The Relationship Between Diesel Engine Maintenance and Exhaust Emissions

Final Report

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The Relationship between Diesel Engine Maintenance and Exhaust Emissions

Executive Summary

In the first months of the DEEP program the Technical Committee solicited ideas for projects that would fulfill the 3-year mandate to provide a toolbox of technologies and information on control and reduction of diesel particulate matter in the underground mining environment. The third project to be proposed to the Technical Committee was one investigating the relationship between improved diesel engine maintenance and associated reductions in emissions. Noranda Technology Centre in Pointe Claire, Québec submitted a project proposal to conduct the project based on previous experience with related work at Noranda and Falconbridge mining operations. In early 1998 the Technical Committee approved the project proposal with stated objectives to:

1. **Drawing on previous research and in consultation with industry authorities, identify the principal engine maintenance procedures and practices which reduce diesel emissions**

2. **Establish a maintenance review process to determine the current status of a maintenance operation and recommendations for improvements to reduce engine emissions**

3. **Test and evaluate this process in an underground mine(s)**

4. **Develop a model of good maintenance practice with an emphasis on reduced emissions**

5. **Perform before and after implementation sampling of exhaust gases and DPM to establish relationship between improved maintenance and reduced emissions and DPM**

6. **Educate and train maintenance personnel on the importance of effective maintenance on diesel engines and exhaust emissions**

To accomplish these objectives a plan was laid out that would involve a wide range of resource participation from several mining companies, engine manufacturers, emission control manufacturers, and research organisations. The project plan was broken into major stages, which were:

- ❖ *Construct a review model for engine maintenance and conduct reviews at 2 mines for selection of a suitable host site for the project*
- ❖ *Develop guidelines and best practices for engine maintenance that would serve as a foundation to implement improvements at the mine*
- ❖ *Begin field work by implementing emissions testing equipment and acquiring baseline emissions values for mobile equipment included in the study*
- ❖ *Implement an improved engine maintenance strategy through a combination of changes to process, tools and training*
- ❖ *Analysis and recommendations resulting from field work*

Auditing Engine Maintenance and Site Selection

Based on an existing audit framework, an audit model for diesel engine maintenance was constructed that could be taken to a mine site and conducted over a one-week period. Common maintenance practices such as condition based and scheduled maintenance activity were built into the evaluation along with focus on the 6 systems of diesel engines identified from previous research. The completed model became an easy to use tool that proved effective in identifying strengths and weaknesses and providing instant value to the host site for the audit even before any corrective actions. By the end of the summer two mine sites had participated in the site review process. The 5 day audits were conducted at Hudson Bay Mining & Smelting's Ruttan Mine in Leaf Rapids, Manitoba and Falconbridge Ltd's Strathcona Mine in Onaping, Ontario. From the final reports of both reviews based on a combination of strengths, weaknesses, opportunities and threats, the Technical Committee approved the recommended selection of Strathcona Mine as the most suitable site to host the project.

Guidelines and Best Practices for Diesel Engine Maintenance

In parallel to the review model and selection process the guidelines and best practices for maintaining engines was put together. Once again the 6 system approach to diesel engines was followed along with the other categories in the audit model. By doing both in parallel the results from the audit could be directly applied to the guidelines and best practices and solutions easily identified. The foundation for the guidelines and best practices was laid down by a five person technical panel of specialists in the field of diesel engine maintenance in the mining industry. Through group brainstorming and compilation of reference information materials from all members the document was built in time to be used for the implementation stage of the project against the results from the audit.

Acquiring an Emissions Baseline

The first phase of the field work at the mine was to move the emissions testing equipment into the shop on 3900 level at Strathcona and begin training and testing with the group of mechanics. The emissions test equipment consisted of a gaseous emissions test system from Noranda Technology Centre called the Undiluted Gas Analysis System (UGAS) and a particulate emissions test system from CANMET called the Undiluted Particulate Sampling System (UPSS). The two systems were integrated into one package situated on the shop floor as a tool for the mechanics to use. In total 13 vehicles were tested and 16 mechanics and leaders were trained over the baseline period of 3 months. Each of the vehicles was tested at least once but in most cases several times over this period. This also permitted enough time for every mechanic to go through the emissions training aspect of the project and at least one mechanic from each of the 4 crews to be trained to an advanced level where he could take emissions tests on his own on shift.

Implementing Change to Process – Tools – Training

At the completion of the baseline stage a meeting was held with the project team and mine management to discuss the implementation of change to the existing engine maintenance system. The results from the audit were presented once again and a short list of the most implementable items yielding the most significant potential was outlined. From this a plan was put together to approach the problem from three directions. Changes would be made to the existing process such as the structure of preventive maintenance with respect to engines. This would be a process with considerable planning and intervention on the part of the mine and would be ongoing through the rest of the fieldwork in the project. The implementation of new tools was immediate and produced both a change in engine performance and positive feedback from mechanics. The mechanics were introduced to the new tools through a training strategy that was the third component to the implementation. The primary level of training was done on a one to one basis between the mechanic and the project leader. To complement this, group training sessions were conducted as individual case studies where a specific vehicle was used for a one-day hands on training session with a small group of four to five mechanics. Training was provided by service representatives from the engine manufacturers. During each case study the mechanics were also shown how to incorporate the new process and new tools along with the training to improve performance and reduce emissions. It was the case studies where the impact to emissions was measured and qualified from a before and after perspective.

Evaluating the Impact of Improved Maintenance

The most effective way to evaluate the effects of the improved maintenance process was through the results in the four case studies. For each case study the vehicle emissions were measured at the start of the day session before any changes were made or maintenance activity. As the session progressed emissions were measured with a final set of tests once the case study was complete and the vehicle was ready to return to work. This gave a comparison of emissions values from when the vehicle arrived at the shop for the study to when it was released back to production.

Results from the case studies showed that gaseous and particulate emissions could be reduced significantly depending on engine design technology and condition. Gaseous emissions reductions (carbon monoxide) as high as 65% were proven and particulate emissions reductions as high as 55% were seen as well.

Conclusions and Recommendations

With the fieldwork and testing behind the focus shifted to analysing the considerable emissions data gathered over the seven-month period at the mine. When looking back to the original project objectives in the proposal the work would appear to have satisfied these and more. Each stage of the project all the way back to the audit model proved to be very effective in application and in educating not only the mine personnel but every person involved with the project at every stage. The modular approach to the project also leads well to succeeding in transferring the knowledge gained through deliverables such as the *Guidelines and Best Practices for Diesel Engine Maintenance* and the *Diesel Engine Maintenance Audit Model* included as part of the final report.

As the first level of control in reducing diesel exhaust emissions, the following recommendations for improved diesel engine maintenance can be adopted as the first steps in achieving reduced emissions.

1. ***Build a team focussed on implementing an improved maintenance strategy. The team should have members including mechanics, operators, supervision, planning, and management from the mine. Responsibilities can be delegated according to an implementation plan and followed up through a report and meeting structure. Ensure that sufficient resources are made available to the team with respect to time, tools, and training.***

2. ***Construct an engine maintenance audit program using the model provided in this report as a template. Select an auditing team from both internal and external to the mine maintenance system. Sometimes it takes an unaccustomed eye to uncover what is obvious and overlooked by someone closer to home. A good audit program has follow up mechanisms built in to it and should be conducted at least annually.***

3. ***Utilize the Guidelines and Best Practices included in this report along with the six system approach to engine maintenance as a foundation in building a strategy for improving existing maintenance practices.***

4. ***Put a program together for testing undiluted tailpipe emissions on underground vehicles. Integrate the program with a structured Maintenance Management record and planning system – preferably computer based. Set action limits on emissions within the system to ensure response to problems. The critical factor in the emissions testing program is not so much in the technology used to measure but in the structured protocol in taking the tests. In order to be useful the emissions must be compared against a known baseline at a known operating state consistently.***

5. ***Make use of the suppliers of diesel engines and related equipment for training and follow up with new tools and other developments. The best way for an engine supplier to improve the relationship with the mine is to provide solutions to problems. The best way to do this is to have service representatives come to the mine and provide hands on instruction with small groups or one on one as described in the case studies for this project.***

Report On Research

Audit and Site Selection

Assembling Guidelines and Best Practices

Emissions Test Equipment

Acquiring Baseline Emissions

Implementing Improved maintenance

Case Studies

Recommendations and Conclusion

Introduction To Research

The research in the maintenance project is a combination of a foundation that was established in previous research work and the application of fundamentals and experience from several resources within the mining industry.

The foundation established by the work done by Waytulonis and the former U.S. Bureau of Mines was used as a platform from which to build from for this project. In the previous work six primary engine systems were identified as critical to focus on improved maintenance. [1] The six systems are:

1. ***Air Intake System***
2. ***Cooling System***
3. ***Diesel Fuel Handling and Quality***
4. ***Fuel Injection System***
5. ***Lubrication System***
6. ***Exhaust System***

These same systems were used in a new order of priority to assist in the construction of both the engine maintenance audit template and the guidelines and best practices that have been produced as part of the research. From this platform two separate groups participated in brainstorming sessions and information gathering to come up with the basic templates that would become the audit model and engine maintenance guidelines and best practices.

With these basic tools in place the project moved to the mine site where the first phase was to conduct the audit to determine the status of current diesel engine maintenance practices. Before any changes could be made the equipment for measuring exhaust emissions as put into place, the mechanics were trained on testing emissions, and baseline emissions values were acquired for the underground production fleet. Once the baseline had been completed and the mechanics had been trained the implementation of improved maintenance practices was undertaken. This involved taking the guidelines and best practices and comparing against the results of the audit to come up with an action plan. The action plan used a combination of changes to existing internal processes, new tools, training, and four case studies to put all components together as a package to improve maintenance and reduce emissions.

ENGINE MAINTENANCE AUDIT AND SITE SELECTION

The first major task in the project was to identify potential mines for participation and then make a selection using an audit process specific to diesel engine maintenance. While the project team was constructing the audit model to be used, the process of soliciting mines for participation in the project was begun. Ironically, the identification of two potential site candidates to even consider participation in the project through the audit process would be one of the biggest challenges in the entire project. After several months of communication with mining companies across Canada two candidates were identified for participation in the audit process. From this process the most suitable site would be chosen based on a combination of strengths and weaknesses specific to site maintenance performance and opportunities and threats specific to the success of the project. The two mine sites chosen to participate were:

- ***Hudson Bay Mining and Smelting – Ruttan Mine, Leaf Rapids, Manitoba***
- ***Falconbridge Ltd. – Strathcona Mine, Onaping, Ontario***

While this process of soliciting candidate mine sites was ongoing the audit model for evaluating and selecting the most suitable site was built. The model was constructed from an existing audit framework used for conducting industrial hygiene audits within the Noranda and Falconbridge group of operations. The basic framework and techniques from this model were taken and modified to fit the diesel engine maintenance process for an underground mining operation.

The audit model template has been included in the appendix section of the report. This is the actual model that was used for conducting identical site audits at both Ruttan and Strathcona Mines.

Site Selection

For confidentiality reasons and the public nature of this document, the details of the final reports from each site audit are not included in this report. The following summary outlines the results presented to the DEEP Technical Committee including the key points discovered from the audits and justification for selection of Strathcona Mine as the host site for the project.

Executive Summary - Site Review Process

The team for the DEEP Maintenance Project completed two site reviews of potential candidates for hosting this project. The HBM&S Ruttan Mine in Leaf Rapids, MB was reviewed in mid July ’98 and Falconbridge's Strathcona Mine in Onaping, Ont was reviewed in mid August ‘98. The final reports for each site were completed and presented to each mine individually and the DEEP Technical Committee.

The summary section at the end of each final report outlined the strengths, weaknesses, opportunities and threats that were established from each review. These were presented at each site with a draft report and closing presentation of findings on the last day of each review. The strengths and weaknesses are findings that are specific to the site and how effective they are at maintaining diesel engines. The opportunities and threats are specific to how this project could potentially succeed or fail based on findings of the review. The following table outlines a comparison summary of the opportunities and threats from each site review as a guideline for decision on the most suitable site to host the project.

HBM&S - Ruttan Mine		Falconbridge Ltd - Strathcona Mine	
Opportunity	**Threat**	**Opportunity**	**Threat**
	Replacement of LHD fleet this fall - loss of baseline	Training - There is considerable training infrastructure available in Sudbury for implementing into this project	
	Location -Leaf Rapids is difficult and costly for travel	Location - Sudbury is within driving distance and 1/4 the cost of travel to Leaf Rapids	
	Absence of a high impact maintenance issue		Absence of a high impact maintenance issue
		Engine Profile - there is a near perfect profile of different engines to include in the study	
		Marcam and CatBase Existing CMMS and electronic parts systems that can be utilized and implemented for this project	
		Existing Emissions Data - Potential for including existing CO test data in baseline data study	
		CANMET - Sudbury The laboratories here could be utilized for support of the DPM apparatus and gravimetric analysis	

Table 1 - Summary of Maintenance Audits

Based on the above summary, the selection of Falconbridge Ltd - Strathcona Mine was recommended as the most suitable site for hosting this project. This decision was based on the total number of potential threats to project success at Ruttan compared to the total number of potential opportunities for project success at Strathcona.

Regardless of which site was chosen to host this project, the review process added value to both mines and all parties involved. It added educational value to DEEP as a new tool and added value to the operations at each site with respect to understanding diesel engine maintenance practices and where their specific needs lie.

Maintenance Guidelines and Best Practices

A critical component in implementing improved engine maintenance practices was to have a guide to assist in building an implementation plan. In parallel to the work on the audit template a set of guidelines and best practices was put together. The foundation for this was based on the previous research from the Bureau of Mines and the six engine system approach as was the case with the audit template.

The first step was to assemble a small group of people with extensive experience in maintaining diesel engines on underground equipment. [2] This group had the task of laying out the framework for the guidelines and providing input based on accumulated experience. The bulk of this work was done during a face to face brainstorming session with all five members in the group with follow up afterwards in assembling the actual materials. The framework for the guidelines was broken down from two main categories, engine systems and operational issues. Each category was divided evenly in terms of relevance and importance to engine maintenance. The prioritized order of engine systems became:

1) INTAKE
2) EXHAUST
3) FUEL INJECTION
4) COOLING
5) FUEL QUALITY AND HANDLING
6) LUBRICATION

Beyond the six-system approach the group identified additional key areas that are critical to proper engine maintenance. These are broken down under operational issues:

1) ATTITUDES
2) TRAINING
3) TOOLS
4) PROCESS AND PRACTICES
5) PM & ENGINE REPAIRS

The first version of the guidelines and best practices was brought into use at the mine after the first 2 months of measuring emissions and gathering baseline values. A meeting was held with mine staff to discuss the results of the baseline emissions and to re visit the results from the audit. The guidelines and best practices were brought out at this time to compare against the audit and build an action plan for implementing improved maintenance. The action plan consisted of:

1) IMPROVE FUEL AND LUBE HANDLING
2) REWORK PM STRUCTURE AROUND ENGINE SYSTEM APPROACH
3) NEW TOOLS
4) TRAINING – INDIVIDUAL AND CASE STUDY APPROACHES
5) FOCUS ON EACH ENGINE SYSTEM AND IMPROVING ON EACH

Each point in the action plan had a link back to the guidelines and best practices. Fuel and lube handling was well defined in the guidelines and used as a start in planning how to clean up the existing system for handling fuel and lube cubes. The engine PM structure was very unspecific in nature and was rebuilt with particular focus on each system in accordance with the guidelines. New tools were included in the project from those described in the guidelines as well as some that were developed as a result of discussion with the mine team and later added to the guidelines. The best example of this is the intake testing system described in the current version of the guidelines and best practices. The use of ether spray was not possible for testing intake systems so an alternative method was required. The team at the mine came up with the idea of pressurized testing with soap and water, which proved to be extremely effective.

