0.13	0.11
"	2/25/02	Per.Car	2.3	0.00	<0.3	0.09	0.07
"	2/25/02	Per.Car	2.3	--	<0.3	0.10	--
44000 CFM	2/26/02	Per.Car	3.9	0.00	0.13	0.11	0.11
"	2/26/02	Per.Car	3.9	0.00	0.18	0.10	0.10
"	2/26/02	Per.Car	3.9	--	0.25	0.09	--

WITH DCL							
56700 CFM	3/26/04	Per.Car	4.1	0.00	<0.12	0.03	0.01
“	3/26/04	Per.Car	4.1	0.00	<0.12	0.02	0.009
“	3/26/04	Per.Car	4.1	--	<0.12	0.03	--
64500 CFM	3/29/04	Per.Car	3.6	0.00	<0.14	0.04	0.00
“	3/29/04	Per.Car	3.6	0.00	<0.14	0.04	0.00
“	3/29/04	Per.Car	3.6	--	<0.14	0.04	--

Note: Per.Car means Personnel Carrier

The results given in Table 41 show undetectable EC in the fresh air supply. For the samples taken on the vehicle, the “without” filter EC had an average of 0.10 mg/m^3 and the “with” DCL filter had an average of 0.03 mg/m^3, which shows good EC reduction by the filter even at the very low EC concentrations yielded by the engine. The exhaust air EC, when testing the “without” condition, was somewhat higher than the exhaust air for the “with” condition; this may have been caused by noticeably more nearby diesel equipment operating during the Feb/02 testing. For the most part the RCD measurements were consistent with the EC measurements; the only significant departure between these results was for one sample of RCD on 2/26/02 that analyzed 0.25 mg RCD/m^3. No reason for this high reading is known.

Table 42: IH sampling results for #820 LHD with and without Johnson Matthey filters.

#820 LHD & J-M	Date	Duty	Sampling time (h)	mg/m^3			
				Supply Air (EC)	At vehicle (RCD)	(EC)	Exhaust Air (EC)
WITHOUT							
86700 CFM	7/5/01	Tram(10)	3.3	0.01	0.17	0.12	0.04
“	7/5/01	Tram(10)	3.3	0.00	0.20	0.12	0.05
“	7/5/01	Tram(10)	3.3	0.00	0.28	0.13	0.05
82200 CFM	7/5/01	Tram(17)	3.2	0.00	<0.15	0.08	0.10
“	7/5/01	Tram(17)	3.2	0.00	<0.15	0.07	0.10
“	7/5/01	Tram(17)	3.2	0.00	<0.15	0.05	0.10
WITH DCL							
30300 CFM	3/17/04	Muck(5)	4.0	0.00	<0.12	0.04	0.04
“	3/17/04	Muck(5)	4.0	0.00	<0.12	0.05	0.04
“	3/17/04	Muck(5)	4.0	--	0.17	0.04	--
66900 CFM	3/18/04	Tram(5)	4.1	0.007	<0.12	0.04	0.05
“	3/18/04	Tram(5)	4.1	0.003	0.14	0.04	0.04
“	3/18/04	Tram(5)	4.1	--	<0.12	0.04	--

Note: Tram (10) means carrying 10 buckets over the sampling period.

The IH data shown in Table 42 indicates that the supply air EC was very low over all sampling periods. During the first period of sampling on 7/5/01 (8-4 shift) the EC at the vehicle was higher than for the second period (12-8 shift). This is likely due to the presence of additional nearby diesel equipment during the 8-4 shift. The EC data at the vehicle “with” the Johnson Matthey filters in place showed modest improvement over the “without” condition. The

RCD results at the vehicle were, for the most part, consistent with the EC readings, but, as noted previously, the detectability and precision of the RCD was inferior to the EC. The exhaust air over all periods was, as expected, marginally higher than the fresh air supply.

It is concluded that the JM filters were doing a good job on soot reduction on this LHD.

Table 43: IH sampling results for #213 LHD with and without ECS Combifilters.

#213 LHD & ECS	Date	Duty	Sampling time (h)	mg/m³			
				Supply Air (EC)	At vehicle (RCD)	(EC)	Exhaust Air (EC)
WITHOUT							
24580 CFM	4/2/05	Tram(60)	6.7		0.35	0.045	0.165
"	4/2/05	Tram(60)	6.7		0.35	0.119	
"	4/2/05	Tram(60)	6.7		0.25	0.109	
39750 CFM	4/3/05	Tram(60)	7.5		0.39	0.109	0.082
"	4/3/05	Tram(60)	7.5		0.39	0.107	
"	4/3/05	Tram(60)	7.5		0.33	0.118	
WITH ECS							
62600 CFM	3/23/04	Tram(30)	4.3	0.00	<0.12	0.005	0.002
"	3/23/04	Tram(30)	4.3	0.00	<0.12	0.005	0.005
"	3/23/04	Tram(30)	4.3	--	<0.12	0.004	--
63500 CFM	3/24/04	Tram(50)	4.3	0.001	<0.14	0.01	0.006
"	3/24/04	Tram(50)	4.3	0.002	<0.14	0.01	0.008
"	3/24/04	Tram(50)	4.3	--	<0.14	0.01	--

Note: Tram (10) means carrying 10 buckets over the sampling period.

The results shown in Table 43 for LHD #213 with and without ECS filters indicate a significant reduction in EC was obtained with the ECS filter. The results for the "without" filter operation showed fairly high RCD with the comparable EC, being from one-third to one-fourth of the RCD. This difference between the RCD and EC may be explained by the presence of more than normal pneumatic oils in the area. These oils report to RCD, but do not get analyzed by the EC method.

12. ASH RESIDUE ANALYSES

Ash samples were collected from several filters after regeneration. These samples were submitted for chemical analysis and morphology to Inco Technical Services Limited in Mississauga.

12.1 Analytical techniques

Carbon was obtained on an as-received sample by combustion using a Leco instrument.

Elements Cu, Ni, Co, Fe, Ca, Al, Mg, Si, As, Pb, Zn, Mn, Cr, P, B, Ag, Au, Ba, Be, Bi, Cd, Ce, Ga, Ge, Hf, Hg, In, La, Li, Mo, Nb, Nd, Pd, Pr, Pt, Re, Rh, Ru, Sb, Se, Sn, Sr, Ta, Te, Th, Ti, Tl, U, V, W, Zr, Na, K, Rb, Cs, Sc, Y, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm and Yb were analyzed by complete digestion followed by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) on the resulting solution. Digestion was accomplished by weighing a known amount of the sample and digesting it with 1 volume of nitric acid plus 2 volumes of hydrochloric acid at $95^{o}C$ for one hour. After cooling to room temperature the solution was diluted to 50mL with ultrapure de-ionized water and centrifuged. To 0.5mL of the resulting solution, 200µL of nitric acid was added and then diluted to 10mL with ultrapure de-ionized water. The ICP/MS unit was a Perkin-Elmer Sciex Elan DRC2 model.

Elements Fe, Ca, S, Zn and P were obtained by complete digestion of a known weight of the sample followed by conventional ICP analysis.

Carbonate analysis was done by boiling a weighed amount of the sample in sulfuric acid. The evolved gas was trapped, its volume measured and then the gas was passed through a caustic scrubber several times, each time returning to the volume measuring chamber. The change in volume after scrubbing is calculated as carbon dioxide and converted to carbonate in the original sample.

Low magnification optical images were taken using a Wild Leitz M8 Zoom Stereomicroscope. SEM secondary electron images at 100X magnification were obtained using a JEOL 6400 Scanning Electron Microscope with a tungsten filament, for which the ash particulate was placed on an aluminum stub using two sided sticky tape and sputtered with gold-platinum to achieve a conducting surface. Higher resolution secondary electron images were done using an Hitachi S5200 cold field emission Scanning Electron Microscope.

12.2 1st Sampling Trial

It should be understood that obtaining samples of ash that is built up inside the filter media after regeneration is not a simple matter. The Stobie team tried to accomplish this initially by trying to blow back the ash into a special clean collection can following regeneration of the filter.

The procedure used to attempt this sampling was limited to filters that fit onto the ECS CombiClean regenerating station described previously in Chapter 7 because this unit allowed the best chance of capturing ash into a special can that attached to the unit. Filters from DCL, ECS and Arvin-Meritor were regenerated as per normal procedure (note that for regeneration the filters are inverted so that the filters' intakes were next to the electrical heating element at the bottom of the holder). Initially the soot-laden filters were cleaned of soot from around the flanges as much as possible. Then the filters were put through their normal regeneration. Finally, the vacuum was turned on and air was blown from the top (reverse from the way the filter operated during soot filtration) to blow out the ash that had resulted from the soot burning.

The problem encountered was that considerable unburned soot was also blown out. This soot probably resulted from non-uniform regeneration temperatures where portions of the honeycomb cells containing soot did not reach adequate ignition temperatures. Figure 124 shows the ECS trap after being treated with seven "cookings" and then being tapped on the table. The black material on the table resembles very fine pencil lead and obviously the material comes directly out of the honeycomb cells in the filter. Since this material is black, one would assume that it is unburned soot. Any white ash that would be in this material would be overwhelmed by the amount of black soot.

Despite these problems, the samples were examined to see what could be learned.