The guidelines and best practices has been a continuous work in progress with new ideas added as the project moved on and even beyond the completion of the field work. A document of this nature should, and will continue to evolve as ideas are shared amongst peers and technologies evolve. The guidelines and best practices are included in the appendix section of the report.

Emissions Test Equipment

Introduction

The first step in doing the field work at Strathcona Mine was to set up the emissions testing equipment that would be used throughout the project as the method of measurement for progress from start to finish. A system was assembled that was basic enough in design for mechanics to be able to train and perform regular emissions tests on their own at scheduled maintenance intervals.

The emissions testing system was comprised of a component for measuring undiluted gas emissions in parallel with a component for measuring undiluted particulate emissions. The most critical component was the testing protocol which brought the sampling components together in a repeatable sequence that the mechanics could follow to perform consistent tests throughout the project on their own.

Undiluted Exhaust Gas Measurement

The framework for the emissions testing was built around the Undiluted Gas Analysis System (UGAS) developed by Noranda Technology Centre.[3] This system incorporates an ECOM AC electronic gas analyzer for measurement of gases using electro-chemical sensor technology as well as sensors for temperatures and pressures. The analyzer is capable of communicating data through an RS-232 communication interface. The UGAS software application was developed specifically for communicating with the ECOM analyzer. The Windows interface was developed to be an intuitive tool for mechanics to use in diagnosing engines. A testing protocol was built into the testing system so as to guide the mechanics through the sampling process so that the tests could be repeatable and accurate for comparison purposes. The gas analyzer, personal computer and related hardware are all assembled in an industrial enclosure on wheels capable of being rolled to a vehicle for engine and emissions diagnostics.

Figure 1 - Emissions Testing System

ECOM AC+ Gas Analyzer

The first component is a commercially available ECOM AC+ electronic gas analyzer, which measures oxygen, carbon monoxide, nitrogen oxide, nitrogen dioxide, gas temperature, and gas pressure. All gas sensors are electro-chemical with a thermocouple and RTD sensor for temperatures, and a piezo resistive sensor for pressure. From the measured parameters the analyzer also calculates additional parameters such as carbon dioxide, total oxides of nitrogen and combustion efficiency. The instrument can incorporate up to six gas sensors, however sulphur dioxide and hydrocarbons sensors are not being used in the UGAS system. A probe and 15 feet of non-heated sampling line connect the analyzer to the exhaust system. Each exhaust system is fitted with ¼" NPT fittings for measuring undiluted exhaust through the probe.

Parameter Description

Measured Parameters	Range	Accuracy	Resolution
Oxygen (O2)	0 - 21%	2% of reading	0.1%
Carbon Monoxide (CO)	0 - 4000 ppm	4% of reading	1 ppm
Nitric Oxide (NO)	0 - 4000 ppm	4% of reading	1 ppm
Nitrogen Dioxide	0 - 500 ppm	4% of reading	1 ppm
Sulfur Dioxide (SO2)	0 - 5000 ppm	4% of reading	1 ppm
Combustibles (CxHy - Hydrocarbons)	0 - 6 %	4% of reading	0.01%
Ambient Temperature	0 - 250° F	3 degrees	1° F
Stack Temperature	0 - 1600° F	3 degrees	1° F
Stack Draft	0 - 40.0" H2O	2% of reading	0.01" H2O

Calculated Parameters	Range	Resolution
Combustion Efficiency	0 - 100%	1.0%
Carbon Dioxide (CO2)	0 - 40%	0.1%
Lambda (λ)	0 - 50%	0.01%
Losses	0 - 100%	1.0%
O2 Correction	0 - 10,000 ppm	1 ppm

The instrument is capable of operation as a stand-alone device, which can acquire gas parameters and print out results. Operations can be performed using the membrane keypad and LCD display. Instantaneous snapshots can be saved into analyzer memory and printed out. Each subsequent sample erases the previous sample from memory. As a stand-alone device the instrument lacks the flexibility to acquire time weighted average samples and store historical data in memory. To overcome this the RS232 serial communication port on the analyzer was utilized. This port communicates all data in real time as it is acquired from the sensors. Communicating this real time data to a software interface permits the flexibility required to store time weighted average samples to an integrated database.

Figure 2 - ECOM Gas Analyzer

UGAS Software Application

The second module of the system is a custom designed Windows software application that communicates directly with the analyzer displaying in real time all measured and calculated values. The interface was designed to be as intuitive as possible for the intended end users, underground mobile mechanics. The gauge controls in the software as shown in figure 3, permit the user to configure warning and alarm display levels for each parameter. The gauge control display window has the flexibility to configure any combination of parameters up to a maximum of eight on each of the two windows.

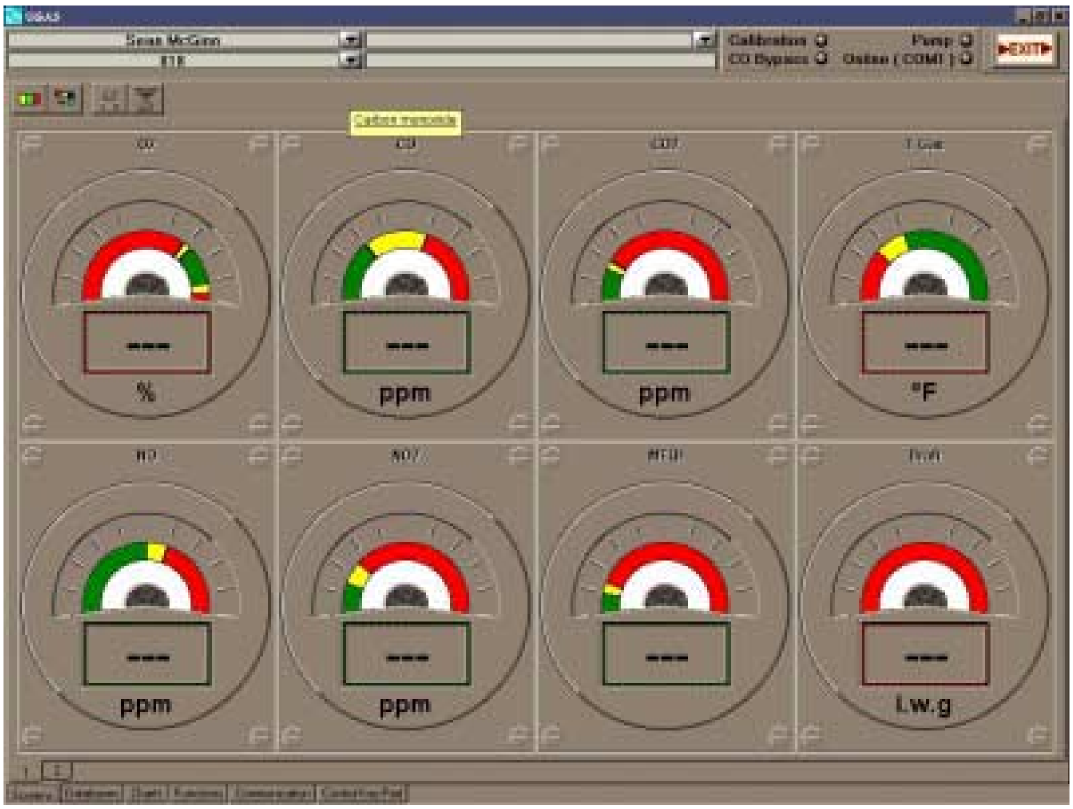


Figure 3 - UGAS Software

The remaining three main display windows are for graphic chart analysis, custom function editing, and databases. The chart analysis window has a list of query filters to select from in querying historical databases. Filters include vehicle number, vehicle type, location, dates and other related fields. The results of each query are displayed in an adjacent graphic analysis screen with flexibility to arrange the data in several different formats.

A function calculator screen is provided to the user for customizing parameters. The function calculator screen allows the creation of custom mathematical functions between the acquired parameters in the database. An example of this is NO_x, which is the sum of NO +NO_2. As functions are created they are added to the list of parameters and draw on the historical data to calculate individual values. Another feature of the function screen is a configuration menu for target values for each parameter on each type of engine.

The database is a series of tables that combine to provide functionality to the software, as well as detailed and descriptive historical data. Multi-level security access has been built into the application to ensure consistency in testing and protect the databases from possible loss due to corruption.

Mechanics log into the application under low level security access and are provided with all necessary tools to conduct the sampling process from start to finish. They are also provided with access to the graphic analysis tools for troubleshooting and evaluating trends. All configuration and database access tools are disabled under low level access. An integrated testing procedure has been built into the software to assist the mechanics in testing emissions. A sequence of screens and menus guides the mechanic from start to finish in the testing process.

Lookup tables from the database provide automated entry of data such as description identifiers for each test. At the completion of a test the final screen provides a test report for the mechanic with measured values, target values, time, date, and user and vehicle information. He then has the option of printing the report and or saving the values to the local database.

A system administrator is responsible for maintaining the software configuration and databases. A large part of this responsibility is ensuring that the databases are backed up on a regular basis to protect the historical data. The software is capable of running on a network where other users are able to access the historical data to view emissions histories and perform filtered searches on the database.

Testing Protocol

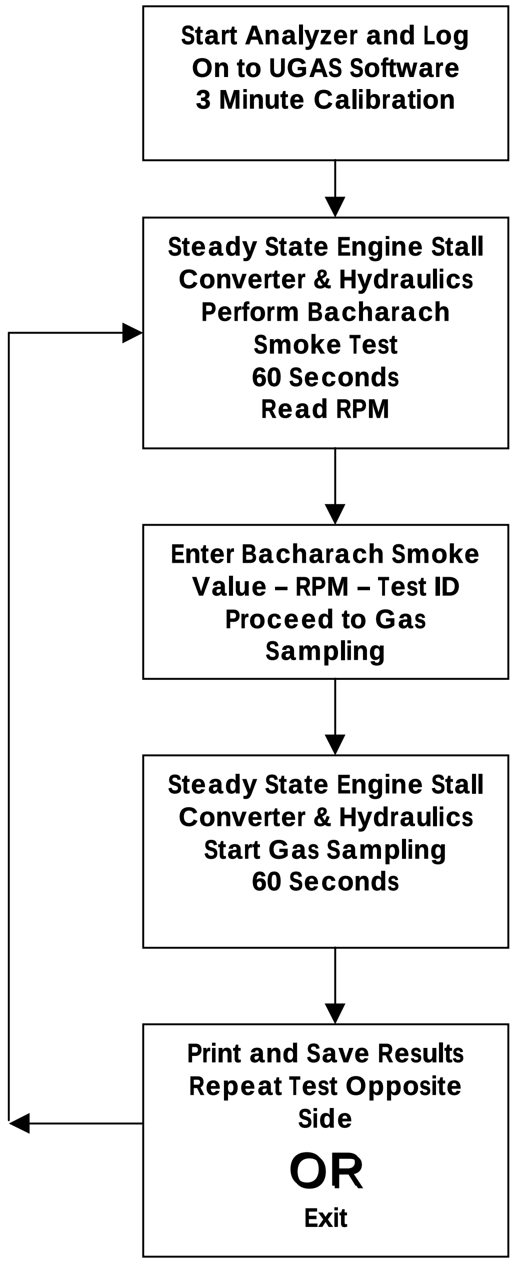
The third and most critical component is the test protocol. In collaboration with CANMET, a standardized protocol for performing a complete undiluted exhaust test on U/G diesel engines was developed. The protocol accounts for all factors from pre test conditions through engine loading factors to time weighted average sampling. Both pamphlets and on-line multimedia tutorials are provided to assist the mechanics and make the protocol as intuitive as possible. The test protocol is designed to ensure, to the greatest degree possible, accurate and consistent testing of diesel exhaust emissions on underground mobile equipment.

Pre Test Conditions

Before taking tests the mechanic must ensure three basic conditions before proceeding:

- ❖ Engine is at full operating temperature.
- ❖ The vehicle exhaust is equipped with ¼" NPT fittings on each side of the exhaust purifier(s). These fittings allow for the insertion of the analyzer probe to acquire undiluted exhaust samples.
- ❖ An instrument such as a hand held photoelectric tachometer is available for measuring engine rpm during tests.

Emissions Testing Protocol



Note:
Exceeding a 60 second stall condition can potentially cause damage to transmission and hydraulic systems. Use of caution and careful monitoring of all temperatures is advised!

UNDILUTED DIESEL PARTICULATE MEASUREMENT

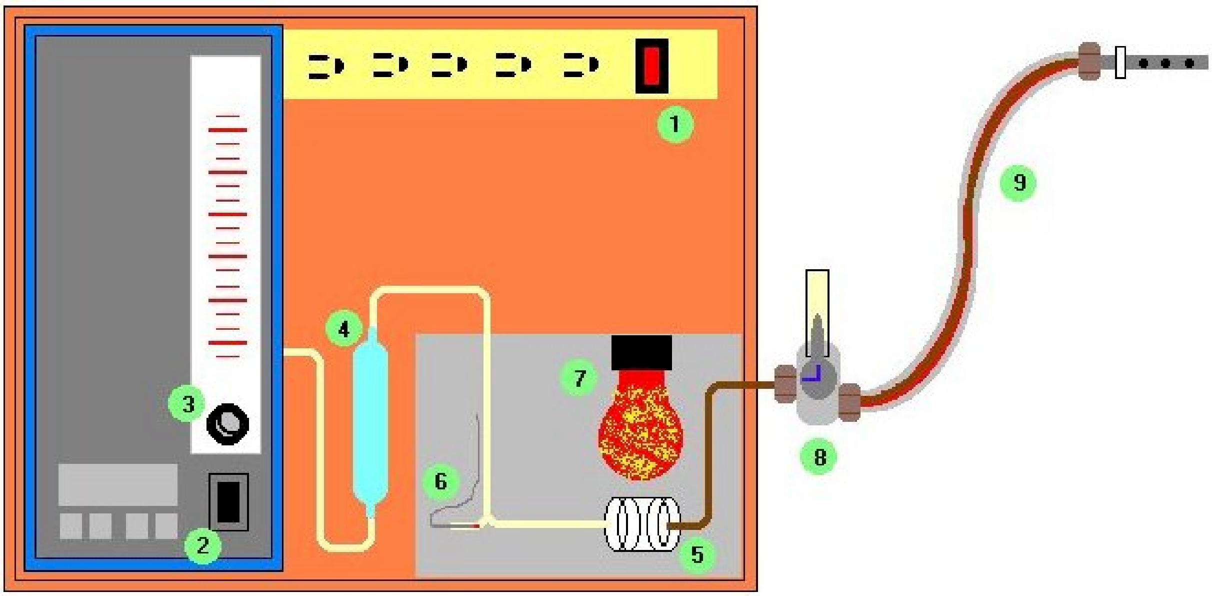
In addition to diesel exhaust gases which are easily and commonly measured, the particulate component was also required to be measured and included for the project. Other than opacity instruments with a correlation to particulate, a portable instrument for measuring undiluted diesel particulate is not commercially available.

Figure 4 - Simultaneous Gas and Particulate Sampling

CANMET has developed a simple portable system for sampling of undiluted particulate matter from vehicles in production. In this system the DPM sample is collected on a pre-weighted filter. After the sample collection, the filter is weighed again to get the total weight of the sample collected during a fixed cycle. The sample is drawn using a constant flow pump for the duration of a cycle. The volume of exhaust gas passed through the filter is obtained by the pump flow rate and sampling duration. The DPM concentration is obtained by dividing particulate mass by the volume of exhaust gas passed through the filter. In the original configuration, a sampling duration of 10 to 20 minutes was employed at a flow rate of 2.5 LPM. However, for this project a higher flow rate for a shorter duration was required. To accomplish this the system was modified to accommodate a Gilian high volume pump calibrated to 12 LPM for a 60 second duration. This was done so the mechanics would be able to take both the gas and particulate samples simultaneously for the 60 second steady state stall condition.

The system uses a stainless steel sampling probe which is inserted in the exhaust pipe. The sample probe is connected to a 15 foot heated line and to a filter cassette. The sampling line is heated continuously using power from the vehicle battery. A proper heated line is essential to make sure that there is no condensation in the sampling line. The sample on the filter is drawn using a calibrated constant flow pump. The system includes sampling probe, heated lines, filter cassette, moisture drier, constant flow pump, and temperature sensor. The temperature of the exhaust gas at the pump location is recorded by the ambient thermocouple form the ECOM analyzer which is simply fitted into the system. As with all other points from the ECOM analyzer, ambient temperature was recorded as a time weighted average over the 60 second stall test. In this system no attempt was made for isokinetic sampling as bulk of the DPM is in submicron size and, therefore, errors introduced due to partial inertia are considered small and non-isokinetic sampling significantly simplifies the sampling system.

Figure 5 - Particulate Sampling System



1. MAIN POWER SWITCH
2. PUMP SWITCH
3. PUMP FLOW ADJUSTMENT
4. DESSICANT DRIER
5. DPM FILTER CASSETTE
6. TEMPERATURE THERMOCOUPLE
7. CASSETTE HEATER
8. DIVERTER VALVE
9. HEATED SAMPLE LINE & PROBE ASSY

Figure 6 - UPSS Schematic

Analysis of Particulate Samples

Measurement and analysis of the particulate sample filters was done at the NRCan CANMET laboratories in Sudbury and Bells Corners, Ontario. Weight analysis for total mass was done at the Bells Corners facility and the analysis by NIOSH 5040 Thermal Optical method [4] was performed at the Sudbury laboratory.

Weight Analysis

- Sample filters (silver membrane) were conditioned in an environment chamber for at least 1 hr at 45% RH +-8%, 22oC +_3oC.
- A Mettler 183 balance, accuracy 1g +-0.00001 g was calibrated using internal calibration procedures.
- A blank filter pair were weighed for determining filter weight changes due to variations in conditions within the weighing chamber between initial and final sample weight determinations.
- Sample filters were weighed and placed in plastic sample holders which were then capped.
- Upon the sample filter's return, filters were removed from plastic sample holders, placed in petrie dishes, covered and conditioned in an environment chamber for at least 1 hr at 45% RH +-8%, 22oC +_3oC.
- The Mettler 183 balance was calibrated using internal calibration procedures.
- The blank filter pair were weighed.
- Sample filters were then weighed.
- DPM mass was determined by subtracting initial from the final sample weights, correcting each DPM for changes in blank filter weights.
- During the field testing 3 batches of sample cassettes were assembled with blanks and shipped to the mine. The numbered cassettes were stored in a locker in the underground shop and brought to the office on surface after sample capture. Cassettes including blanks were sent to the CANMET laboratory in Bells Corners for analysis.

Thermal Optical Method

In brief, NIOSH method 5040, speciation of organic and elemental carbon is accomplished through temperature and atmosphere control, and by an optical feature that corrects for pyrolitically generated “EC” (or char) formed during the analysis of some materials (e.g., cigarette and wood smoke). A light from a pulsed diode laser is passed through the filter to allow continuos monitoring of filter transmittance. The analysis process is done in two stages.

In the first stage, organic carbon and carbonate carbon (if present) are volatized from the sample in a pure helium atmosphere the temperature is stepped to a maximum (about 860^{o}C). Evolved carbon is catalytically oxidized to CO_2 in a bed of granular MnO_2, reduced to CH_4 in a Ni/firebrick methanator, and quantified as CH_4 by a flame ionization detector (FID).

During the second stage of the analysis, a pyrolysis correction (if needed) and EC measurement are made. The oven temp is reduced, an Oxygen (2%)-helium mix is introduced, and the oven temperature is again raised. As oxygen enters the oven, pyrolitically generated EC is oxydized and a concurrent increase in filter transmittance occurs. Correction for the char contribution to EC is accomplished by identifying the time at which the filter transmittance reaches its initial value. This point is defined as the "split" between organic and elemental carbon. Carbon evolved prior to the split is considered "organic" (including carbonate), and carbon after the split and prior to the peak used for instrument calibration (final peak) is considered "elemental."

The 5040 method was used to analyze the first set of samples that were taken on quartz fiber filters. This was done due to inconsistencies measuring total weight due to high humidity combined with quartz fiber filters. There were 21 samples in the first set analyzed with 5040 and quartz fiber filters. For correlation purposes and verification of accuracy, three samples with silver membrane filters were measured with 5040 and correlated to previous samples on the same vehicles with quartz fiber.

Calibration of Instrumentation

ECOM AC+ Gas Analyzer

The electro-chemical gas sensors used in the ECOM unit are recommended for calibration every 6 months. The analyzer for the project was purchased new from ECOM America and was delivered with all sensors calibrated. The calibration gases used are:

Carbon Monoxide – 1000 ppm
Nitrogen Oxide – 100 ppm
Nitrogen Dioxide – 100 ppm
Oxygen – Verified against O_2 concentration in NO or NO_2 cal gas

The ECOM analyzer incorporates a 3-minute calibration each time the unit is started. All gas sensors are "zeroed" against the ambient air drawn through the probe for the 3-minute period. For this reason it is critical that each time the analyzer is turned on the probe remains in as fresh an ambient environment as possible and nowhere near any running exhaust gases.

Particulate Sampling – Gilian Pump

The undiluted particulate sampling system incorporated a Gillan high volume 30 LPM pump for drawing the exhaust through the 37 mm cassettes. Under ideal conditions this instrument would be calibrated for each sampling session. In the case of this project however, the mechanics were relied upon to conduct the tests on their own, unassisted. Calibration of this instrument was beyond the scope of the mechanics expected work and therefore had to be performed by project leader

Over the 6 month period of field work where the particulate sampling system was employed, the Gilian pump was calibrated a total of 7 times. A Gilibrator primary standard airflow calibrator was used for calibrating the pump. A 2 – 30 LPM flow cell was used for generating pulsation bubbles to calibrate the pump at 12 LPM for the exhaust sampling. Calibration marks were put on the flow scale of the pump for the mechanics to centre the flow ball for each test. The calibration setup included a 37 mm cassette filter assembly and a desiccant drier in line with the pump. All pump calibrations through the project were found to be within + - 5% of the flow rate setpoint.

Figure 7 - Calibration of Gilian Pump

Acquiring Baseline Emissions

Introduction

With the emissions testing equipment in place the next step in the project was to acquire an emissions baseline. A significant advantage in hosting the project at Strathcona Mine was the wide spectrum of engine technologies and manufacturers. The vehicles chosen to be included in the study were all scooptrams with mid to high range horsepower engines. This decision was taken in order to cover the highest horsepower range in the mine as well as facilitating the emissions testing protocol of full load steady state – converter and hydraulic stall. Many light duty vehicles either use manual transmissions and or do not incorporate a hydraulic system for loading the engines. The one exception to this case was the inclusion of a Caterpillar M120 grader with a 3304T engine. This vehicle was included for a broader spectrum with a Caterpillar mechanically injected engine in the project.

In parallel to acquiring the emissions baseline the mechanics were individually trained to take accurate and repeatable tests. In total 16 mechanics and leaders were trained to use the emissions testing equipment and follow the test protocol. On average, training for each mechanic took four hours. During the training for each person the project goals were explained and specifically the baselining stage of the project. Each mechanic was made aware that for this first stage we would only be measuring emissions without making any changes to current maintenance practices. The instinct to investigate and solve problems detected with emissions testing would come into play later in the implementation stage of the project. This point of not making any changes or improvements during baselining was strongly emphasized with each mechanic.

Vehicles and Engines

The scooptram fleet at Strathcona Mine can be divided into two sections. The smaller JCI machines are used for mucking in the development headings. From the heading the scoop will haul to an intermediate relay point. The larger ST8-Bs are used to draw muck from the intermediate “re-muck” bay and haul to the ore passes.

The smaller scooptrams are equipped with 2 different models of Deutz mechanically fuel injected engines. The F5L413FW engine is an in-line 5 cylinder air cooled engine with a Bosch in-line type fuel pump system. The newer technology BF4L1013 engines are an in-line 4 cylinder water cooled engine with unit injection fuel pumps operating off the camshaft with injector nozzles in the cylinder head.

The ST8-B scooptrams use the Detroit Diesel Series 60 engine technology. This is an in-line 6 cylinder four stroke engine with an electronic unit injection fuel system. The DDEC system controls fuel injection and combustion through a network of electronic sensors and central processing.

Vehicles 219 and GR002 were included in the study to improve the mix of engine technologies. Both machines are equipped with Caterpillar 3304 engines. Vehicle 219 has a naturally aspirated intake system while GR002 has a turbocharged engine. Both vehicles were slight exceptions to the profile as 219 is a scooptram that has been retrofitted to a forklift and GR002 is a grader.

Veh #	Mfgr	Location	Model	Engine
201	JCI	3900	JCI-250M	F5L413FRW
203	JCI	3900	JCI-250M	F5L413FRW
204	JCI	3900	JCI-250M	F5L413FRW
205	JCI	3900	JCI-250M	F5L413FRW
207	JCI	3900	JCI-250M	BF4M1013
208	JCI	3900	JCI-250M	BF4M1013
209	JCI	3900	JCI-250M	BF4M1013
210	JCI	3900	JCI-250M	F5L413FRW
219	JCI	3900	JCI-220M	3304
818	WAGNER	3900	ST8B	SERIES60
819	WAGNER	3900	ST8B	SERIES60
820	WAGNER	3900	ST8B	SERIES60
GR002	Caterpillar	3900	M120	3304T

Table 2 - Profile of Vehicles in Project

Baseline Emissions

Acquiring emissions measurements on all the vehicles for a baseline proved to be a challenge in more ways than one. To minimize the inconvenience and impact to mine production the project worked around existing availability and schedules as much as possible. This meant that vehicles included in the study were tested as they showed up in the shop for any type of repairs. The first set of tests on each vehicle required the installation of 4 test fittings on the exhaust system – 2 upstream of the purifier and 2 downstream. The ¼ " NPT fittings required drilling and welding on the exhaust piping which could take up to a few hours depending on availability of equipment, welders, etc. Once the fittings were installed the emissions testing would be done, which for the first few months would take longer than usual due to the training for emissions testing for individual mechanics. Each mechanic was walked through the process as many times and as slowly as necessary to understand and be able to repeat the test process. For these reasons the vehicles were only tested as they became available in the shop to minimize interference to production to the project. If a vehicle was already down for repairs in the shop we could most often do a test without interrupting shop activities and mine production saw no added disruption.

The emissions measurement process itself required some debugging through the baseline stage as well, in particular the particulate sampling. The first set of cassettes were assembled using glass fiber filters. This proved to be a major problem in that the measured mass of the filters came out to be less after the samples were loaded with diesel particulate than when they were measured new before assembly. The reason for this was determined to be a problem with the compression of the 37 mm plastic cassette assemblies and a crushing action on the glass fiber filters. The end result was a negative mass value for each of the glass fiber samples taken in the first set. To compensate for this each of the samples was also analyzed using the Thermal Optical – NIOSH 5040 method to determine the total carbon value along with the split between elemental and organic carbon. For this reason some of the DPM values shown in the tables below will be indicated as total carbon (TC) instead of the standard mass measurement.

There were also some problems for the first month or two with getting repeatable sampling for every sample on particulates. The mechanics were able to go through the process for testing gas emissions because the process was heavily integrated and automated, although there was the occasional case of improper steady state stall conditions or advance warm up. Following the steps for particulate sampling at the same time as gas sampling proved to be more of a challenge for the first while. While the mechanic took the gas test he had to perform several steps such as positioning the cassette in the sampling line, setting the pump flow, and timing the start and finish of the sample. When the mechanics were on afternoon or night shift and tried to do tests on their own some of the samples would be either taken improperly or not at all. The tests logged in the database would show up as gas emissions values only with nothing entered for particulates. Through the course of the baselining stage we were able to correct these problems with better training and instructions for the mechanics.

All of the situations described above should help explain any obvious discrepancies in the baseline emissions tables below. Some of the vehicles show very few tests done over the baseline period while others have many. This is due to the availability in the shop for these vehicles to have tests performed. The vehicle emissions baselines shown below are for those vehicles that were selected for the case studies later in the implementation stage of the project. This gives a comparison of the baseline values here to the emissions with improved maintenance in the case study. The emissions values for all vehicles in the project were formatted in an Excel spreadsheet file. Due to the sheer size of the amount of raw data for all emissions tests on all vehicles in this file, only the four vehicles from the case studies are explained in detail here.

207 Scooptram

Test	Desc	O_2 %	CO ppm	CO_2 %	NO ppm	NO_2 ppm	Smoke Index	DPM mg/m^3
1	UPSTR	11.80	184.17	6.73	442.37	32.47	9	6.00
2	DNSTR	12.97	32.00	5.88	374.77	25.37	9	143.00

Table 3 - Baseline Emissions 207 Scoop

Unfortunately 207 was one of the rare situations where we were only able to perform one set of emissions tests in the baseline stage. The gas emissions values appear to be fairly consistent with other 1013 series Deutz engines that were tested in the project. The excellent CO conversion efficiency is certainly consistent with all scooptrams of this model. The DPM values however, are definitely inconsistent. Both samples were taken using silver membrane filters, which proved to be very consistent through the project, but the extremely low value for the first sample indicates a problem possibly with the taking of the sample. On the other hand, the second DPM value would appear to be higher than normal, which could also be explained as before.

818 Scooptram

Test	Desc	O_2 %	CO ppm	CO_2 %	NO ppm	NO_2 ppm	Smoke Index	DPM mg/m^3
1	No DOC	10.88	170.9	7.43	2322.27	35.53	6	*5.6
2	No DOC	11.1	116.83	7.3	1439.13	24.2	7	*5.5
3	No DOC	12.51	118.2		461.7	15.5	7	
4	No DOC	13.23	127.13	5.69	307.03	17.53	7	
5	No DOC	10.83	95.233	7.48	617.47	22.3	8	
6	No DOC	12.67	100	6.12	392.43	22.47	6	
7	No DOC	12.15	123.44	6.48	393.53	16.95	9	7.5
8	No DOC	13.02	130.31	5.83	289.98	18.42	6	9.17
9	No DOC	12.81	156.08	6.02	401.64	12.73	9	
10	No DOC	13.36	175.55	5.59	432.39	13.11	7	
11	No DOC	12.58	126.27	6.16	802.62	17.82	9	8.33

*Total Carbon measured using Thermal Optical method **

Table 4 - Baseline Emissions 818 Scoop

In the instance of 818 we were able to take many tests. What appears to be 11 separate tests is actually 5 sets of tests (upstream / downstream) and 1 separate test. Originally it was thought that this machine was equipped with a diesel oxidation catalyst (DOC) identical to all the rest. Later in the project but before the case study it was discovered that in fact under the insulation wrap on the exhaust system there was only a silencer with no purifier. Therefore on tests 1 thru 10 although they indicate simply “No DOC” they are in fact 5 sets of tests upstream and downstream of the silencer!