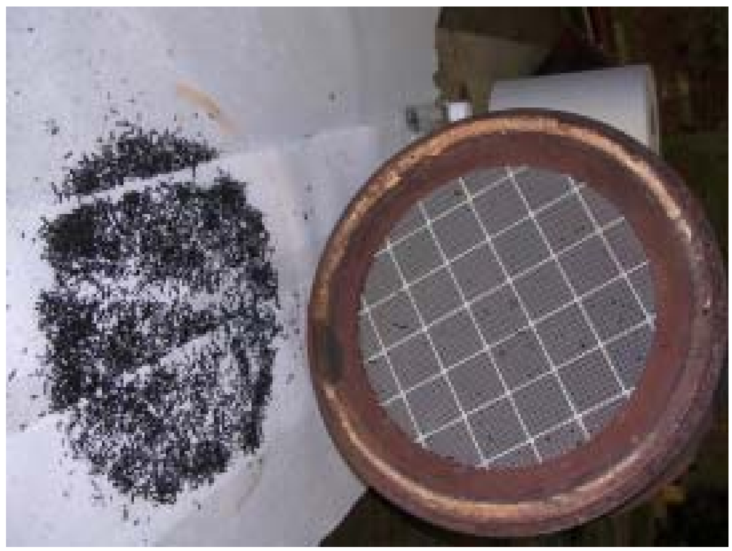


Figure 124: Material falling out of the ECS filter after seven regeneration cookings

2.2.1 Results

Five ash samples were examined and assigned identification numbers:

Ash from the DCL filter on #017 Tractor;	Lab ident.# 76937
Ash from the ECS filter on #3013 Tractor;	Lab ident.# 76938
Ash from the ECS filter (a) on #213 LHD;	Lab ident.# 76939
Ash from the ECS filter (b) on #213 LHD;	Lab ident.# 76940
Ash from the Arvin-Meritor filter on #111 LHD	Lab ident.# 76943

Bulk chemical analyses of the samples are given in Table 44. It should be noted that one of the samples listed in the Table (Lab Ident.# 76942) has no results because of insufficient sample mass available; another sample (Lab Ident.# 76941) came from a filter that Inco was operating outside the Stobie Project.

The first thing that is evident is that the carbon analyses for all samples are generally high and this is undoubtedly due to the contamination of the ash samples by unburned soot (see above).

The optical and scanning electron microscope images are complex because of the unburned soot contamination. In some of the photographs the distinction between soot and ash is evident. However, in the highest magnification photographs it is not clear whether the agglomerated particles are unburned soot (many of them probably are) or are ash that has taken the same agglomerated morphology as the parent soot. Because of the similarity of most of the samples, a typical high carbon sample of ash from the DCL filter is shown below. Another sample containing the lowest amount of carbon, from the ECS filter, is also shown.

Table 44: Bulk chemical analyses of selected ash samples.

Inco
Report of Analysis
Inco Technical Services Limited **Research and Development**

Description: Analysis of Diesel Particulates
Project #: Analysis of Diesel Particulates
Date: SP1-3174 55809

LIMS ID	05-03-17 14:08	C	CO3	Fe	Ca	S	Zn	P	Cu (MS)	Ni (MS)	Co (MS)	Fe (MS)	Ca (MS)	Al (MS)	Mg (MS)	Si (MS)
		%	%	%	%	%	%	%	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
78937	Stobie 017 tractor DCL	83.0	<0.5	4.79	6.54	2.20	3.80	3.87	900	370	20.6	>10000	>10000	1600	1930	2820
78938	Stobie 3013 Tractor ECS	11.0	<0.5	3.70	21.5	4.70	7.32	11.0	1716	540	17.7	>10000	>10000	3250	6900	2780
78939	Stobie 213 Trap #1 ECS	88.0	<0.5	11.1	3.19	2.10	1.84	1.81	8828	1230	45.7	>10000	>10000	3270	3030	1800
78940	Stobie 213 Trap #2 ECS	74.0	<0.5	5.62	0.86	0.90	0.48	0.32	3700	840	46.9	>10000	6803	2510	1600	1540
78941	107 2934.5 HRS	31.0	<0.5	17.2	11.9	3.80	5.31	5.81	2105	1060	45.3	>10000	>10000	3400	8690	4140
78942	111 Before	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes
78943	111 After	41	<0.5	6.59	10.6	7.00	4.19	3.46	1200	2190	41.3	>10000	>10000	2470	4440	2690

		As (MS)	Pb (MS)	Zn (MS)	Mn (MS)	Cr (MS)	P (MS)	B (MS)	Ag (MS)	Au (MS)	Ba (MS)	Be (MS)	Bi (MS)	Cd (MS)	Ce (MS)	Ga (MS)
		µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
78937	Stobie 017 tractor DCL	7.84	64.8	>10000	31.2	149	>10000	<5	0.87	2.5	39.8	<0.5	0.205	11.07	2.61	1.02
78938	Stobie 3013 Tractor ECS	32.7	843	>10000	152	278	>10000	<5	0.4	0.9	81.7					
78939	Stobie 213 Trap #1 ECS	13.2	159	>10000	61.2	385	>10000	<5	0.86	0.8	30.3	<0.5	1.65	10.34	6.81	1.29
78940	Stobie 213 Trap #2 ECS	4.33	54.6	4040	29.7	173	3200	<5	0.45	<0.5	48.6	<0.5	0.87	8.19	4.35	0.9
78941	107 2934.5 HRS	92	814	>10000	164	314	>10000	<5	0.5	<0.5	66.2	<0.5	6.11	10.39	7.28	1.72
78942	111 Before	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes
78943	111 After	6.13	183	>10000	59	1317	>10000	<5	3.49	<0.5	68.2	<0.5	0.53	6.63	5.05	1.24

		Ge (MS)	Hf (MS)	Hg (MS)	In (MS)	La (MS)	Li (MS)	Mo (MS)	Nb (MS)	Nd (MS)	Pd (MS)	Pr (MS)	Pt (MS)	Re (MS)	Rh (MS)	Ru (MS)
		µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
78937	Stobie 017 tractor DCL	<1	0.02	<0.05	0.012	1.32	4.97	84.3	0.38	1	0.9	0.24	0.3	<0.005	<0.2	<0.2
78938	Stobie 3013 Tractor ECS		0.07	<0.05	0.031	4.83	7.22	44.9	3.51	1.67	1.9	0.42	1.4	<0.005	<0.1	<0.1
78939	Stobie 213 Trap #1 ECS	<1	0.02	<0.05	0.023	2.54	4.44	54.1	1.15	1.9	0.7	0.48	<0.1	<0.005	0.1	<0.1
78940	Stobie 213 Trap #2 ECS	<1	0.11	<0.05	0.036	1.88	2.71	23.5	0.74	1.42	1.5	0.35	<0.1	<0.005	<0.1	<0.1
78941	107 2934.5 HRS	<1	0.05	<0.05	0.037	3.74	12.48	61.2	3.87	2.87	3.5	0.87	0.7	0.007	<0.1	<0.1
78942	111 Before	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes
78943	111 After	<1	0.03	<0.05	0.014	2.43	14.55	36.4	1.74	1.92	0.7	0.41	<0.2	0.009	<0.2	<0.2

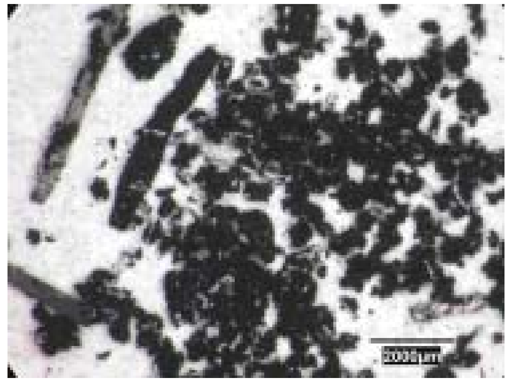
		Sb (MS)	Se (MS)	Sn (MS)	Sr (MS)	Ta (MS)	Te (MS)	Th (MS)	Ti (MS)	Tl (MS)	U (MS)	V (MS)	W (MS)	Zr (MS)	Na (MS)	K (MS)
		µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
78937	Stobie 017 tractor DCL	4.36	3.89	53.8	27.2	0.01	<0.05	0.33	91	<0.05	0.416	41.3	6.2	0.74	2000	522
78938	Stobie 3013 Tractor ECS	3.85	2.93	48.8	79.1	0.01	0.2	0.43	164	<0.05	0.815	2973	37.1	3.53	3100	1211
78939	Stobie 213 Trap #1 ECS	1.41	0.9	20.6	17.4	<0.01	0.19	0.39	94	<0.05	0.388	200	26.7	0.64	3200	741
78940	Stobie 213 Trap #2 ECS	0.48	0.75	7.02	7.85	<0.01	0.11	0.31	164	<0.05	0.202	16.3	5.57	2.94	1400	607
78941	107 2934.5 HRS	8.17	4.94	71.4	45.6	0.01	0.59	0.69	180	<0.05	0.633	3694	65.3	2.33	6900	3348
78942	111 Before	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes
78943	111 After	2.46	2.62	31.9	57.9	<0.01	0.19	0.58	143	<0.05	0.579	35.5	28.8	0.87	8500	794

		Rb (MS)	Cs (MS)	Sc (MS)	Y (MS)	Sm (MS)	Eu (MS)	Gd (MS)	Tb (MS)	Dy (MS)	Ho (MS)	Er (MS)	Tm (MS)	Yb (MS)
		µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
78937	Stobie 017 tractor DCL	1.89	0.059	0.8	1.15	0.19	0.03	0.19	0.03	0.14	0.02	0.06	0.01	0.04
78938	Stobie 3013 Tractor ECS	1.71	0.505	1	1.81	0.36	0.07	0.83	0.05	0.24	0.04	0.11	0.02	0.13
78939	Stobie 213 Trap #1 ECS	3.45	0.151	0.8	1.81	0.38	0.06	0.35	0.05	0.29	0.05	0.13	0.02	0.07
78940	Stobie 213 Trap #2 ECS	3.81	0.187	0.7	1.11	0.22	0.04	0.28	0.03	0.18	0.02	0.07	0.01	0.05
78941	107 2934.5 HRS	3.07	0.874	1.3	2.28	0.55	0.11	0.49	0.07	0.37	0.07	0.19	0.02	0.18
78942	111 Before	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes	nes
78943	111 After	3.24	0.218	1.3	1.47	0.35	0.08	0.29	0.04	0.23	0.03	0.12	0.01	0.11

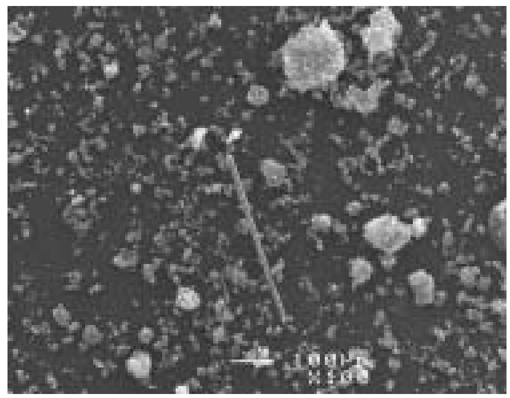
Ash from DCL on #017 Tractor

(high carbon content)

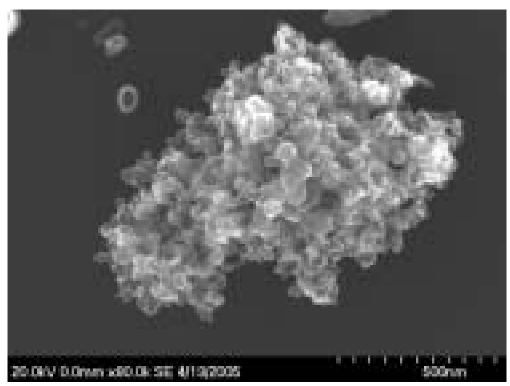
Wide field
Low magnification
2000 µm scale at lower right



Wide field
100X magnification
100 µm scale at lower center



Typical particle agglomerate
SEM image
500 nm scale at lower right



Another agglomerate
SEM image
200 nm scale at lower right

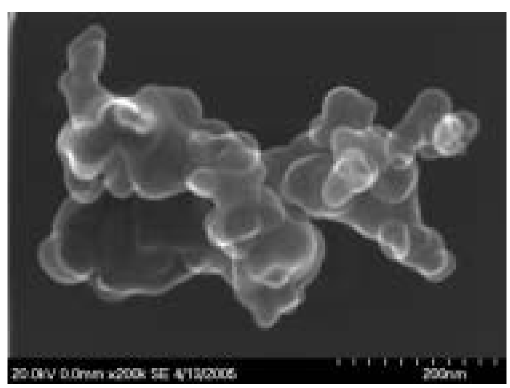


Figure 125: Photos of ash particles from DCL filter.

Ash from ECS on #3013 Tractor

(low carbon content)

Wide field
Low magnification
2000 µm scale at lower right

Wide field
100X magnification
100 µm scale at lower center

Typical particle agglomerate
SEM image
500 nm scale at lower right

Another agglomerate
SEM image
500 nm scale at lower right

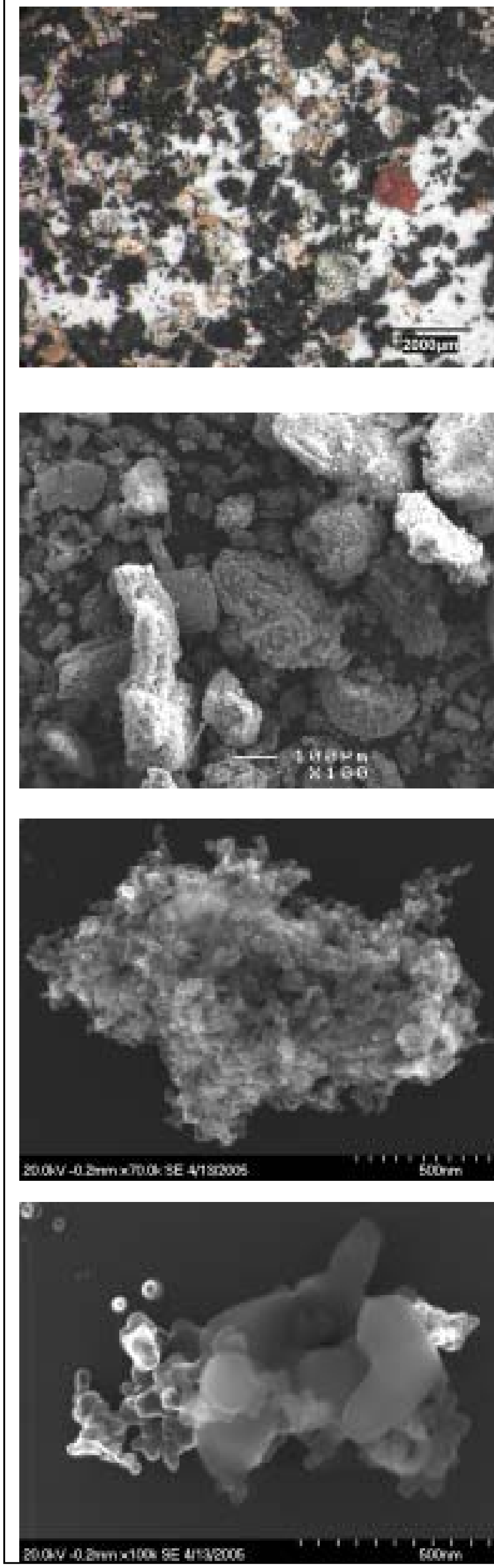


Figure 126: Photos of particles from ECS filter.

12.3 2nd Sampling trial

A second sampling of ash trial was carried out on the ECS filter on Tractor #3013. An attempt was made to minimize the amount of unburned soot by handling the filter with great care as it was put into the CombiClean oven chamber. Then the cooking was carried out for seven consecutive periods without removing the filter from the oven. The filter was then carefully removed so as not to jar loose any unburned soot. When the inside of the oven was examined, as shown in Figure 127, a fine white dust was visible on horizontal surfaces. Samples of this dust were removed using an eyedropper and were combined into an ash sample.

Figure 127: Inside of oven after seven "cookings" of the ECS filter.

12.3.1 Results

Chemical analyses of two samples are shown in Table 45. Sample #95294 was the ash sample recovered by the eyedropper from the oven. Sample #95295 was the material blown out of the regenerated filter.

Table 45: Bulk chemical analyses of 2nd sampling trial.

ITSL#	Sample Description	C	S	Cu	Ni	Co	Fe	Ca	Al	Mg	Si	As	Pb
		%	%	%	%	%	%	%	%	%	%	%	%
95294	Combi clean station ash	nes	6.93	0.24	0.27	<0.02	12.4	17.6	0.39	0.46	3.58	<0.02	0.06
95295	Combi station/trap soot	71.2	0.44	0.02	<0.02	<0.02	10.7	1.13	0.09	0.02	0.18	<0.02	<0.02
		Zn	**Mn**	**Cr**	**P**	**B**	**Ag**	**Au**	**Ba**	**Be**	**Bi**	**Cd**	**Ce**
		%	%	%	%	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
95294	Combi clean station ash	9.99	0.25	0.32	9.15	40	5	63	49	<1	1.1	32	14
95295	Combi station/trap soot	0.55	<0.02	<0.02	0.40	7	0.2	3.3	3	<0.2	<0.1	2	0.6
		Ga	**Ge**	**Hf**	**Hg**	**In**	**Ir**	**La**	**Li**	**Mo**	**Nb**	**Nd**	**Pd**
		µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
95294	Combi clean station ash	<5	N/A	<5	3	<0.5	4	4	134	700	<5	<5	20
95295	Combi station/trap soot	<1	N/A	<1	<0.2	<0.1	0.3	0.3	2	46.5	<1	<1	0.7
		Pr	**Pt**	**Re**	**Rh**	**Ru**	**Sb**	**Se**	**Sn**	**Sr**	**Ta**	**Te**	**Th**
		µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
95294	Combi clean station ash	<5	3	<0.5	<1	<1	9	9	451	57	<5	1	<5
95295	Combi station/trap soot	<1	0.3	<0.1	<0.2	<0.2	0.6	2	22.7	3	<1	<0.2	<1
		Ti	**Tl**	**U**	**V**	**W**	**Zr**	**Na**	**K**	**Rb**	**Cs**	**Sc**	**Y**
		µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g
95294	Combi clean station ash	350	<5	1	839	240	10	8780	1600	<5	<5	17	9
95295	Combi station/trap soot	56	<1	0.1	40	13	<1	521	80	<1	<1	1	<1
		Sm	**Eu**	**Gd**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**	**Yb**			
		µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g	µg/g			
95294	Combi clean station ash	<5	<5	<5	<5	<5	<5	<5	<5	<5			
95295	Combi station/trap soot	<1	<1	<1	<1	<1	<1	<1	<1	<1			

There was insufficient sample of the white ash to analyze for carbon content, but visually there existed very little soot in it. The other sample, clearly black in colour, had obviously been contaminated by unburned soot and contained 71% carbon by weight.

Only the "clean" ash sample, #95295, was examined further.

XRD Results:

The ash sample gave a weak and diffuse XRD pattern. This made it very difficult to properly identify certain phases, but possible phases of calcium phosphate [$Ca(PO_3)_2$], calcium iron phosphate [$Ca_{19}Fe_2(PO_4)_{14}$], anhydrite [$CaSO_4$] and hematite [Fe_2O_3] were suggested.

SEM Results:

The ash sample was sprinkled on a stub mount and placed in the SEM to attempt to identify the compounds present. Figure 128 shows the sample with 10 μm shown as the bright horizontal line.

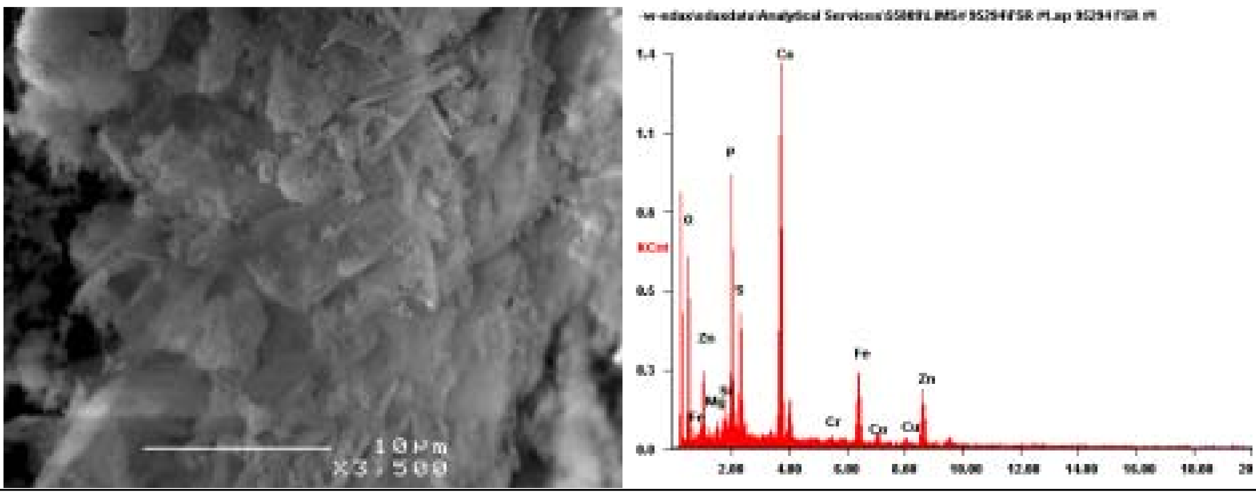


Figure 128: Scanning electron microscope backscatter image of ash sample (left) and x-ray spectrum of a large area of the sample (right).