The gaseous emissions show fairly good consistency both with respect to this individual machine as well as others with Series 60 Detroit Diesel engines. The particulate emissions are fairly representative as well and certainly consistent with the other Series 60 engines. It is also interesting to note the fairly good correlation between the Thermal Optical samples at the top compared to mass – total weight analysis.

820 Baseline

Test	Desc	O_2 %	CO ppm	CO_2 %	NO ppm	NO_2 ppm	Smoke Index	DPM mg/m^3
1	UPSTR	10.39	82.97	7.8033	537.53	27.33	6	*2.9
2	DNSTR	10.28	62.47	7.82	569.3	30.23	7	*3.9
3	UPSTR	9.6	70.33	8.4	1811.77	151.77	3	13.33
4	DNSTR	18.2	0	2.1	55.57	2.2	6	5.83
5	UPSTR	19.37	25.6	1.1933	129	12.47		
6	DNSTR	14.92	46.13	4.4627	291.93	26.36		

**** Total Carbon measured using Thermal Optical method***

Table 5 - Baseline Emissions 820 Scoop

We had the opportunity to acquire 3 sets of emissions tests on 820 during the baseline. Once again the DPM values correlate fairly well between Thermal Optical and mass measurement as well as consistent with other Series 60 engines.

GR002 Baseline

Test	Desc	O_2 %	CO ppm	CO_2 %	NO ppm	NO_2 ppm	Smoke Index	DPM mg/m^3
1	UPSTR	14.60	284.27	4.68	188.53	50.70	9	
2	DNSTR	14.70	215.30	4.60	208.47	27.00	9	
3	UPSTR	15.13	319.40	4.29	235.90	49.83	9	151
4	DNSTR	15.25	259.60	4.25	252.83	24.60	9	116
5	UPSTR	15.51	201.16	4.04	247.31	33.18	8	135.83
6	DNSTR	15.57	193.34	3.96	225.01	17.42	8	114.17
7	UPSTR	15.30	288.67	4.20	271.58	63.31	9	
8	DNSTR	15.22	179.69	4.28	294.99	36.18	9	

Table 6 - Baseline Emissions GR002 Grader

In total there were 4 sets of tests done on the grader during baselining. The gaseous emissions values are very consistent between all sets. This was the only engine in the study of its type so there are no other engines to compare against in this case. The particulate emissions, although only sampled for 2 of the 4 sets also show good consistency. The DPM samples were acquired using silver membrane filters and total mass measurement.

Implementing Improved Engine Maintenance

Introduction

Upon completion of the baselining phase of the project a team meeting at Strathcona was held to discuss what the next steps would be in implementing improvements to the current engine maintenance system. The first step was to review the results of the baseline emissions testing and have a second look at the results from the engine maintenance audit that had been done at Strathcona a few months earlier. The second step was to make a short list from the audit results of the most easily do-able improvements with respect to time, resources, cost and complexity. The final step was to take the list of improvements and look to the *Guidelines and Best Practices* for a solution to each.

Maintenance Process Improvements

Changes to the existing process for maintaining engines at Strathcona would be the largest in scope and therefore the most challenging to implement. In some cases however, the items addressed had been internally discussed by mine management in the past and therefore were simply justification for completing past commitments.

Fuel and Lubrication Oil Management and Handling

This was one of the more obvious weaknesses discovered during the audit and was an item that had been addressed by mine management in the past. A survey of the handling and storage system for managing fuel and lube oils revealed that there was little if any accountability for any mine department in maintaining the plastic cube reservoirs. These reservoirs are moved between surface and the underground fuel bays. Empty cubes are brought to surface where they are refilled from bulk storage and then brought back underground. The problem was that no responsibility and follow up had been given to maintaining and cleaning the cubes between emptying and filling. A tour of the underground fuel bays revealed both fuel and lube cubes contaminated with dirt, garbage and water inside as well as fill covers cracked or broken leaving the contents exposed to contamination from the atmosphere. Discussions with mechanics revealed chronic problems with this system and reports of water contamination while filling engine crankcases with fresh lube oil during PM service.

The solution to the problem was quite simple and easy to implement. A service contract was given to an off site contractor to maintain the cubes on a scheduled basis. Each cube was given an identification code and scheduled to be sent out for service. Service would include complete inspection, cleaning inside and out, and structural repairs as required. The entire inventory of fuel and lube cubes was set into a rotating schedule for service.

Figure 8 - Lube Cube Before Service

Figure 9 - Lube Cube After Service

Engine Lube Oil
It was discovered that Strathcona had two separate engine lube oils in use. The primary engine lube oil was a recycled 30 grade oil supplied from Breslube. This oil was used for engine crankcases in all mobile equipment except for the Detroit Diesel Series 60 engines in the ST8-B scooptrams. The recycled 30 oil was managed in bulk with the cube reservoirs explained above. The second lube oil in use was a 15W40 multi grade oil used for the Series 60 engines only based on the strong recommendations from Detroit Diesel. This oil was managed in both 5 gallon plastic pails as well as 1 liter plastic containers. The oils classifications for each were applied to the chart in the Guidelines and Best Practices for applicability.

- Recycled 30 Oil — CC Rating
- 15W40 Oil — CH-4 Rating

Classification "Commercial"	Application	Meets OEM Requirements for:
CC	Moderate to severe duty diesel and gasoline	MIL-L-2104B; 1964
CH-4	Severe duty diesel engine service	High speed, 4-stroke engines since 1998

Upon further investigation it was discovered that the CC rated oil was currently recommended for topping up purposes only and not for primary engine crankcase lubrication oil.

For these reasons the decision was taken to discontinue the use of the recycled 30 oil at Strathcona in favour of one standard premium multi grade oil maintaining a CH-4 rating.

Restructuring Engine PMs – System Approach
The existing scheduled Preventive Maintenance (PM) routine on mobile equipment at Strathcona was felt to lack the proper focus on specific systems with respect to engines. It was agreed that the existing PM details remained valid and necessary but that additional points had to be added specifically to deal with engine system diagnostics. The new knowledge, skills, training and tools that were implemented as part of this project needed to be incorporated into the PM structure. In order that this would work effectively and be accepted by the mechanics a separate engine diagnostic evaluation PM was created to allow mechanics sufficient time and focus to prove and practice the condition based maintenance principles. The engine system diagnostic PMs were scheduled separately from the other standard PM and allowed the mechanics sufficient time to make all the checks on the list and objective evaluations. The list was constructed based on the engine system approach in the *Guidelines and Best Practices* and the new tools implemented as part of the project. Frequency for the engine diagnostic PMs was set at 250 hours in parallel with the vehicle PMs and in accordance with engine manufacturers recommended service intervals.

```
Date :  6/08/99          FALCONBRIDGE LIMITED - SUDBURY OPERATIONS       WOR103
Time : 10:03:45
User : PLANSTUMP1                          Work Order

Project #

W/O #       Entity number                 Type      Sub      Cls      Pty  Requested
813505      16TESTSCOOP001                EQ        M        PM       PM     6/08/99
            TEST SCOOP I.D. FOR OPERATING STATS.
--------------------------------------------------------------------------------------
Supervisor- Blake R.J                      Originator-   LACROIX
Planner   - LACROIX G.                     Required      6/08/99
                                           Wo Type       M
Job Description : 1NGINE EXHAUST EMISSIONS AND INTAKE SYSTEM PM


Work Order Manpower
        Trade Men Hrs       Trade Men Hrs       Trade Men Hrs       Trade Men Hrs
--------------------------------------------------------------------------------------
        IM3     1     4.00

         Task
Seq#  Activity                                                   Charge
--------------------------------------------------------------------------------------
 1.0  ENGINE EXHAUST EMISSIONS AND INTAKE SYSTEM PM          813505 01
      BEFORE STARTING TESTS MAKE SURE ENGINE IS AT FULL OPERATING TEMP

      **CAUTION**
      TAKE APPROPRIATE SAFETY PRECAUTIONS AROUND HOT EXHAUST AREA

      INTAKE SYSTEM TEST
      ------------------
      1) REMOVE AIR FILTER(S) AND INSERT PLUG FILTER(S)
      2) CONNECT REGULATOR AND PRESSURE CHARGING ASSY AT #4 FITTING
      3) REGULATE STATIC PRESSURE IN INTAKE TO 25 PSI MAX
      4) SPRAY SOAP & WATER SOLUTION ON ALL FLANGES, COOLERS, CLAMPS,
         HOSES AND CONNECTIONS
      5) CHECK FOR LEAKS AND REPAIR AS REQUIRED
      6) VERIFY OPERATION OF SERVICE INDICATORS
      7) VISUALLY INSPECT ENTIRE INTAKE SYSTEM FOR INTEGRITY
         --CRACKS, WEAR, DAMAGED HOUSINGS, ETC
      8) INSTALL PROPER INTAKE FILTER ELEMENTS AND CLOSE UP SYSTEM
      9) MAKE NOTES OF ALL DEFECTS FOUND AND REPAIRS MADE

      EXHAUST EMISSIONS TEST
      ----------------------
      1) SWITCH ON POWER FOR GAS ANALYZER-SELECT "DIESEL FUEL"
         AND PRESS "E"
      2) OPEN UGAS SOFTWARE AND LOG IN WITH USER AND VEHICLE I.D.
      3) ONCE 3 MIN CALIBRATION COMPLETES CLICK CAMERA BUTTON TO BEGIN
         TEST SEQUENCE
      4) CHECK THE "SMOKE TEST" BOX AND PERFORM SMOKE TEST SEQUENCE
         - insert the paper disc in probe and fit probe in exhaust - pre ptx
         - run engine @ full throttle - full stall (conv & hyd)
         -click"ok"when set
         - in UGAS enter the reason for test, rpm, and smoke value
         - click "SAVE" and proceed to the gas sampling menu in UGAS
      5) GAS SAMPLING - RUN ENGINE @ FULL THROTTLE - FULL STALL
      6) CLICK "START" BUTTON IN UGAS TO BEGIN 60 SEC SAMPLE
      7) AFTER COUNTDOWN COMPLETES NOTE THE RESULTS IN THE REPORT SCREEN
      8) CLICK "PRINT" AND "SAVE" BEFORE CLOSING REPORT SCREEN
      9) CLICK CAMERA BUTTON AND REPEAT STEPS FROM "SMOKE TEST" DOWN
```

Figure 10 - Engine System PM - page 1

```
Date :  6/08/99          FALCONBRIDGE LIMITED - SUDBURY OPERATIONS       WOR103
Time : 10:03:45
User : PLANSTUMP1                          Work Order

Project #

W/O #      Entity number                Type     Sub      Cls      Pty  Requested
813505     16TESTSCOOP001               EQ       M        PM       PM    6/08/99
           TEST SCOOP I.D. FOR OPERATING STATS.
-------------------------------------------------------------------------------
Supervisor- Blake R.J                     Originator-    LACROIX
Planner    - LACROIX G.                   Required       6/08/99
                                          Wo Type        M
Job Description : 1NGINE EXHAUST EMISSIONS AND INTAKE SYSTEM PM


        Task
Seq#  Activity                                                Charge
-------------------------------------------------------------------------------
         FOR OPPOSITE SIDE OF EXHAUST (AFT PTX)
      10) MAKE NOTE OF EXHAUST VALUES AND/OR INCLUDE PRINTOUT OF REPORTS
          PRE PURIFIER          AFT PURIFIER
          ------------          ------------
          CO______              CO______
          NO______              NO______
          NO2______             NO2______
          RPM______             RPM______
      11) AFTER TESTING IS DONE TURN OFF ANALYZER AND CLOSE SOFTWARE

         CALCULATE CO CONVERSION EFFICIENCY OF PURIFIER
                 CO VALUE AFTER PURIFIER
         ( 1-    ====================== ) X 100
                 CO VALUE BEFORE PURIFIER


         ( 1-    ------------------------) X 100 = .........%


      CLEAN PURIFIER IF NECESSARY


      SERIES 60 DDEC ENGINE - DIAGNOSTIC LINK
      ---------------------------------------
      1) CONNECT CABLE TO DDL PLUG ON DASH
      2) WITH IGNITION SWITCHED ON OPEN THE DIAGNOSTIC LINK SOFTWARE
      3) GO TO THE VIEW MENU AND SELECT ENGINE/TRIP DATA
      4) PRINT OUT SCREENS FOR BOTH TRIP AND ENGINE DATA
      5) FROM THE VIEW MENU SELECT RESET TO SET TRIP DATA BACK TO ZERO
      6) GO TO THE DIAGNOSTIC MENU AND SELECT CYLINDER CUTOUT
      7) PERFORM CYLINDER CUTOUT TEST @ 1000 RPM AND PRINT RESULT
      8) FROM DIAGNOSTIC MENU SELECT INJECTOR RESPONSE TIMES
      9) RUN ENGINE @ FULLL THROTTLE - FULL STALL AND PRINT RESULT
         OF INJECTOR RESPONSE TIMES
      10) RECORD STALL SPEED FROM INJECTOR RESPONSE TEST
         RPM________
      11) CHECK FOR INACTIVE AND ACTIVE CODES
          MAKE NOTES AND REPAIRS TO CLEAR ALL CODES
                                                    HOURS..........

Task Manpower
 Seq#  Trade Men Hrs     Trade Men Hrs     Trade Men Hrs     Trade Men Hrs
-------------------------------------------------------------------------------
```

Figure 11 - Engine System PM - page 2

Computerized Maintenance Management Systems (CMMS)

Strathcona Mine has a CMMS package in place at the mine along with a computerized parts cataloging system. The audit identified a situation where the systems were under utilized by the mechanics in the shop. The mechanics at the mine had little or no knowledge of how to use these systems as part of their day to day work such as managing work orders and looking for parts. This became another case of the project justifying completion of a task that had previously been identified as worth doing by the mine.

The CatBase electronic parts cataloging system has been in place at Strathcona Mine for several years with limited use. This system provides a quick and easy to use interface for mechanics to search through parts catalogs on line instead of through hard copy parts books. Parts manuals often serve as a valuable source of information to mechanics for many reasons such as troubleshooting. This system was implemented on the same computer station set up for emissions testing as part of the new approach. Training for each of the mechanics on basic use of the CatBase software along with the Marcam system for managing work orders was provided by in house mine personnel.