Clearly this sample has a morphology very different from the 1st sampling trial samples. Very little of the typical agglomerates of diesel soot were present in this ash. The x-ray spectrum of a fairly large area of the sample is shown in the right side of Figure 128. It shows the presence of oxygen, iron, zinc, magnesium, silicon, calcium, chromium, cobalt and copper.

Additional detailed portions of the sample were focused on, as identified in Figure 129 and 130, and x-ray spectra obtained. These analyzes confirm the crude identifications seen by x-ray diffraction, namely, that the sample contains significant quantities of complex phosphates and sulfates of calcium and iron, and that some iron oxides and zinc oxide are likely also present.

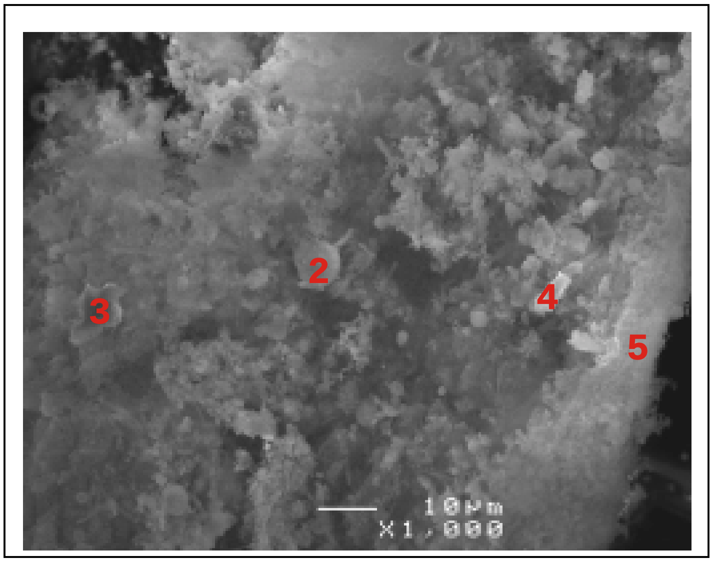
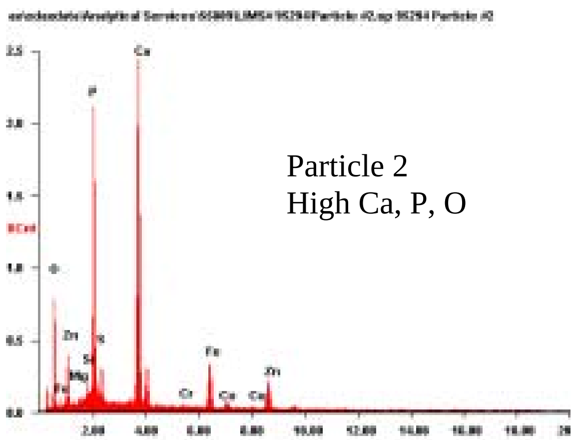
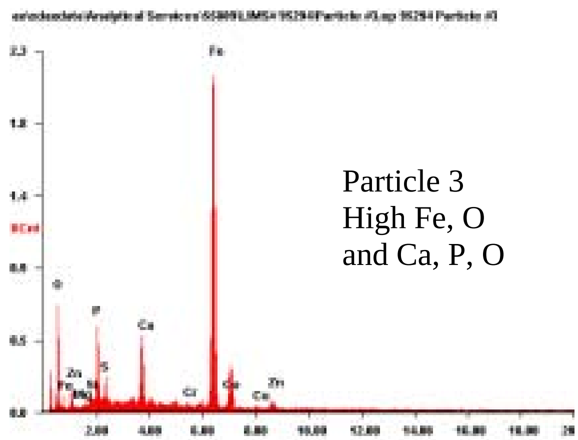
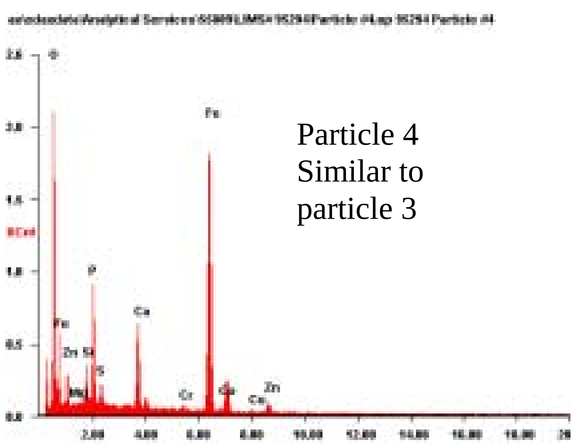
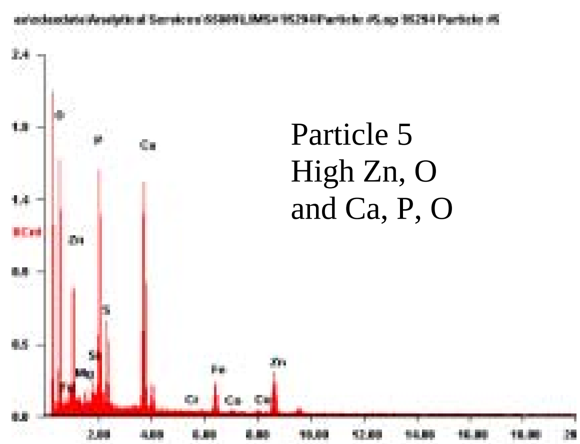


Figure 129: Ash particles, indicated by red numbers, for which specific x-ray spectra were obtained, as shown below.









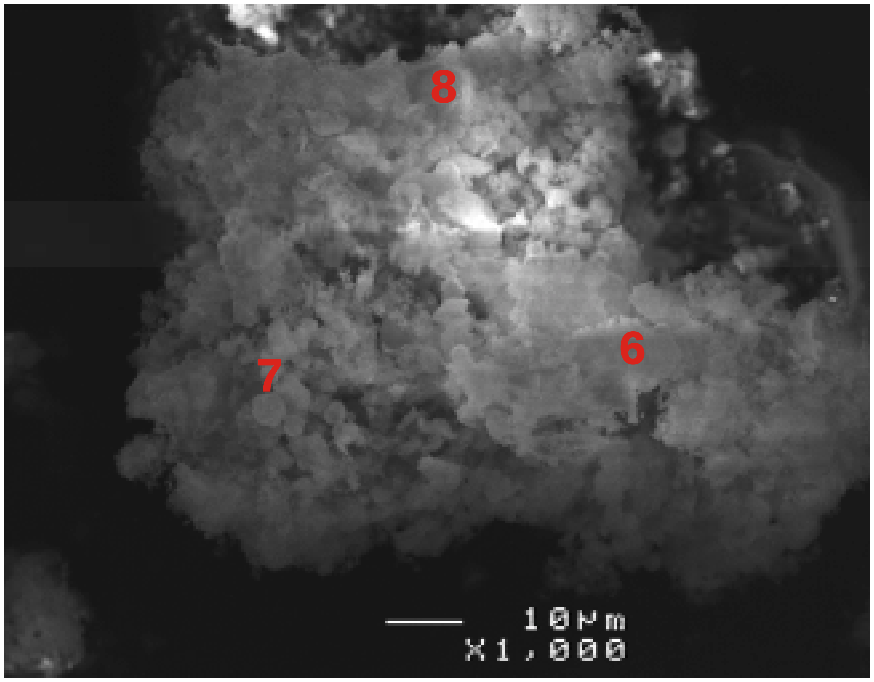
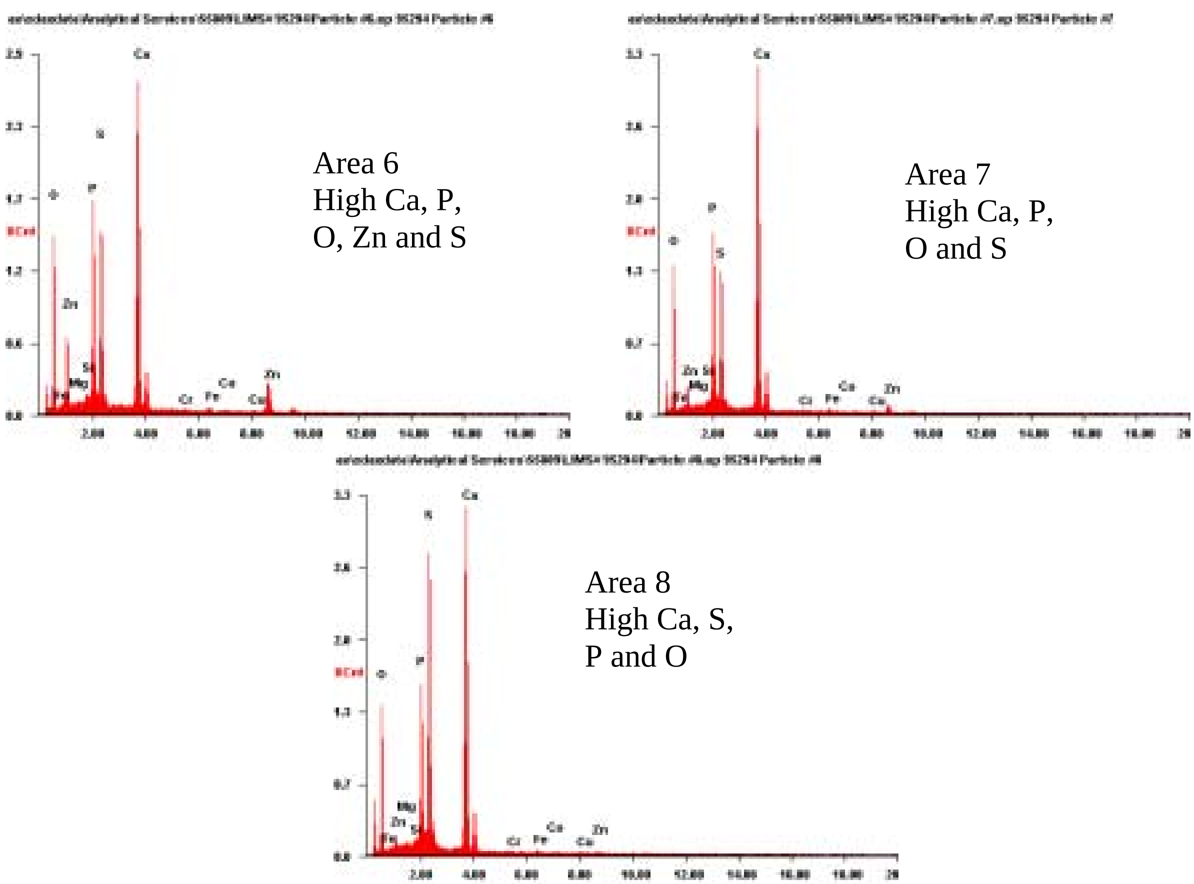