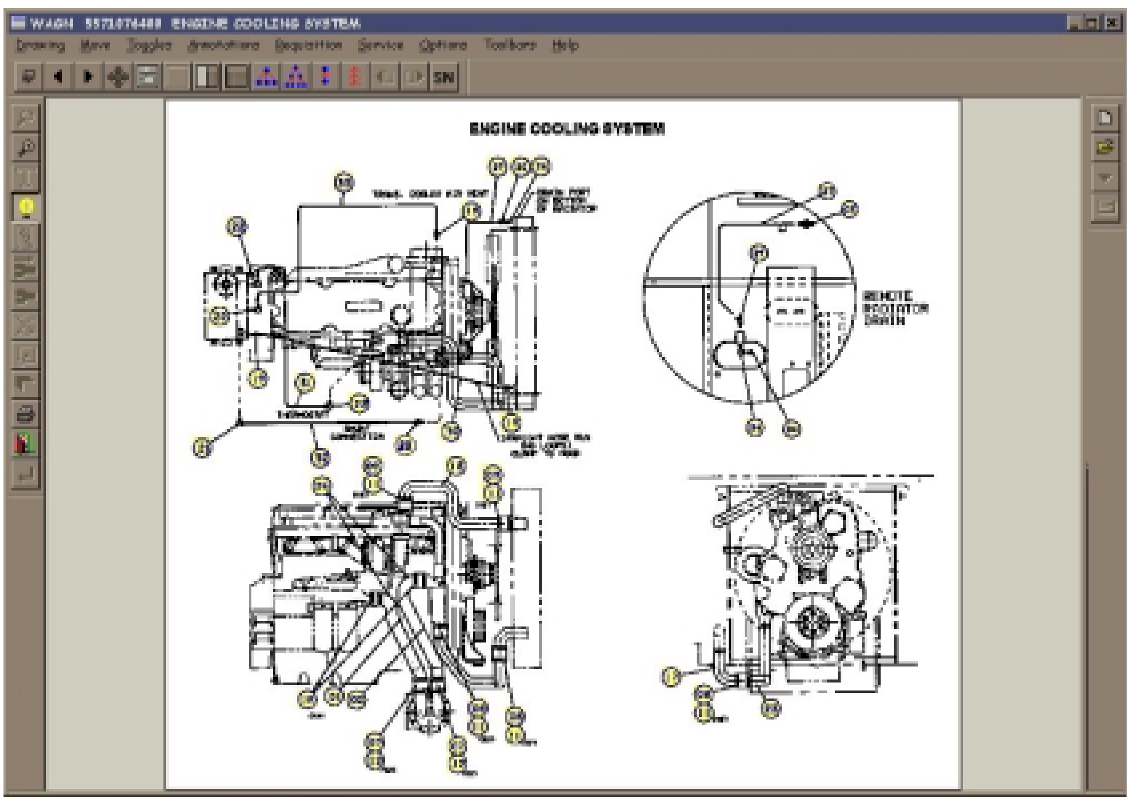


Figure 12 - CatBase Electronic Parts Catalog

NEW TOOLS FOR MAINTAINING ENGINES

Another critical component in improved engine maintenance was the integration of new tools that could best fit the scope of engine maintenance that the mechanics in the underground shop were responsible for. This would mean that new tools would be focused on the basics of engine diagnostics and repair. The mix of new tools would be a combination of the most technically simple and basic to the latest in computer based diagnostics. The common thread between them was that they were all developed to focus on engine basics and were usable by any mechanic regardless of technological skill level. This was in keeping with the general theme of the project in *"Doing the Basics Better".*

UGAS

The UGAS system was the first tool implemented with the mechanics at Strathcona Mine. As described previously in the emissions testing section, this system was designed specifically for mechanics to take emissions measurements for diagnosing engines. Implemented as part of the new engine PM structure, the mechanics were trained from the beginning of the project on how to take a set of emissions tests as part of each scheduled PM. This was the only exception where a new tool was introduced from the beginning of the project instead of during the implementation stage. Not only was this necessary for acquiring baseline emission values, but it also proved valuable in creating a smooth transition from the old ways to a new philosophy for maintaining engines. During individual training with each mechanic on UGAS, each was not only trained on how to take emissions tests but also on why it is important and the reasoning behind the maintenance project. This individual training took better than two months to cover all 16 mechanics but proved invaluable in gaining their acceptance and getting ready for the changes and new tools to come.

Intake Testing

The intake system can easily be considered the most critical with respect to maintenance and emissions. Ironically the intake system has the least known tools for servicing. In the past ether spray was used for detecting intake leaks by listening for engine acceleration where ether would leak by into the intake and combustion chamber. Problems with ether including extreme flammability and potential catastrophic engine failure when improperly used have led to the discontinuation of its use. This situation left a huge gap where the only activity associated with intake systems was the regular replacement of air filter elements and blind faith that this practice alone was sufficient.

As part of the project, the team at the mine put together a system for methodically testing intake systems with no risks to either the person doing the test or the engine. The system was simply a used intake filter element sealed externally with duct tape, an air pressure regulator and hose assembly, and a spray bottle containing a mixture of soap and water. During service the plugged filter element(s) is installed in the intake housing and the air pressure regulator is connected to a fitting on the intake. Compressed air is regulated inside the intake system to no more than 5 psi for safety reasons. Even with the leakage across valves and turbocharger enough static pressure remains in the system to produce bubbles when the soap and water solution is sprayed on all hoses and connections. This system is explained in detail in the *Guidelines and Best Practices*.

Figure 13 - Intake Testing System

Intake Restriction and Exhaust Backpressure
These simple measurements are often overlooked due to both a lack of understanding and lack of proper tools. As with the intake testing system above, the solution was very simple. A good quality and relatively inexpensive mechanical gauge was incorporated as part of the new system of tools to be used by the mechanics. A Magnehelic Gauge from Dwyer Instruments with a range from 0 – 80 inches of water gauge was introduced. The gauge is capable of differential pressure measurements and therefore has two fittings, one for pressure and the other for vacuum measurement. This made it ideally suited for measuring intake vacuum restriction which is normally in the range of 10 inches of water, as well as exhaust backpressure, typically around 20 inches of water.

In addition to the portable gauge for servicing, a replacement program was initiated for the intake tell tale service gauges that were currently in use. The original small plastic plunger units were found to be anywhere between ineffective to defective from the audit. Most of the indicators were installed in locations that were not visible from the operator's compartment so that on the rare occasions that they were actually checked, they weren't being checked properly. A replacement indicator gauge was found to alleviate this. The gauge was purchased from Donaldson who manufactures the intake housing and filter systems. The gauge was a standard 3 inch mechanical bourdon tube with an appropriate range and scale for the intake system. The plunger indicators were replaced by the gauges and installed in appropriate locations within sight of the operator's compartment.

Figure 14 - Magnehelic Gauge For Intake And Exhaust

Figure 15 - Intake Service Indicator Gauges on ST8-B

Temperature Probe
A portable infrared temperature probe was introduced to the mechanics specifically for diagnosing cooling systems. This was a simple hand held instrument that measures surface temperature with a simple point and shoot operation. An LCD display on the instrument updates the value instantly or is capable of logging the value to memory. This was particularly effective in demonstrating and diagnosing cooling systems. In seconds the efficiency of a radiator could be verified by measuring the differential temperature from top to bottom. Thermostat operation was easily verified by pointing at the thermostat housing and observing the temperature transition as the thermostat opened and closed.

Detroit Diesel Diagnostic Link
The challenge of measuring and analyzing engine performance has grown and at the same time been simplified with the implementation of electronically controlled engines. Detroit Diesel has long been a leader in this area and the use of DDEC engine technology in underground mining equipment has been growing rapidly. Other engine manufacturers are also providing electronically controlled engine technology as well. While the technology has proven to be very effective from a performance and cost perspective, maintaining these engines requires a new approach with special knowledge and special tools.

In order to diagnose the DDEC system a communication interface is required to translate the electronic signals into meaningful information that mechanics can understand. The most popular system in use until recently was the ProLink hand held reader which interpreted DDEC signals onto an LCD screen display. The mechanic would read the information and transmit commands to the engine from the keypad and screen menus on the reader. Although this is a very powerful tool that provides total communication and control capability with the engine, it lacks an intuitive interface and is often intimidating to mechanics.

The next generation for this tool is now commercially available from Detroit Diesel and is known as Detroit Diesel Diagnostic Link (DDDL). It takes the exact same communication protocol from the engine and replaces the interface with a Windows software application and graphic user interface that is much more intuitive to mechanics. The dynamic displays and visual controls present the information in a manner that is easy to read and understand. Navigation is very straightforward and can be mastered by most tradespeople in less than an hour of training. The software has the added benefit of incorporating the diagnostic flowcharts form the engine service manuals into the package as a standard help file to guide the mechanics through the troubleshooting process online without leaving the engine. The primary components of the tool are:

- Display of measured and cumulative engine data
- Integrated diagnostics and troubleshooting – eg: Cylinder Cutout Test
- Engine configuration and calibration
- Integrated technical and service information

The tool comes with the software package and a communications translator box that connects the engine diagnostic connector to an RS232 serial connection on a PC. The system was incorporated into the project and installed on the diagnostic workstation PC with the emissions testing apparatus. Mechanics from all four crews were trained on basic use of the system. It was then implemented as part of the engine system diagnostic PM for the Series 60 DDEC engines. The PM checkpoints for the DDDL are shown on the Engine System PM form back in Figure 11.

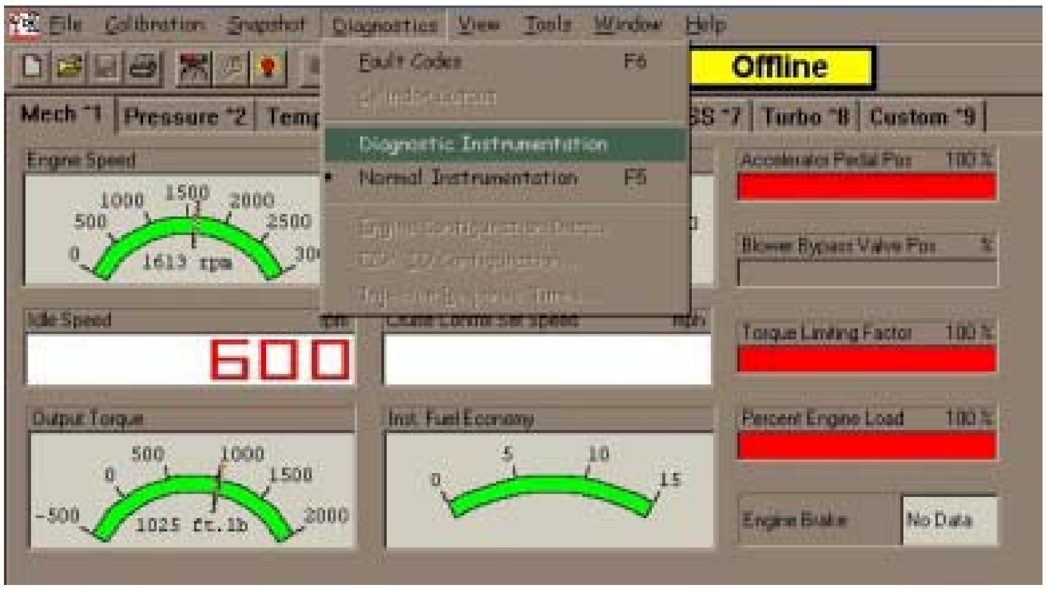


Figure 16 - DDDL

Information Utilities

A common problem in underground mobile maintenance facilities is readily accessible information. Mechanics are often frustrated by time consuming searches for service information, specifications, or simple calculations.

Noranda Technology Centre had developed a set of basic software utilities in previous maintenance work. The set was made available for this project and installed with the rest of the software tools on the diagnostic workstation PC. While the tools are very basic by nature, they provide quick and easy access to a wide range of information. The utilities included:

- An equipment specification lookup tool
- A conversion utility for units of measure
- A conversion utility for taps and drill bits
- The standard Windows calculator

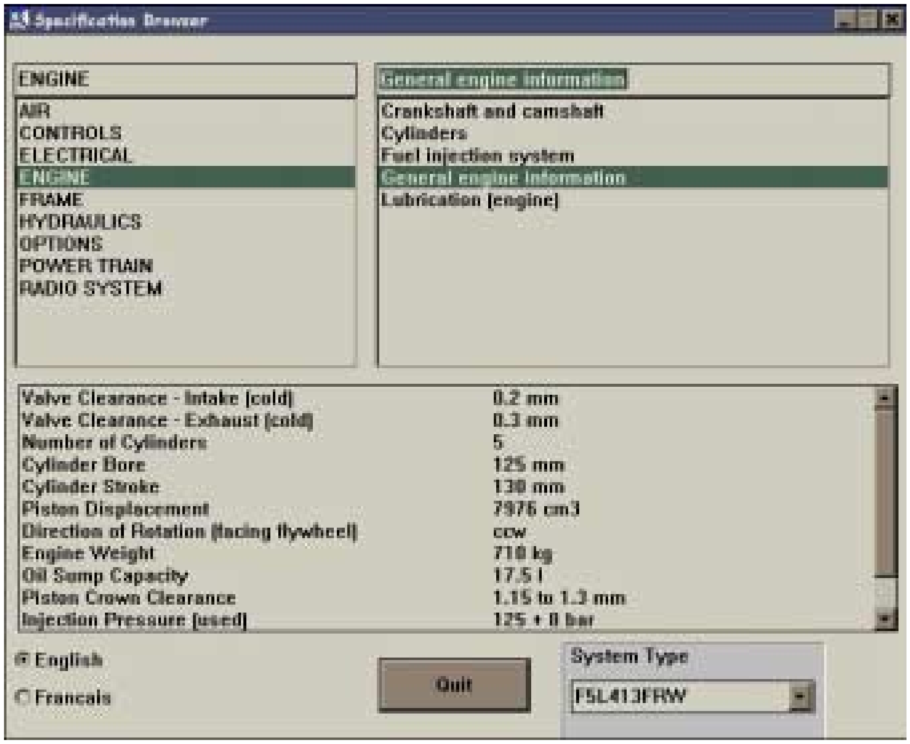


Figure 17 - Equipment Specification Lookup

Training

At the post baseline meeting the project team put together a general plan for training the mechanics within the project objectives. Once again this was an issue that overlapped an existing commitment at the mine for providing training and upgrading. The project was a good fit within the company training objectives and it was agreed that the training modules within the project could be added to the employee file as with any other company sponsored training program. The costs to the mine with respect to equipment and labour resources would easily be offset by the benefits of fulfilling existing training commitments and especially by the increased level of technical skills.

The training approach followed the *Guidelines and Best Practices* with respect to small groups in a hands on environment as well as using supplier service representatives for providing training. It was decided that the training should follow a two level approach. The new process and tools within the project would be introduced first on an individual training basis in the shop between the project leader and the mechanic. The follow up to process and tools would be the training in group sessions for the case studies. The engine profile at Strathcona provided the opportunity to have several case studies where separate engine manufacturers could be approached to bring in service representatives and provide a short hands on training session to a small group of mechanics. In total 3 engine manufacturers and 1 exhaust aftertreatment manufacturer participated in hands on training sessions with small groups of 4 to 5 mechanics in each. In addition to the manufacturer specific training the mechanics were also shown how to incorporate the new process and tools as part of improved maintenance. Each of the training case studies is described in detail later in this report.

CASE STUDIES

Case Study I – Deutz BF4M 1013 Engine

Introduction

There are 8 JCI 250M scooptrams currently in use at Strathcona Mine. These units are utilized for mucking directly at the production faces. As such, they are exposed to the most extreme operating conditions in the mine environment. Conditions range from high vibration and impact to less than ideal air quality for intake and combustion. Of these 8 units 5 are equipped with Deutz F5L413 air cooled inline engines and the other 3 are Deutz BF4M 1013 water cooled engines. This first case study in the project was conducted on unit 207 which is equipped with one of the newer BF4M 1013 engines.

Peter Prince from KHD Canada in Sudbury provided the technical guidance and training for the case study. Four mechanics from 3900 shop spent the day with Peter going through a complete engine evaluation according to the *Guidelines and Best Practices*. To begin the study, a complete set of emissions tests was done on the engine before any maintenance activities to provide a set of values for comparison. A set of emissions tests consists of both undiluted gaseous and particulate emissions upstream and downstream of the DOC. The evaluation, diagnostics and repairs to the engine were done on a system by system approach using the *Guidelines and Best Practices* as a foundation. Each system was evaluated and repaired as required before moving on to the next area.

Participants

Peter Prince – KHD Canada (Deutz) Field Service Representative

Paul Marcoux – Mechanic, Strathcona Mine

Al Jones – Mechanic, Strathcona Mine

Bruce Lapping – Mechanic, Strathcona Mine

Paul Serpell – Mechanic, Strathcona Mine

Scott Chisolm – Mechanic, Strathcona Mine

Tim Hinds – Project Site Champion, Strathcona Mine

Sean McGinn – Project Leader, Noranda Technology Centre

Figure 18 - Deutz Engine Case Study

INTAKE SYSTEM

In the Guidelines and Best Practices the intake system was assigned the highest priority of the 6 engine systems. The case study on the engine in #207 validated this ranking and the use of the intake testing tools described there as well.