Figure 130: An agglomerate consisting of many small particles. Three areas highlighted by the red numbers were specifically analyzed and each x-ray spectrum is shown below.



13. Post-Testing Efficiencies and Analyses

At the completion of the in-mine testing six DPFs were evaluated by the Diesel Emission Research Laboratory of CANMET-MMSC in Ottawa by means of:

- Emission testing using engine dynamometers;
- Characterizations of emitted DPM for soluble organic fractions, sulfate and PAHs;
- Inspections of the filters for internal and external damage.

The entire CANMET Report is contained in Appendix D and readers are referred to it for details.

13.1 Filters

The filters provided to CANMET and their tests on them are listed in Table 46.

Table 46: Tests run on filters at CANMET.

Filter	Test No.	CANMET I.D.	Vehicle No.	Vehicle Type
None	1	Baseline-heavy duty		
Johnson Matthey	2	HD820	820	LHD
ECS/Unikat	3	HD213-A	213	LHD
ECS/Unikat	4	HD213-B	213	LHD
None	5	Baseline-light duty		
ECS/Unikat	6	LD612	612	Tractor
DCS Titan	7	LD2180	2180	Tractor
Engelhard	None	I362	362	LHD

13.2 Experimental procedures

Two diesel engines were used in the laboratory testing. A Liebherr D914T engine was used for those filters that had serviced LHDs at Stobie and a Kubota V3300 TE engine was used for the filters that had serviced the tractors. Figure 131 shows a filter connected to an engine at CANMET. The fuel used contained 0.033 wt% sulfur.

The Schenck Pegasus Corporation AC dynamometer used at CANMET, shown in Figure 132, is extremely rugged and can be controlled by a DC 6000 controller with high accuracy.

Raw diesel exhaust gas concentrations were measured by a California Analytical Instruments Company unit shown in Figure 133. This unit included a gas sampling and conditioning system, emission analysers, a 64 point gas divider for calibration, and an NOx efficiency tester.

The mass of DPM emitted was measured gravimetrically using a Sierra BG-2/3 Particulate Partial Flow Sampling System. The samples were collected on Palliflex T60A20 teflon-coated glass fiber filters.

Particle size distributions were obtained using a Scanning Mobility Particle Sizer (SMPS) similar to the one described in Chapter 8. A NanoMet sampler (also discussed in Chapter 8) was used with a photoelectric aerosol sensor to obtain information about the elemental carbon portion of DPM.

Smoke opacity was measured with a Bosch RT 100 meter according to the SAC J1667 snap acceleration test protocol.

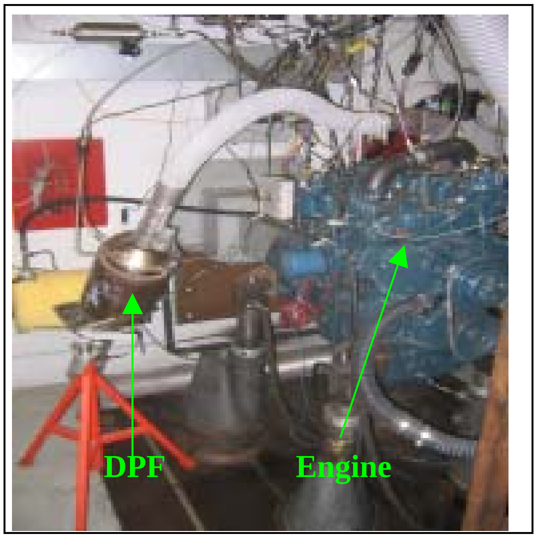


Figure 132: Filter being tested.

Figure 131: Dynamometer
.

Figure 133: Raw gas analysis unit.

Table 47: ISO 8178-C1 8-mode test cycle.

Mode #	1	2	3	4	5	6	7	8
Engine Speed	Rated Speed				Intermediate Speed			Low idle
Torque, %	100	75	50	10	100	75	50	0
Weight factor	0.15	0.15	0.15	0.1	0.1	0.1	0.1	0.15

The test cycles used were:

- 7-modes per ISO-8178-C1 specifications. The integrated values for each parameter were obtained by using the weights assigned for each mode (see Table 47);
- 3-modes (full torque converter stall, high idle without load and low idle without load);
- Snap acceleration.

Analyses of DPM samples for each mode were impossible due to insufficient sample mass. Since each mode used two filters, each 8 mode test resulted in 16 filters and these were combined into one sample to obtain the soluble organic fraction, PAHs and sulfate.

Inspections of each filter were done visually and by X-rays prior to laboratory testing and by borescope and sometimes destructive inspections following the laboratory testing. The borescope was purchased from the Karl Stortz Industrial Group. It used fiber-optic light to illuminate the internal channels of the ceramic monolith filters.

13.3 Results

The 8-mode conditions for all DPF tests were within 1% of the engine baseline data and this indiated that the various modes run were duplicated very well. Therefore, any changes in emissionhs with a filter in place were attributed to the filter. The emissions reduction data for the 5 DPF tests (relative to the baselines) are given in Table 48.

Table 48: Emissions reductions for integrated 8-mode tests.

	HD820 Johnson Matthey	HD213A ECS Combifilters (used in parallel; tested separately)	HD213B	LD2180 ECS Combi S5	LD621 DCL Titan
CO_2	-0.3%	0.9%	-0.2%	0.1%	-1.3%
CO	8%	-3%	-4%	-7%	1%
NO_2	67%	38%	63%	44%	44%
NO	2%	1%	1%	-3%	-5%
THC	28%	8%	16%	15%	18%
DPM (Mass)	89%	85%	93%	94%	95%
EQI	43%	37%	44%	59%	58%

The filtration efficiencies, based on numbers of DPM particles, is given in Table 49. The efficiencies for DPM based on PAS (elemental carbon) are shown for comparison in Table 49.

Table 49: DPM filtration efficiencies

	Efficiencies based on numbers of particles						Efficiencies based on PAS (elemental carbon)				
Modes	**HD820 JM**	**HD213A ECS**	**HD213B ECS**	**LD2180 ECS**	**LD621 DCL**		**HD820 JM**	**HD213A ECS**	**HD213B ECS**	**LD2180 ECS**	**LD621 DCL**
1	99.0%	91.8%	99.5%	100.0%	99.7%		95.5%	93.7%	99.8%	73.4%	89.6%
2	99.5%	91.9%	99.7%	100.0%	99.7%		90.8%	77.6%	99.3%	80.4%	88.5%
3	99.0%	94.7%	99.9%	100.0%	99.7%		90.6%	80.1%	99.5%	82.4%	88.4%
4	99.0%	96.0%	99.9%	100.0%	99.5%		65.6%	34.9%	96.5%	85.9%	90.6%
5	98.7%	95.7%	99.9%	100.0%	99.0%		79.1%	70.8%	98.5%	84.5%	89.5%
6	98.8%	94.6%	99.9%	100.0%	98.8%		56.0%	35.3%	96.0%	83.9%	88.7%
7	99.2%	96.8%	99.9%	100.0%	98.8%		55.9%	33.3%	94.8%	83.7%	88.3%
8 (LI)	94.4%	83.7%	99.7%	99.4%	87.4%		47.5%	19.6%	93.0%	84.0%	88.3%
FTC	98.6%	95.9%	99.9%	100.0%	99.1%		81.8%	78.4%	98.8%	72.5%	87.7%
HI	99.2%	95.9%	99.9%	100.0%	99.3%		93.1%	96.2%	99.7%	52.6%	87.5%
Average (8-mode)	98.4%	93.2%	99.8%	99.9%	97.8%		72.6%	55.7%	97.2%	82.3%	89.0%

Note: LI=low idle; FTC=full torque converter stall; HI=high idle. Modes 1-8 refer to 8 mode test.

The filters collecting DPM coming from the test engines, with and without DPF in place, were analyzed for sulfate, soluble organic fraction, and PAHs. Results are given in Table 50.

Table 50: Analyses of mass and percent reductions for components of DPM

Sample	Baseline	HD820	HD213A	HD213B	Baseline	LD2180	LD621	Blank filter
SO_4, µg	275	182	193	155	200	230	214	<MQL
Reduction in SO_4	--	34%	30%	44%	--	- 15%	- 7%	--
SOF, mg	3.65	2.04	2.71	2.54	1.53	1.72	1.03	1.03
Reduction in SOF	**--**	44%	26%	30%	--	12%	33%	**--**
PAH, ng	2775	478	830	313	2716	273	336	100
Reduction in PAH	**--**	83%	70%	89%	--	90%	88%	**--**

13.4 Inspections of DPFs

Johnson Matthey (from LHD #820): This filter had a large dent in the outer shell (Figure 134,left), but the inner filter canister was undamaged (Figure 134, right). The mat used to hold the ceramic monolith tightly against its canister had severly degraded (Figure 135) and this likely allowed some leakage of DPM to occur between the monolith and the canister. It is also likely that the degradation of this mat resulted in the monolith separating from the inlet and outlet rings (Figure 136) and the concomitant soot blowthrough that was evident at this point (Figure 137).