Checkpoints:

- ✓ *Checked operation of filter indicator and measured restriction*
- ✓ *Measure turbo boost pressure with gauge – 8 psi*
- ✓ *Pressure test intake system for leaks*

Deficiencies:

- ⌦ *Low turbo boost pressure*
- ⌦ *Intake piping leaks at hoses and clamps*
- ⌦ *Damaged air to air cooler – leaking*
- ⌦ *Secondary intake filter plugged*

Actions:

- ❖ *Replaced damaged connector hose and sealed intake connections*
- ❖ *Replaced air to air cooler (Figure 18)*
- ❖ *Replaced secondary air filter*

Figure 19 - Pressure Testing Intake System

Figure 20 - Intake Leaks

Exhaust System

Before any maintenance activities were undertaken a set of emissions tests were performed, taken upstream and downstream of the purifier. This provided a set of values from which to compare the impact of the maintenance activities through the day. In addition to the emissions the exhaust backpressure was also measured with a standard mechanical gauge.

Checkpoints:

- ✓ *Emissions tests before and after exhaust purifier*
- ✓ *Check exhaust backpressure*
- ✓ *Visual inspection of complete system for leaks, cracks, etc*

Deficiencies:

- ⌦ *None*

Actions:

- ❖ *Noted the excellent performance of the exhaust purifier in converting CO*

Fuel Injection System

The fuel injection system on the 1013 series engines at Strathcona are equipped with mechanical unit pump injectors that are actuated off of the camshaft. The unit pumps supply high pressure fuel through short lines to the injector nozzles mounted in the cylinder head. The only regular service points on this system are to verify RPM settings, pressure test the nozzles, and setting the intake and exhaust valves at the same time while the valve covers are removed.

Checkpoints:

- ✓ *Hi and Lo idle RPM settings*
- ✓ *Fuel boost pressure*
- ✓ *Pressure (pop) test injector nozzles*
- ✓ *Intake and exhaust valves*
- ✓ *Water separator*

Deficiencies:

- ⌦ *3 of 4 nozzles leaking at tip*
- ⌦ *No water separator on unit*

Actions:

- ❖ *Replaced all 4 injector nozzles*
- ❖ *Generated work request to have water separator installed*

Figure 21 - Pressure Testing Injector Nozzles

Figure 22 - Servicing Injectors and Valves

Cooling System

The 1013 engine has an integrated cooling system mounted to the side of the engine for compact installation. The side installation protects the radiator from extreme operating conditions such as dirt and impacts associated with rear mounted installations. The cooling system checked out well with no action items required.

Checkpoints:

- ✓ *Thermostat operation (I.R. temperature gun)*
- ✓ *Radiator cleanliness and flow through*
- ✓ *Pressure test*
- ✓ *Fan and belt adjustment and condition*

Actions:

- ❖ *None*

Lubrication System

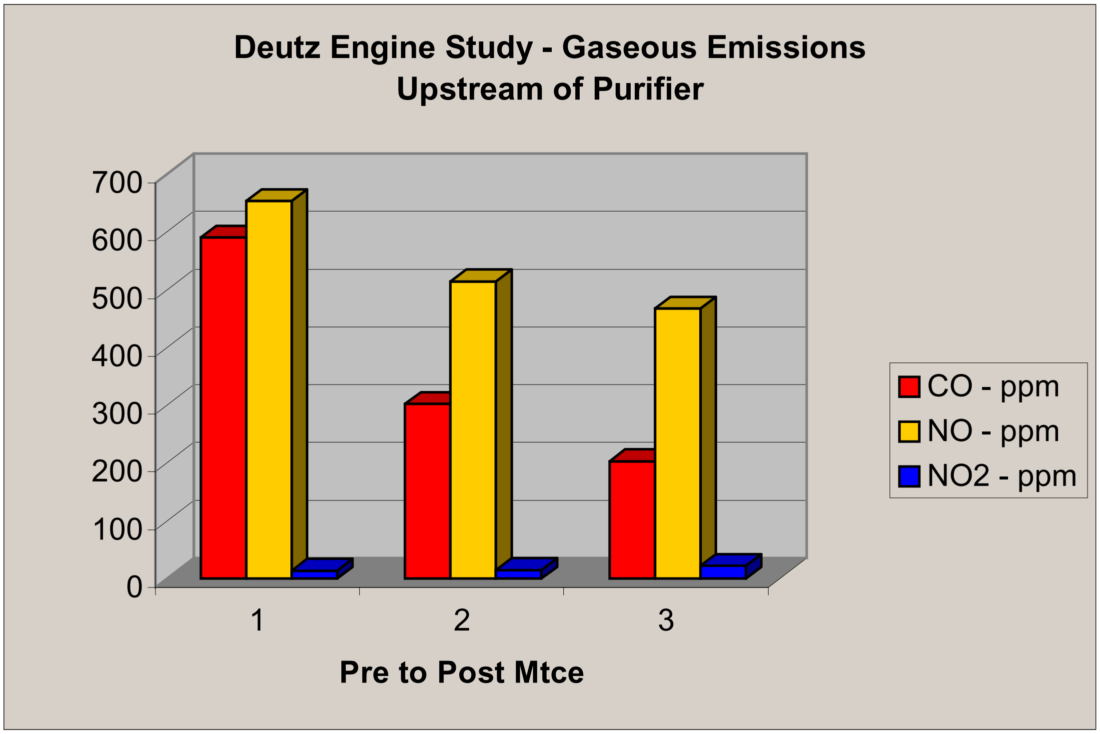
Before conducting the final set of emissions tests to evaluate the change in emissions due to the repairs on the engine that day we had a short discussion session on lubrication and best practices. It was emphasized that maintaining a proper oil level in the crankcase is essential to minimizing emissions. The practice of overfilling a crankcase at the start of a shift to compensate for leaks or oil consumption creates more problems than it solves, especially with respect to emissions. This issue is more of an education practice that the mechanics were encouraged to follow up on with operators.

EMISSIONS RESULTS

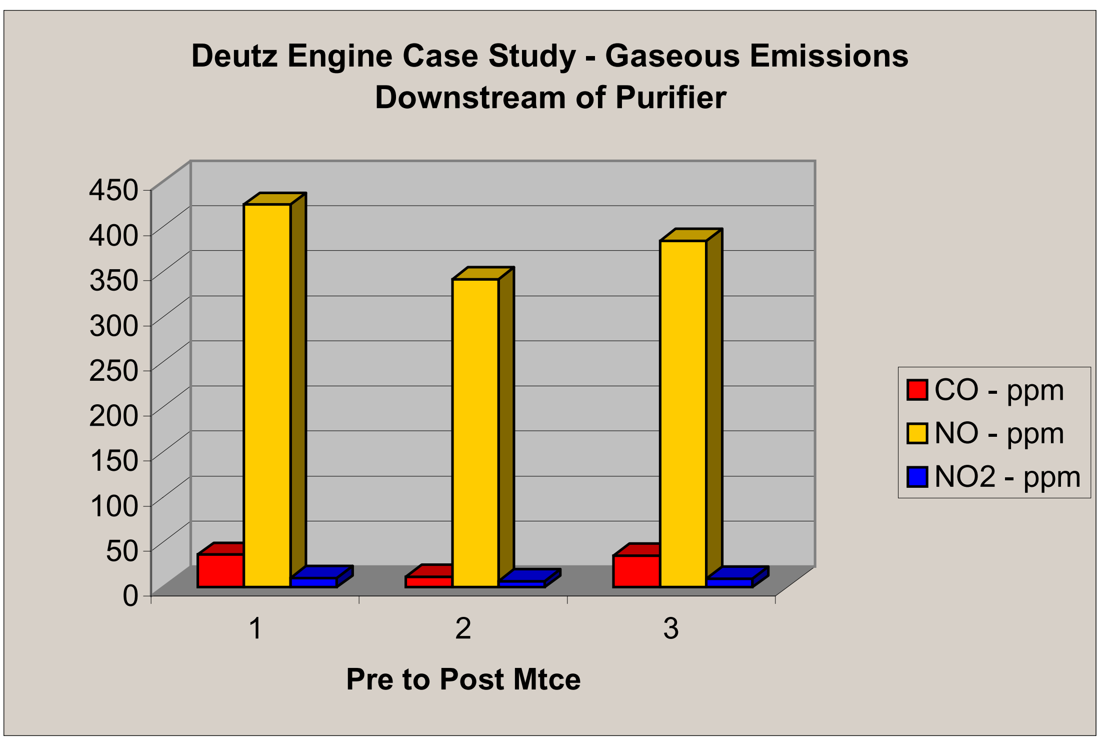
Test	Desc	O2	CO	CO2	NO	NO2	Smoke	DPM
		%	ppm	%	ppm	ppm	index	mg/m3
1	UPSTR-Pre Mtce	7.49	590.06	9.90	653.28	13.80	9	61.67
2	DNSTR-Pre Mtce	9.56	36.27	8.39	424.37	10.29	9	69.17
3	UPSTR-Mid Mtce	9.01	302.67	8.81	514.59	15.11	9	25.83
4	DNSTR-Mid Mtce	11.85	11.82	6.71	341.75	6.59	9	30.83
5	UPSTR-Post Mtce	10.56	203.30	7.65	467.41	21.91	9	29.17
6	DNSTR-Post Mtce	12.35	35.36	6.34	384.07	9.53	9	34.17

Table 7 - Deutz Case Study Emissions Data

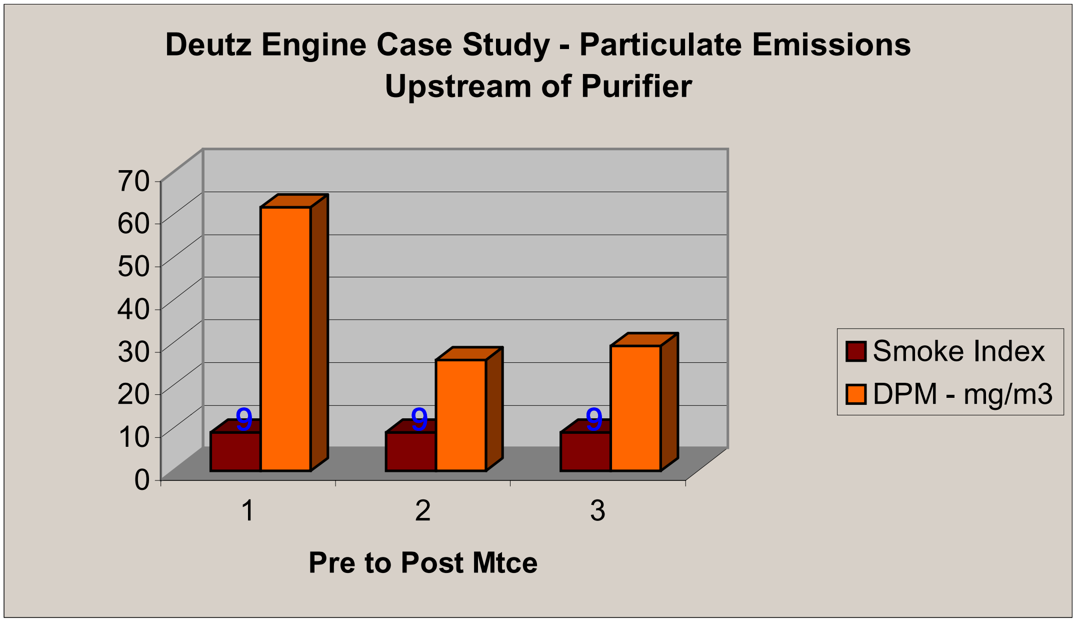
Note that pre, mid and post maintenance indicated in Table 7 refers to a the sequence of testing. A set of tests was taken at the start of the case study before any evaluation or repairs, another set in the middle of the day half way through the list of engine systems, and the last set after all engine systems had been evaluated and all repairs made. All DPM samples were taken on silver membrane filters and analyzed for total weight.

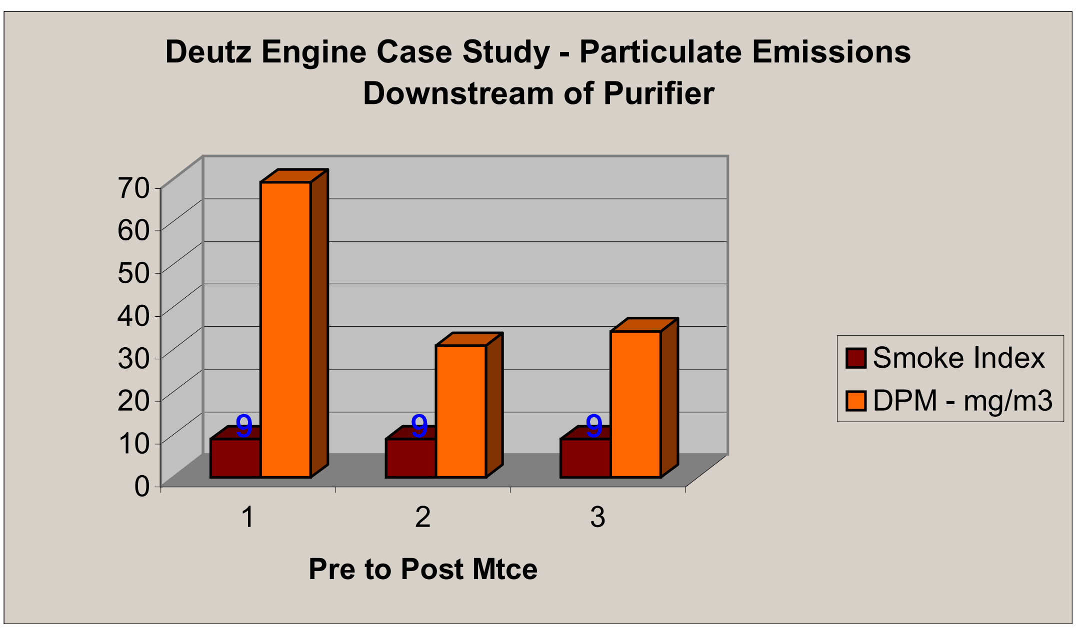


Deutz Engine Study - Gaseous Emissions
Upstream of Purifier
700
600
500
400
300
200
100
0
1
2
3
Pre to Post Mtce
CO - ppm
NO - ppm
NO2 - ppm



Deutz Engine Case Study - Gaseous Emissions
Downstream of Purifier
450
400
350
300
250
200
150
100
50
0
1
2
3
Pre to Post Mtce
CO - ppm
NO - ppm
NO2 - ppm


Deutz Engine Case Study - Particulate Emissions
Upstream of Purifier
70
60
50
40
30
20
10
0
9
9
9
1
2
3
Pre to Post Mtce
Smoke Index
DPM - mg/m3


Deutz Engine Case Study - Particulate Emissions
Downstream of Purifier
70
60
50
40
30
20
10
0
9
9
9
1
2
3
Pre to Post Mtce
Smoke Index
DPM - mg/m3

Conclusions and Summary

In total there were 3 sets of emissions tests done over the study. A set of emissions tests consists of gaseous and particulate measurements both upstream and downstream of the purifier. The first set of tests was done to establish values before any maintenance activity. The second set of tests was done after the work on the intake system. The final set of tests was done at the end of the work to include all repairs and adjustments done on the engine over the day.

Gaseous Emissions

The gas emissions upstream of the purifier showed a consistent decline over the 3 tests. In total the largest impact was on Carbon Monoxide which saw a reduction from 590 ppm to 203 ppm or 66% from start to finish.

The downstream emissions were more consistent across the 3 sets of tests due to the high efficiency of the DOC. The final set of tests still saw a CO conversion efficiency of 83% even after the upstream CO emissions had been reduced by 66%.

The high reduction in CO can be directly attributed to the fact that all repairs were associated to the air and fuel systems which have a direct impact on CO emissions. The intake system was leaking so badly that the turbo boost pressure had dropped significantly. The injector nozzles were leaking by on 3 of 4 which directly affects the mixture of air and fuel in the combustion chamber.

Particulate Emissions

The undiluted particulate emissions were quite consistent. The overall reduction was 53% on the upstream side of the DOC and 51% on the downstream side. From the charts it is evident that the greatest impact on reducing particulate was the work performed on the engine intake system. The difference in particulate values between tests 2 and 3 were quite small and the only maintenance activity separating them was the fuel injection service. An interesting point of note is that the particulate values on the downstream side of the purifier are just slightly higher than the values upstream. In this instance this would prove to be the exact opposite of what would be expected of a DOC.

Case Study II – Exhaust Aftertreatment Systems

Introduction

All underground vehicles at Strathcona Mine are equipped with an exhaust aftertreatment device. Each vehicle is equipped with a DOC for gaseous emissions and in some cases a fume diluter as well. There are systems in place from several different manufacturers. From the audit at the beginning of the project it was apparent that there was no program in place for evaluating and maintaining these systems and a lack of understanding as to how they work, what they do, and how to maintain them.

Mr. Brent Rubeli from DCL International in Toronto came to Strathcona for a daylong hands on training session focussed solely on exhaust aftertreatment systems. The entire morning was spent in the training classroom on 3900 level. Brent went through all aftertreatment technologies that are currently used on underground mobile equipment. For each technology he explained the function and design, intended effects, and service tips. In the afternoon the group moved next door to the shop on 3900 to put the knowledge to practice. A vehicle was randomly selected from those available in the shop that afternoon. A Marcotte platform truck with a Deutz F6L912 air-cooled engine was available for our use. The vehicle had approximately 460 total operating hours on it.

Participants

Brent Rubeli – Technical Representative, DCL International

Paul Marcoux – Mechanic, Strathcona Mine

Al Jones – Mechanic, Strathcona Mine

Bruce Lapping – Mechanic, Strathcona Mine

Paul Serpell – Mechanic, Strathcona Mine

Scott Chisolm – Mechanic, Strathcona Mine

Tim Hinds – Project Site Champion, Strathcona Mine

Sean McGinn – Project Leader, Noranda Technology Centre

Classroom Theory Session

The goal of the theory session was to provide the basics for understanding the components of exhaust emissions and the different aftertreatment control systems used to reduce and control emissions.

Topic I – Understanding Diesel Exhaust Emissions

- Listed the gas and particulate components of diesel exhaust
- Described how each emission component is created
- Described typical measured undiluted levels for each emission
- Described the potential health and environmental effects of each emission

Topic II – Diesel Oxidation Catalyst (DOC)

- Functional description
- Construction and assembly
- Operation and associated chemical reactions
- Performance characteristics with respect to CO, HC, and DPM
- Explanation of formula to calculate CO conversion efficiency
- Summary of key points

Topic III – Passive Particulate Filters

- Explanation of diesel particulate and related concerns
- Design and function of particulate filters
- Operation description of a passive filter system
- Key points and limitations

Topic IV – Active Particulate Filters

- Design description and comparison against passive systems
- Active regeneration technologies
- Installation and maintenance considerations

Topic V – Selective Catalytic Reduction (SCR)

- Explanation as a new developmental technology
- Operation and associated chemical reactions
- Design and operation description

Summary

The conclusion to the theory session focussed on the need for mechanics to play a more active role in measuring and controlling emissions. The existing aftertreament technology employed in mines today requires much better focus from maintenance people than has been done in the past. This situation will become increasingly important as the new aftertreatment and control technologies develop and are introduced to the mining industry.

Figure 23 - Theory Session at 3900 Classroom

PRACTICAL HANDS ON SESSION

The afternoon was spent in the shop putting the morning's theory into practice. A platform truck was in the shop waiting for parts and thus available for our group to perform a few tests on the exhaust system.

The mechanics performed a set of gas emissions tests upstream and downstream of the purifier. The critical CO gas component was taken and applied to the CO conversion formula. With 102 ppm upstream and 56 ppm downstream, the resulting CO conversion factor was 45%. It was explained once again that DOCs should maintain a minimum of 65% conversion efficiency and that this particular unit was in need of service or replacement.

The group disassembled the purifier and did a visual inspection of the element. There was considerable buildup of soot and carbon under inspection with a light from behind. The element was steam cleaned and blown through with compressed air before being soaked in a container of clean diesel fuel. Although it is recommended to soak the element for 2 hours or more, we opted to clean out and re-install after 20 minutes due to our tight schedule constraints that day.

After half an hour of service and cleaning our final set of emissions tests revealed that our upstream CO value was consistent at 100 ppm, but the downstream value had now dropped to 22 ppm. This calculated to 78% CO conversion efficiency after only 30 minutes service.

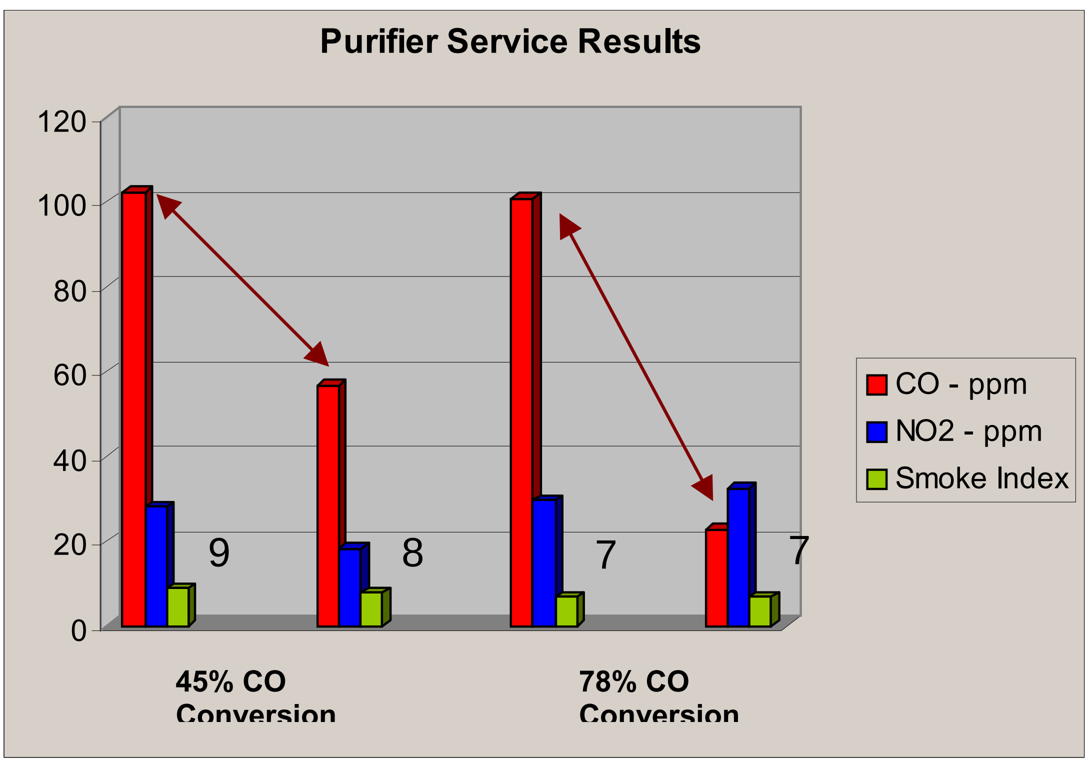
Figure 24 - Cleaning Purifier in Diesel Fuel

Figure 25 - Inspection Using Backlighting

EMISSIONS RESULTS

Test	Desc	O2 %	CO ppm	CO2 %	NO ppm	NO2 ppm	Smoke index
1	UPSTR-Pre Service	12.44	102.16	6.28	630.55	28.22	9
2	DNSTR-Pre Service	12.38	56.62	6.32	669.02	18.24	8
3	UPSTR-Post Service	12.38	100.81	6.32	585.99	29.67	7
4	DNSTR-Post Service	12.36	22.85	6.34	586.99	32.35	7

Table 8 - Aftertreatment Case Study Emissions Data



SUMMARY

The focus on a specific system proved to be invaluable to the mechanics in this instance. Exhaust aftertreatment systems remain a technical mystery in many aspects to mechanics and the new knowledge presented in this one day session was completely absorbed by the group. The combination of half-day theory and half hands on was largely responsible for this. The theory session provided more than enough technical information without going too far so as to lose the interest of the group. Moving into the shop in the afternoon gave the mechanics the chance to practice the knowledge and verify with their own hands. The emissions results as seen above removed any skepticism from the group.

It was interesting to note that through the remaining fieldwork in the project, mechanics continued to practice the procedures explained, specifically the calculation of CO efficiency. On each emissions test report that came through the planning department after completion, the hand calculation was done at the bottom of the report. In cases where the efficiency was low there was a service of the aftertreament system with accompanying explanation.

Case Study III – Detroit Diesel Series 60 Engine

Introduction

Strathcona Mine uses 3 ST8-B scooptrams for primary heavy haulage of mine ore to the ore pass system. The ST8-Bs draw the ore from re-muck bays which are kept full by the smaller scooptrams working in the production headings. As such, the ST8-Bs are working in good conditions with well maintained roadways and a good supply of ventilation. For this reason the majority of the maintenance activity with these machines is predictive or scheduled as opposed to more of the breakdown or emergency maintenance associated with the smaller machines operating under more extreme conditions. A Detroit Diesel Series 60 engine –11.1 Liter – 325 horsepower powers each of the ST8-Bs.

Mike Meadows from Detroit Diesel Canada in London, Ontario spent 2 days providing training, troubleshooting and evaluation of the Series 60 engines. Tom Serpell from Harper Detroit Diesel in Sudbury also assisted on both days. The 2-day format permitted the evaluation of 2 separate vehicles with 2 groups of mechanics for training. It also permitted having a chance for a large group of mechanics to get a closer look at the Series 60 DDEC technology, which is increasingly becoming more common as a power choice in heavy mobile power applications in Canadian mines.

Participants

Mike Meadows – Service Representative, Detroit Diesel Canada

Tom Serpell – Service Representative, Harper Detroit Diesel Sudbury

Blair Sagle – Mechanic, Strathcona Mine

Mike Lalonde – Mechanic, Strathcona Mine

Maurice Mainville – Mechanic, Strathcona Mine

Scott Chisolm – Mechanic, Strathcona Mine

Pat Sweeney – Mechanic, Strathcona Mine

Paul Serpell – Mechanic, Strathcona Mine

Al Jones – Mechanic, Strathcona Mine

Tim Hinds – Project Site Champion, Strathcona Mine

Heather Langfeld – Industrial Hygiene Specialist, Falconbridge Ltd

Dr. Mahe Gangal – CANMET, Diesel Laboratories – Bells Corners Complex

Sean McGinn – Project Leader, Noranda Technology Centre

INTAKE SYSTEM

The engine system approach was used to evaluate the engines in both 818 and 820 scooptrams. The approach to evaluating the intake system was identical on both machines with separate results. In addition to the basic checklist points a detailed explanation on the Series 60 intake system was given with specific focus on turbocharger operation and diagnostics. The intake system evaluation for both vehicles is listed below.

Checkpoints:

- ✓ *Measured restriction with magnehelic precision gauge*
- ✓ *Measured turbo boost on DDDL system*
- ✓ *Pressure test intake system for leaks*

Deficiencies:

- ⌦ *818 – intake restriction near limit*
- ⌦ *818 – intake leaks at hoses*
- ⌦ *820 – no deficiencies found*

Actions:

- ❖ *Replaced air filter elements and re-checked restriction*
- ❖ *Repaired leak at hose to cooler*

The only deficiencies were encountered on 818 scooptram. Although the intake filter restriction was still below the limit (measured 10 “wg – limit 20” wg), the outer elements were replaced and a 2nd set of emissions tests performed afterward to determine the effect of reduced intake restriction. The measured restriction afterward was down to 5” wg. The most noticeable effect was a reduction in CO from 175 ppm before replacing the filters to 115 ppm with new filters. It was also interesting to note that although both filter elements were visibly loaded with dirt, the intake restriction was still only half of the limit specification. This was explained by the vehicle design application where double the required filtration capacity for the Series 60 engine has been installed on the vehicle. Where a normal Series 60 application would have only one of the Donaldson intake canister / filter systems, the ST8-Bs have been equipped with two.

Figure 26 - Turbocharger Troubleshooting Techniques

Figure 27 - Intake Leaks

Exhaust System

The first checkpoint for an exhaust system is the emissions testing. Before any other diagnostics or evaluation emissions tests were conducted on both vehicles. The procedures for taking the tests and emissions values were explained to the mechanics. Each emission component (gases and particulates) was explained individually with the expected levels and causes for exceptions to expected levels. The exhaust aftertreatment system was explained along with the formula for calculating CO conversion efficiency. It was noted that the exhaust system on 818 scooptram was not equipped with a DOC as indicated in the vehicle specification. All 3 scooptrams with Series 60 engines employ "Jake" engine brakes. This is a system that uses a solenoid and piston over the exhaust valves in the cylinder head for a braking action at the end of the crankshaft. The function and setting of this application was explained in detail on both vehicles.

Checkpoints:

- ✓ *Emissions tests before and after exhaust purifier*
- ✓ *Check exhaust backpressure with magnehelic gauge*
- ✓ *Visual inspection of complete system for leaks, cracks, etc*
- ✓ *Checked operation and setting of Jake Brakes*

Deficiencies:

- ⌧ *820 – Diesel oxidation catalyst (DOC) – poor efficiency and loose substrate inside housing*

Actions:

- ❖ *820 – Serviced purifier and generated work order to replace with new*

Fuel Injection System

Series 60 engines are controlled by the DDEC electronic control system. This uses signals from various electronic sensors on the engine to send corresponding control signals to solenoids on each electronic unit injector. This technology tends to challenge many mechanics who sometimes find the newer technology confusing depending on the explanation and tools used for diagnostics. Considerable time was spent on both vehicles explaining this system to the mechanics and proper diagnostics. A valuable new tool that aids in simplifying this for the mechanics is the Detroit Diesel Diagnostic Link (DDDL) software. This is a Windows software application that gives the mechanic a simple interface to view the engine for diagnostics and is a direct replacement to the ProLink hand held reader.

In addition to this, Tom Serpell from Harper Detroit Diesel demonstrated hands on with the mechanics the proper adjustments for injectors and valves at the cylinder head. In the case of 820 scooptram, it was decided to examine the effect of replacing all 6 injectors based on hours rather than emissions. The net result was a reduction in CO of only 20 ppm upstream of the purifier. Injector faults are most noticeably picked up by high CO readings during testing and should produce a sizeable drop when injectors are replaced. This served to reinforce the fact that a critical decision such as injector replacement should be based only on performance and emissions rather than a predictive decision based on hours.