Figure 134: Johnson Matthey outer shell dent (right) and undamaged inner canister (left).

Figure 135: Degradation of mat holding JM monolith in place.

Figure 136:Separation of monolith from canister ring.

Figure 137: Blackened soot blowthrough at points of monolith separation.

ECS/Combifilters (from LHD #213): These filters had been used in dual mode (parallel configuration) on LHD #213. The outlet sides of the filters had some surface damage to the monoliths. At certain points (see Figure 138a) the ceramic bonding the individual honeycomb cells together was missing to depths of 10-20 cm, but no specific soot blowthrough appeared at these points. Soot blowthrough was noted on the outlet side face in some areas (see Figure 138b). Following the testing of the filters, several of the channels in the blowthrough areas were

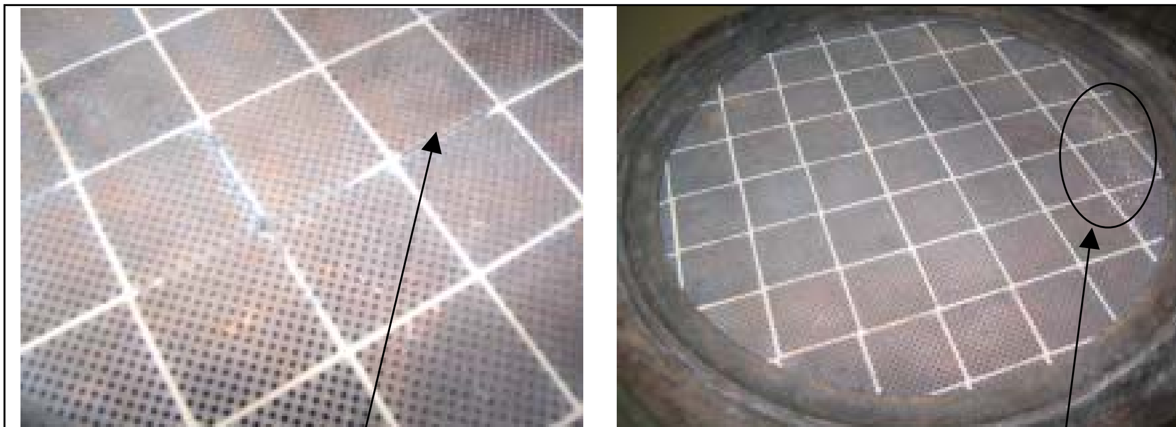


Figure 138: (a) Missing ceramic on inlet side of ECS/Combifilter; (b) area showing some surface abrasion.

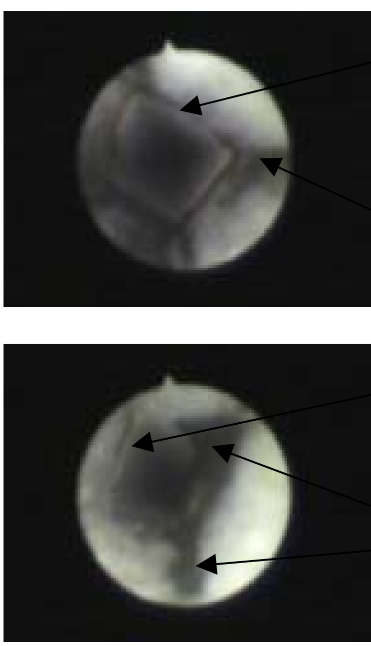


Figure 139: Borescope photographs of

investigated with the borescope, as perpendicular to the axial direction of the channels on the discharge side. It is surmised that these cracks were caused by differences in thermal expansion between these cells and neighbouring cells. This could occur if soot is not uniformly distributed among the inlet side channels. If soot is ignited in some channels, causing them to heat significantly, but soot is absent from neighbouring channels, which are relatively cooler, then thermal expansion stresses can be generated. This kind of stress might be expected from SiC honeycombs because the channels are glued together with non-conductive refractory paste, which would not conduct heat as effectively as would, for example, a cordierite monolith honeycomb.

ECS/Unikat Combifilter S5 (from tractor #2180): The honeycomb of this unit appeared to be structurally sound with no surface damage and no cracking. Some of the spider support welds had broken off the face ring (see Figure 140) and there was a very small amount of DPM blowthrough evident. With a simple re-welding of the spider support, this unit could have gone on operating.

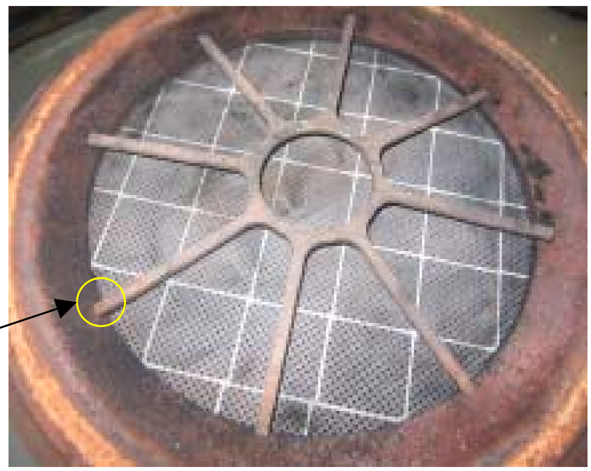


Figure 140: Welds for the spider support were broken.

DCL Titan (from tractor #621): The DPF inlet side had a few surface abrasions. Some of the honeycomb blocks were cracked where they contacted the retaining ring. This may have occurred during excessive vibration. The discharge side of this filter, shown in Figure 141, showed evidence of DPM blow through (< 50 cells) in one honeycomb block section.

Figure 141: Soot blowthrough on the discharge side of the DCL filter.

A particular cell in the area of the blowthrough seen in Figure 141 was investigated by positioning the borescope at various depths along the length of the cell. Photographs of these positions are shown in Figure 142 going from left to right from discharge side to inlet side. It is clear that the soot accumulation increases nearest the inlet side and this may indicate that the end caps at the inlet end of the discharge channels were leaking. While not evident in the blowthrough zone because of the large amount of soot obscuring the view of the wall, several nearby cleaner cells were seen to have minor cracks, as shown in Figure 143.

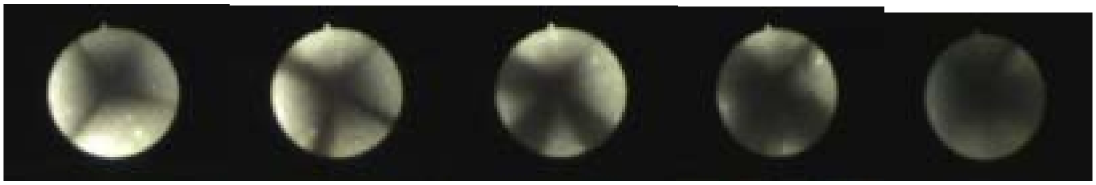


Figure 142: Images along the length of a cell showing blowthrough in the DCL filter. Left to right the images go from the inlet side to the discharge side.

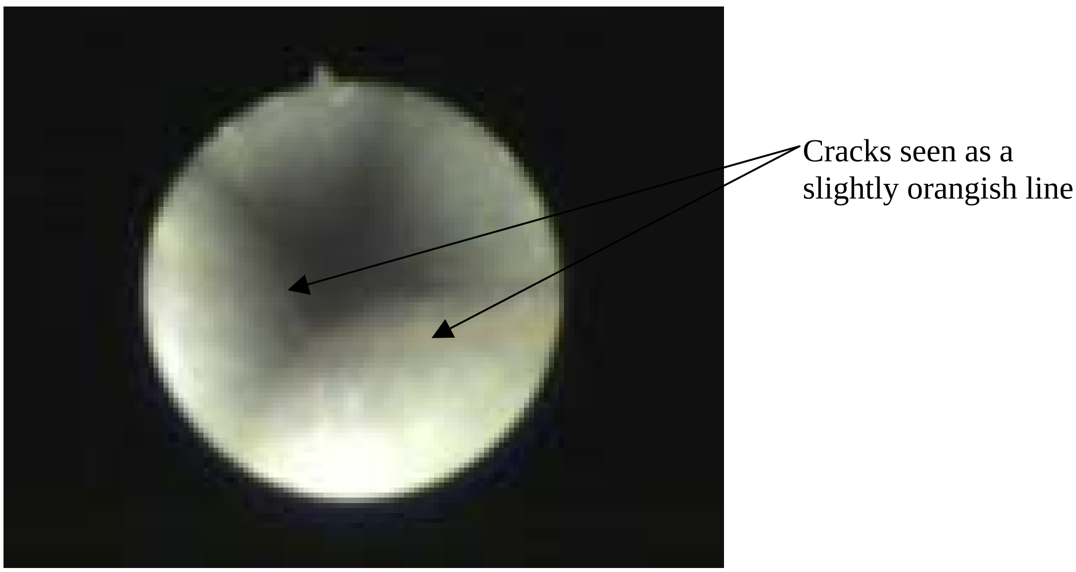


Figure 143: Minor cracks in the wall of a cell in the DCL filter.

<u>Engelhard (from LHD#362):</u> This unit was not found suitable for bench testing because excessive oil had entered the inlet from a turbocharger failure, which had occurred during the field testing at Stobie. The filter, cut open as shown in Figure 144, showed the oil contamination to be extensive.

Figure 144: Engelhard filter showing the extent of oil contamination it suffered from the turbocharger failure on LHD #362.

14. Project Management

14.1 Team Construction

The project was carried out in production mode and, therefore, production people were formed into a Stobie team. However, all team members took on responsibilities for the project as additional duties to their normal job. This caused some problems with time constraints and personal priorities. There was, however, no other way to conduct the project at Stobie. The personal dedication of the personnel on the Stobie project to spending extra time on the project when it was necessary went a large way toward minimizing disruptions in the project schedule.

Going into the project, the team recognized the potential difficulties in the geographical separation with the primary technical consultant, but the Stobie team believed that Mr. Mayer's technical expertise was essential for the project to be successful. For that reason, the project had several visits of Mr. Mayer to Stobie, and these visits were well justified. Extensive use was made of the internet for sending large quantities of raw datalogging results and this worked fairly well. While overall Mr. Mayer's expertise was effectively applied to the project, some technical challenges would have been more efficiently solved by more opportunity for face-to-face meetings with him.

14.2 Team Communications

Regular team meetings were an important part of the project and were held weekly virtually over the entire time. Minutes of all meetings were recorded and archived by the team's secretary. These Minutes are available for inspection, if desired.

14.3 Data records

The datalogger files are organized in a relatively straightforward manner by identifying the vehicle, the PFS and the time period. However, what was not as straightforward was recording the vehicle/PFS status. The creation of log books for each PFS solved part of this problem. Daily operating sheets were instigated so that vehicle operators could report what had happened during each shift. All of this information is archived an Inco Sudbury server. Of course, one of the consequences of recording such data is that a team member had to be designated to review the reports and cross reference events with datalogging.

14.4 Training and communicating with operators

The Inco Training Department undertook responsibility for packaging information about each PFS and communicating with relevant Inco personnel. Training Manuals exist as a result of these actions and they may be reviewed by outside parties, if desired.

One of the most critical and difficult part of the project was getting vehicle operators to take routine responsibility for active regeneration of certain filters. To some operators this likely was viewed as yet another thing for them to have to do, and in some cases the importance of regeneration was not realized. Due to good feedback received from operators, it became known to the team that some regeneration was not being carried out because of inconvenience of getting the vehicle to the regeneration station at the end of a shift. Based on this feedback, the locations of regenerating stations were optimized and this assisted in getting more routine regeneration.

Another challenge was to limit the operation of the test vehicles to those operators whom had undergone the necessary training in the PFS for their vehicle. This was easier for the LHD vehicles than for the tractors because an LHD tends to be driven by a small team of operators, whereas the tractors are used in a collective mode by anybody needing transportation. Putting labels on LHDs, informing operators not to use the vehicle unless trained in the PFS, worked fairly well. However, similar labels on tractors were not effective because often a test tractor was the only one available and mine operation took precedence over project operation.

14.5 Limited vehicle use

The hit and miss use of certain tractors meant that some operating hours fell short of expectations. This was sometimes caused by the perception that some tractors were prone to problems (problems not associated with the project) and some tractors required more general vehicle-engine maintenance than others. In certain cases PFSs were changed from one tractor to another tractor so that operating hours could be accumulated more rapidly.

14.6 Managing change

Inco has found it beneficial to manage change in operating environments. Usually this includes a complete review of what is being changed and a strategy for how to communicate the need for the change and to monitor the acceptance of change. All of the PFSs and associated equipment (regenerating stations) were subjected to this analysis before being brought underground. In some cases a more extensive program of systematic hazard review was necessary. This kind of work took more effort than the team initially forecast.

14.7 Technical knowledge transfer of Stobie results

There exist several types of technical transfer.

(a) Within the Stobie mine: Extensive interactions between mine personnel and the Stobie project team took place throughout the four years of testing. In addition, Mr. Mayer and his datalogging expert, Mr. Nöthiger, were brought over from Europe for several weeks at a time to provide knowledge transfer to the Stobie team and mining personnel.

(b) Within the DEEP membership: Two major workshops were held in Sudbury for members of DEEP. The first of these in November 2000 was related to the duty cycle monitoring results and the criteria for selecting PFSs for the Stobie project; the second in July 2004 reviewed results of the Stobie project in a general way. The presentations from both of these workshops are included in the Appendices to this Final Report.

(c) Within the mining community: Presentations on the Stobie project status and results were given in 2001, 2002, 2003, 2004 and 2005 at the Mining Diesel Emission Conference (MDEC) held in Markham, Ontario. Organized by CANMET staff, these conferences aim to keep stakeholders in diesel emission issues aware of developments throughout the world. Usually attended by more than 100 people from Canada and the United States, the Conference in recent years has had expanded interest from Europe, Japan and Africa. As part of DEEP’s technology transfer initiative, Dr. Stachulak made presentations about the Stobie project at four regional workshops held in mining centres across Canada: at Marathon, Ontario in Sep 2003, at Val d’Or, Quebec in Oct 2003, at

Saskatoon, Saskatchewan in Oct 2003 and at Bathurst, New Brunswick in May 2004. Combined these workshops attracted 133 underground and open pit mining personnel.

(d) International: The Stobie project has been presented at the following international technical conferences:

- **a.** Mine Expo 2000 in Las Vegas, Nevada;
- **b.** 6th International Symposium on Ventilation for Contaminant Control in 2000 in Helsinki, Finland;
- **c.** 4th International Occupational Hygiene Association Conference in July 2000 in Cairns, Australia;
- **d.** 7th International Mine Ventilation Congress in 2001 in Cracow, Poland;
- **e.** Mine Health and Safety Conference in April 2002 in Sudbury, Ontario;
- **f.** National Institute of Occupational Safety and Health Diesel Workshop in February 2003 in Cincinnati, Ohio;
- **g.** The Society of Mining Engineers Annual Conference in 2003 in Cincinnati, Ohio;
- **h.** The Caterpillar Engine Conference/Workshop held in February 2004 in Peoria, Illinois;
- **i.** 8th International Mine Ventilation Congress in July 2005 in Brisbane, Australia.

(e) On-going: The Stobie team intends to continue its technology transfer across Inco's other mines in Ontario and Manitoba and to assist, where requested, other mining companies in implementing PFS technology to existing or new diesel equipment.

14.8 Project expenditures

The project had a cash budget originally of $467,124. Due to adjustments during the project, the final cash budget was $419,962.

DEEP consortium	319,962
Ontario WSIB	100,000

Inco's in-kind contributions are difficult to quantify accurately, but an estimate can be made by accounting for employee hours spent on the project and for the non-budgeted equipment expenditures directly associated with the project. The employee hours spent on the project are summarized below:

	person-hours
Site preparation and project planning	470
PFS installation & maintenance	6540
Data loggers installation & downloading	290
Technology Transfer	1190
Meetings and communications	9840
Training operators/mechanics	730
Performance testing	770
External interfacing & training	410
Reporting	1846
Project management	5700
Total	27700

One of these lines is labeled "meetings and communications", which consisted of 333 meetings of the core Stobie team.

It is estimated that Inco's personnel time contribution amounted to > $2.3 million. Excluded from this amount are the contributions of personnel and equipment from supporting companies (engine manufacturers, control equipment manufacturers, etc.) and from assisting agencies (NIOSH, other scientists).

It is estimated that the complete Stobie project had a total cost, inclusive of cash and in-kind contributions of around $3.0 million.

15. CONCLUSIONS AND RECOMMENDATIONS

The Stobie Project was successful in meeting its objectives.

- It tested eight state-of-the-art particulate filter systems on a total of nine vehicles operating in underground production mode.
- Both heavy duty and light duty vehicles were used in the tests.
- Extensive duty cycle monitoring was conducted so that filter system characteristics could be chosen to properly match engine performance.
- In a number of the systems operational time with high filtration efficiencies exceeded 2000 hours.
- Exhaust analyses were carried out routinely on all systems and special high intensity analyses were carried out three times.
- Industrial hygiene measurements were obtained with and without trap installments.
- Post-test analyses were conducted on certain filters.

15.1 General conclusions

(1) Both heavy duty and light duty vehicles in underground mining operations can be retrofitted with high efficiency Particulate Filter Systems (PFSs) for DPM removal.

(2) Taking time to correctly match the vehicle duty with an appropriate PFS is essential for a retrofitting program to be successful.

a. This matching must be done to correctly size the filter medium so that an acceptable soot collection period is obtained. Too small a filter will result in loading the filter too quickly and will negatively impact on vehicle productivity. Too large a filter will result in cramped space for the unit on the vehicle and this could negatively impact safe use of the vehicle and ease of its maintenance.

b. This matching must be done to obtain the optimum method of regeneration of the filter. The optimum method of regeneration must take into account issues such as the complexity of the regeneration system, the period of time needed for regeneration, maintenance of components of the regeneration system, ease of installation and use, and cost.

(3) Proper communication with vehicle operators is essential. The presence of a filter on the exhaust manifold of an engine means that the filter, when working, will cause an increase in the backpressure of the engine. Operators must be attentive to non-conventional alerts and alarms for high backpressure or else serious harm could be done to the engine.

(4) Simple, but effective, dashboard signals of the state of the filter are needed in order to give information to the vehicle operator about the filter's effectiveness.

(5) All of the systems tested required more close attention than desired, although there existed a wide variation in the amount of attention needed. Ideally, a PFS would be invisible to a vehicle's operator and almost invisible to the maintenance department. That is, people would go about their jobs in a conventional manner and would not need to pay attention to the filter or its regeneration. This was clearly NOT the case for any of the filters being tested in the Stobie project and this remains a critical issue in any successful program for retrofitting or for installing PFSs as OEMs.

(6) The increased emission of noxious gases is often a consequence of the way in which some PFSs regenerate and these emissions, particularly NO_2 must be watched carefully. While there may exist ways to control such emissions, system complexity by adding on components is undesirable.
(7) An emissions-based maintenance component of an overall vehicle/engine maintenance program is essential. Proper functioning of a PFS should be evaluated as part of routine maintenance. Training of maintenance personnel in the specifics of each PFS is essential.

15.2 Specific conclusions for heavy duty (LHD) vehicles

Engelhard:
The system was a passive type with low complexity and required relatively low amounts of attention. Filtration efficiency of soot was high, but backpressure readings exceeding 300mbar were observed occasionally to last for extended periods. It is not known what role, if any, these high backpressures may have played in the turbo failure (and fire) of the LHD after 2221 hours of operation of the PFS. Because of the catalytic properties of the filter's wash coat, the increased emission of NO_2 was noted. The system was robust and survived an accidental circumstance in which mud penetrated the discharge side of the filter.

Johnson-Matthey:
The system was somewhat complex because of the need to meter the fuel-borne catalyst. Use of an auxiliary electrical heater for regeneration turned out to be essential for the particular LHD on which the system operated. This was due to the unconventional (non-mucking tasks) and rather broad duty cycle of LHD #820's use at Stobie Mine. The system had excellent filtration efficiency throughout the tests and no observed increase in NO_2 emissions. After over 1000 hours one of the honeycomb filters became slightly separated from its canister, but filtration efficiencies still were good. Only after another 900 hours did the separation increase to the point where filtration efficiency was compromised. The companion filter (dual exhaust system) operated well without incident for nearly 2400 hours. The electrical regeneration components showed less than desired reliability.

ECS/Unikat Combifilter:
This active system showed excellent performance as long as operators were attentive to its regeneration. The first system installed on an LHD failed because of lack of necessary regeneration. Another system was installed on another LHD with significant communication with the vehicle operators and this system performed well until the project's conclusion (over 2000 hours). The filter was robust when properly regenerated. The electrical system worked well.

Oberland-Mangold:
Despite this system being relatively complex due to the pumping system of the fuel-borne catalyst, the performance of the system was a disappointment. The Stobie team had spent considerable resources to get the system properly installed. Two maintenance people from Stobie had gone to Germany for a week of intensive training at the Oberland-Mangold facility. Despite these efforts, the system showed undesirable soot emissions from the tailpipe right away and it had to be removed from further testing.

Arvin-Meritor
This system employed an active exhaust manifold burner for regeneration. As it was the only in-situ burner tested in the Stobie project, much time and effort were made by both Arvin-Meritor and Inco personnel to install it and educate Inco maintenance people about its operation. Stobie mechanics spent a week in Columbus, Indiana, to learn about the system. It was, therefore, very disappointing when this system failed to give good filtration efficiencies from the beginning of its service. The Stobie team concluded that the system was too complex and was not as fully developed as needed for this kind of field trial.

15.3 Specific conclusions for light duty vehicles

ECS Combifilter
This filter gave excellent soot removal efficiencies throughout the nearly three years of testing on a tractor used for personnel transportation within Stobie mine. NO_2 concentrations were slightly decreased downstream of the filter. The short regeneration time (60 minutes) by electrical heating fit nicely into the scheduled use of the vehicle. It was essential that good communication be established with prospective users of the vehicle because of the active attention these users had to have for regenerating the filter after each shift. It was found that the fewer the number of drivers led to more responsibility being taken by the drivers for the vehicle. With more drivers there was a tendency to “let the next guy take care of it” and this can lead to difficulties with the filter. Given appropriate attention to active regeneration by the operators, this system is a good fit for light duty vehicles.

DCL Titan
This filter was very compact and was very easy to use, regenerate and service. The potential challenge associated with changing filters alternately was not realized due to the quick-disconnect flanges and ease of removing and installing filters. Excellent filtration efficiencies were present throughout the nearly three years of operation of the filter. The regeneration station worked well. No NO_2 increase was seen downstream of the filter. The same comment about the need for operator attention to regeneration that was made above is applicable here as well and, as long as that occurs, this system is a good fit for light duty vehicles.

ECS/3M
This system was only tested for eight months and showed marginal soot removal effectiveness. It was removed from the testing program because 3M announced they would cease production of the glass fiber filter medium. It is therefore not a candidate any longer for light duty vehicle service.

15.4 General recommendations

Several technical issues arose during the Stobie testing program. These were solved, some taking considerable time and others being very simple. In order to avoid others encountering the same problems and struggling through them, the Stobie team offers the following recommendations to mines interested in either testing PFSs or installing PFSs on existing on new diesel equipment.

(a) Periodic gas and Soot Number measurements at the tailpipe of a vehicle using gas analyzers and smoke test equipment are very good ways to determine the status of a PFS.

These measurements are most effectively carried out by skilled mechanics during scheduled vehicle maintenance and it is relatively easy to include this in the routine maintenance performed as part of the normal vehicle servicing.

(b) Dataloggers are essential for any testing contemplated; while they would be extremely useful for trouble-shooting during routine operation of PFSs, the additional care and maintenance they require are likely too intensive for such service. However, dataloggers that are part of the PFS as supplied by the PFS manufacturer, then their serviceability would likely be good and they would add much to the PFS as a whole. If dataloggers are employed in testing scenarios, then it is important to buy from a local supplier so that their maintenance and troubleshooting can be handled in a timely fashion. The specifications for the dataloggers should not deviate much from those used in this study.

(c) While it is obvious that the filters must be sized and operated in coordination with the duty cycle and planned use of the diesel vehicle, it is less obvious, but very important, that close attention should be given to the design, specifications and installations of auxiliary equipment to the filters. Such equipment includes electrical circuits, fuses, heating elements, timers, air flow controllers associated with electrical regeneration. In other types of regeneration, such as fuel-borne catalysts and burner-assisted exhaust heating, special equipment required needs attention to ensure that it meets Canadian standards for safety, that consumables can be purchased easily and that maintenance is straight-forward.

(d) Equipment suppliers must be contracted to have an on-going service commitment for their units.

(e) Heat wrapping of exhaust pipes (and filters where possible) was found to be effective in improving PFS performances.

(f) The use of welding gloves when handling filters or in plugging in units for electrical regeneration was found to be advantageous.

(g) The use of metal electrical connectors (instead of the supplied plastic connectors) was found to improve their ruggedness, resulting in less attention to breakage or shorting.

(h) Using shock absorbing mounts were found to be advantageous when installing filters.

(i) Mounting filters high enough on an LHD was found to be beneficial in limiting the amount of mud/water that can enter the bottom (often housing an electrical heater) of the housing. Sometimes electrical connections in these locations can become compromised. As an alternative to mounting the filter higher, it is also possible to design and install a cover that does the jobs of both heat dissipation (when the heater is on) as well as protection. Another option is to redesign these filters so that the electrical heater is not carried with the filter canister, but can be quickly snapped into place when regeneration is needed.

(j) Mechanics should be careful when installing the filter and associated exhaust manifolds to stay well away from fire suppression actuators located on the vehicle. The Stobie test had one incident in which an activator was initiated due to its close proximity to the new routing of the exhaust manifold.

(k) It was found beneficial to redesign electronic control modules (ECMs) on electronically-controlled engines so that an engine can be ramped down if excessive overpressure is sensed.

(l) It was found beneficial to substitute mine air for compressed air modules on vehicles requiring air for regeneration. Air compressors and air pumps were found to require excessive maintenance. Attention should also be given to removing moisture from the mine air line. This can be done easily with conventional moisture separators.

(m) It was found necessary to adjust the air supply during regeneration on some units. Excessive air can cause excessive cooling with the result that combustion temperatures are not met or are not maintained long enough for soot removal. Originally set air flow criteria supplied with some units were found to need adjustment.

(n) Long exhaust manifold ductwork and additional bends in such ductwork are to be minimized for optimum performance.

References

American Conference of Governmental Industrial Hygienists, *TLV and BEI Booklet*, ACGIH: Cincinnati (1995).

Birch, E. and Cary, “Elemental carbon-based method of occupational monitoring of particulate diesel emissions: Methodology and exposure issues”., *Analyst, 121*, 1183-1190 (1996).

Burtscher, H. “Physical characterization of particulate emissions from diesel engines: a review”. *J. Aerosol Science, 36* (7), 896-932 (2005)

Dainty, E.D., Mogan, J.P., Lawson, A., and Mitchell, E.W. “The status of total diesel exhaust filter development for underground mines”, presented at the XXIst International Conference of Safety in Mines Research Institutes, Sydney, Australia (1985).

Health Effects Institute’s Diesel Working Group, “Diesel exhaust: a critical analysis of emissions, exposure and health effects”. Health Effects Institute (April, 1995).

Hews, C. and Rutherford, J.G., “Trackless Mining”, Underground Diesel Seminar, Johannesburg, South Africa (1973).

International Agency for Research on Cancer (IARC), Monograph on the Evaluation of Carcinogenic Risks to Humans, No. 46, Diesel and Gasoline Engine Exhausts and Some Nitroarenes. IARC: Lyons, France (1984).

Kittlelson, D. “Engines and Nanoparticles: A Review”, *J. Aerosol Science, 29* (5/6), 575-588 (1998).

Maskery, D., “Respirable combustible dust Inco method No. 1H011A” Inco Limited, Sudbury, Ontario (1978).

McGinn, S. “Final Report of Investigation: Noranda Inc. Brunswick Mine Diesel Particulate Filter Field Study”, Diesel Emissions Evaluation Program, CAMIRO: Sudbury, Ontario (October, 2004).

McKinnon, D.L. et al. ,”Diesel particulate filter underground trial at Brunswick Mining and Smelting No. 12 Mine”, SAE Paper 891846 (September, 1989).

Mines Safety and Health Admistration (MSHA), “Diesel Particulate Matter Exposure of Underground Metal and Non-metal Miners, Final Rule”, Federal Register, Vol. 70 (107), 30CFR Part 57, 32868 (June 6, 2005).

National Institute of Occupational Safety and Health (NIOSH), “Carcinogenic effects of exposure to diesel exhaust”, NIOSH Current Intelligence Bulletin 50, Publication No. 88-116, Centre for Disease Control: Atlanta, GA (1988).

National Institute of Occupational Safety and Health, Elemental Carbon (Diesel Exhaust) 5040, Manual of analytical methods, 4th edition, NIOSH: Pittsburgh (September, 1999).

Rutherford, J.G. and Elliot, W.T., "Monitoring the workroom environment: the Inco program", 46th annual MAPAQ meeting, Toronto (1977).

VERT Filter List: Tested and Approved Particulate-Trap Systems for Retrofitting Diesel Engines, edited by A. Mayer, published by the Swiss Agency for the Environment, Forests, Landscape: Luzern, Switzerland (2004).

VERT Report: Results of a 4 year European joint project: Curtailing Emissions of Diesel Engines in Tunnel Sites, A. Mayer, Report W11/12/97 VERT/SUVA/AUVA/TBG/BUWAL (May, 1997).

World Health Organization's Environmental Health Criterion 171: Diesel Fuel and Exhaust Emissions, World Health Organization: Geneva, Switzerland (1996).