Checkpoints:

- ✓ *Hi and Lo idle RPM settings*
- ✓ *Fuel temperature and coolers*
- ✓ *Injector setting and calibration*
- ✓ *Intake and exhaust valves*
- ✓ *Fuel filters and water separator*

Deficiencies:

⌧ *None*

Actions:

- ❖ *820 – Replaced injectors based on hours – net zero effect*

Figure 28 - Setting Injectors and Valves

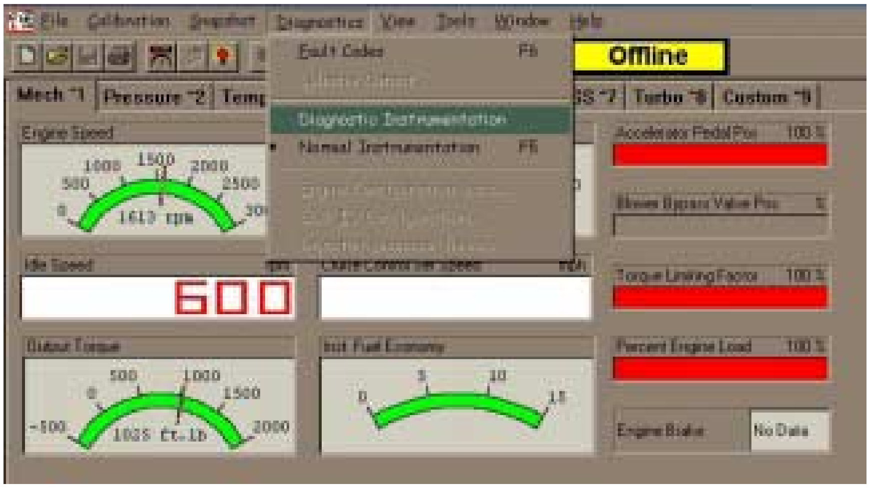


Figure 29 - Detroit Diesel Diagnostic Link

COOLING SYSTEM

The cooling system although relatively basic in design is often misdiagnosed by mechanics. For this reason considerable focus was put on explaining this system and the proper checks. Points such as bleeding air out of water pumps and measuring system efficiency with differential temperature measurement were demonstrated. It was explained that the Series 60 engines incorporate 2 thermostats only for the purpose of backup in case of failure. The importance of regular checks for the condition of additives and inhibitors were also explained. The same points were covered with both groups of mechanics on both vehicles.

Checkpoints:

- ✓ *Thermostat operation and differential temperature (I.R. temperature gun)*
- ✓ *Check rad for plugging and proper air flow*
- ✓ *Test strips for additive / inhibitor condition*
- ✓ *Fan and belt adjustment and condition*

Actions:

- ❖ *None*

Lubrication System

The importance of not overlooking simple details was emphasized in the explanations of the lubrication system for the Series 60 engines. Detroit Diesel recommends only the use of a premium multi grade oil. Strathcona Mine uses 15W40 oil for all Series 60 engines. The importance of maintaining a proper level on the dipstick was explained. While low level problems will obviously cause wear and eventual failure problems, overfilled oil will cause problems with excessive emissions.

Emissions Results

818 Scooptram

Test	Desc	O2 %	CO ppm	CO2 %	NO ppm	NO2 ppm	Smoke Index	DPM mg/m3
1	No DOC	11.95	173.17	6.66	401.79	20.82	7	5.83
2	No DOC	12.44	114.29	6.28	374.91	20.35	4	
3	No DOC	12.34	142.17	6.18	345.56	20.00	7	8.33
4	No DOC	11.98	156.69	6.45	435.10	15.67	7	5.00
5	No DOC	12.11	114.57	6.37	448.01	16.92	7	

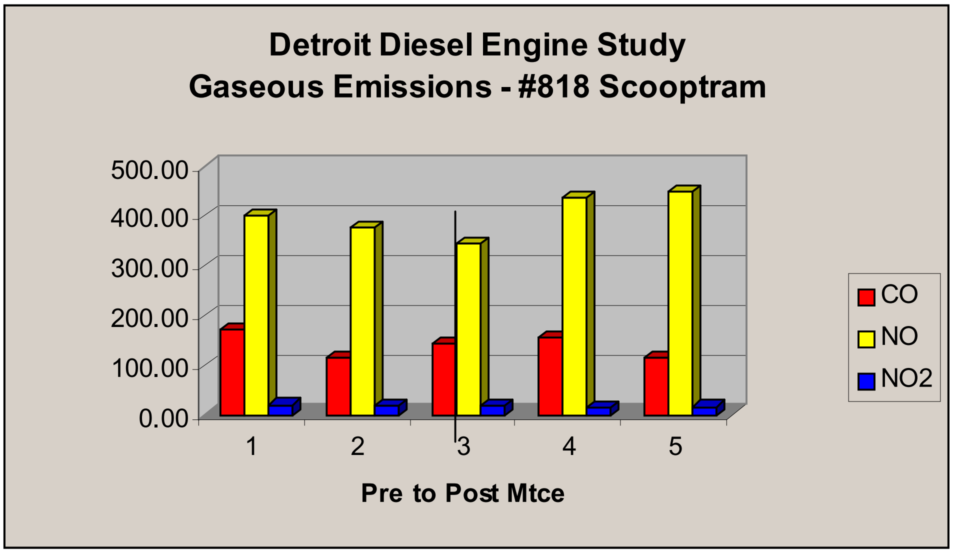
Table 9 - Detroit Diesel - 818 Case Study Emissions Data

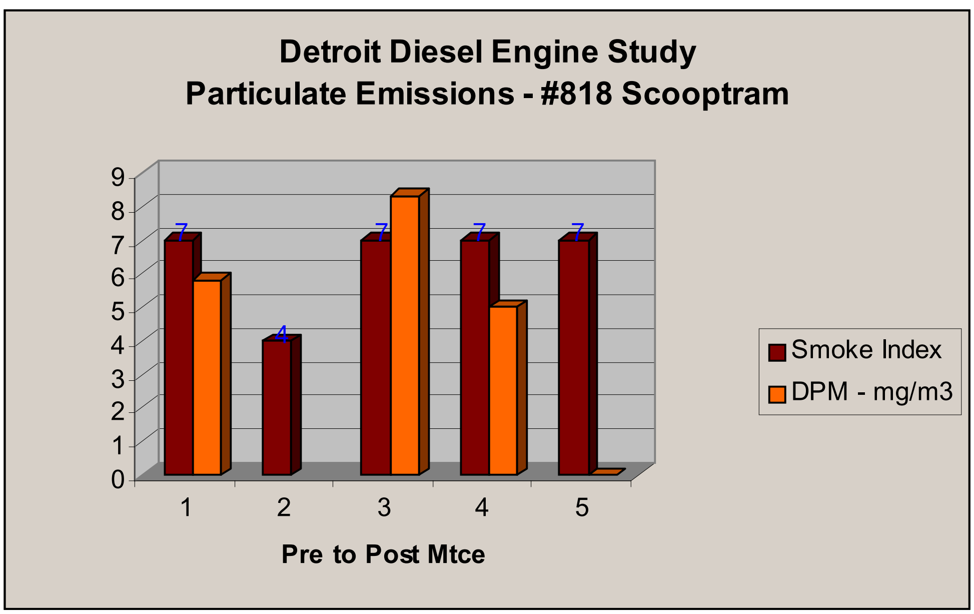
820 Scooptram

Test	Desc	O2 %	CO ppm	CO2 %	NO ppm	NO2 ppm	Smoke Index	DPM mg/m3
1	UPSTR-PreMtce	11.15	117.24	7.21	1160.01	94.89	6	4.17
2	DNSTR-PreMtce	11.69	50.04	6.81	1022.76	89.79	6	4.17
3	UPSTR-PostMtce	11.87	96.98	6.51	1251.70	93.02	6	1.67
4	DNSTR-PostMtce	12.29	19.76	6.21	829.90	128.71	5	

Table 10 - Detroit Diesel - 820 Case Study Emissions Data

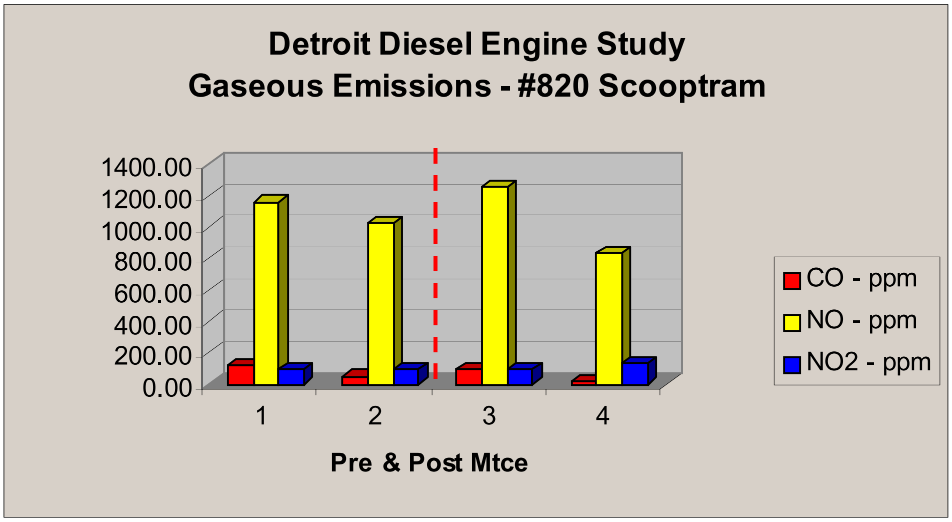
818 Scooptram Emissions Graphic Analysis

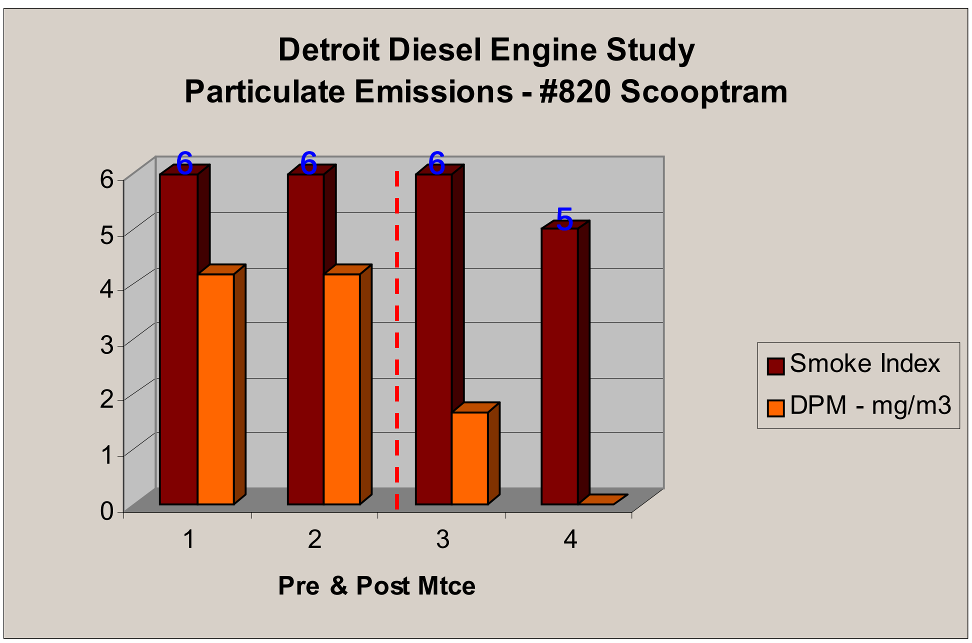




- 818 Scooptram is not equipped with a DOC so the results above appear as individual tests instead of upstream and downstream of the purifier on the other vehicles

820 Scooptram Emissions Graphic Analysis





- 820 Scooptram is equipped with a DOC so the results reflected above represent two sets of tests, each set consisting of a sample upstream and another downstream of the purifier.

SUMMARY

On day one of the study a total of 5 emissions tests were done on 818. The results reflect the maintenance activities through the day. The most significant activities would be the replacement of the air filters between tests 1 and 2, the intentional overfilling of engine oil between tests 3 and 4, and the 5^{th} and final results reflecting proper engine condition including the setting of valves and injectors. Of noteworthy interest if the fact that the Series 60 engine in 818 had over 11,000 operating hours accumulated at the time of the study. During the evaluation there were very few if any discoveries covering each of the engine systems. Even with 11,000 hours the engine was still performing well within specifications for power and emissions without any sign of deterioration. Looking at the emissions values for both gases and particulates it becomes evident that the DDEC electronic control system keeps the engine running at a fairly constant state from an emissions standpoint, even when adjustments are made to valve and injector settings.

Day two was the study on 820, with 2 sets of emissions tests done. The first set was done at the start of the study to have emissions from the as is state to compare from later. The 2^{nd} set was done at the end of the day after all maintenance activity was complete. Significant maintenance activities would include the servicing of the DOC, replacement of 6 injectors and setting the valves. The drop in the CO emissions after the purifier indicate that the servicing of the purifier had the greatest effect while the constant level before the purifier between the tests indicates that the injector replacement had no effect. This was a valuable lesson as proof that major adjustments or replacements for engine systems should be based on emissions only and not accumulated hours.

Although the graphic data depicts the changes and reductions in emissions, particular attention should be given to the relatively low scale from which the changes are being viewed. The DDEC electronic technology provides for very low emissions levels to begin with so effecting significant changes through routine maintenance becomes challenging. What did become evident however, is that the electronic control technology means that the mechanic requires a more sophisticated approach to diagnosing these engines. The same engine system approach still applies, but the mechanic must think in terms of how the electronic control system is measuring and controlling specific to each engine system.

Case Study IV – Caterpillar 3304T Engine

Introduction

Strathcona Mine employs one Caterpillar grader for maintaining roadways, in particular the ramp between 3700 and 4200 levels. There is generally only one operator who uses the grader between the four crews. When in use, the vehicle duty cycle is quite light due to the fact that most of the work is performed facing down ramp with a light load on the mouldboard. For this reason the engine exhaust temperatures would be somewhat lower than ideal for the majority of operating hours on the engine.

Toromont Caterpillar in Sudbury supplied the services of a field technician for the two-day study. Four mechanics actively participated for both days under the guidance of the Toromont representative. A complete set of emissions tests was done followed by an evaluation of the engine on a system by system approach using the *Guidelines and Best Practices* as a foundation. As defects were discovered and explained, they were repaired before moving to the next system.

Participants

Robert Lafond – Toromont Caterpillar Field Technician

Paul Marcoux – Mechanic, Strathcona Mine

Larry Thompson – Mechanic, Strathcona Mine

Maurice Mainville – Mechanic, Strathcona Mine

Denis Laplante – Mechanic, Strathcona Mine

Tim Hinds – Site Champion, Strathcona Mine

Sean McGinn – Project Leader, Noranda Technology Centre

Figure 30 - Caterpillar M-1 Grader

INTAKE SYSTEM

Evaluation of the engine intake system was done using checkpoints, techniques and tools from the guidelines and best practices along with the critical know how of the Caterpillar field technician.

Checkpoints:

- ✓ *Measure intake restriction with vacuum gauge*
- ✓ *Pressure test intake system for leaks*
- ✓ *Inspect intake manifold for dirt and leaks*
- ✓ *Inspect turbocharger for visual defects*

Deficiencies:

- ⌦ *Leaks at intake filter housing*
- ⌦ *Intake housing contaminated with dirt and oil*
- ⌦ *Turbocharger bearings and seals blown (blowing oil)*

Actions:

- ❖ *Repaired leaks at intake filter housing and rechecked*
- ❖ *Replaced turbocharger*

Figure 31 - Testing For Intake Leaks

Figure 32 - Turbocharger and Intake Inspection

Exhaust System

The exhaust system was a good example of how a few seemingly simple maintenance checks can easily be overlooked. The combination of visual inspection and emissions tests revealed some major deficiencies that were relatively simple to repair.

Checkpoints:

- ✓ *Emissions tests before and after exhaust purifier*
- ✓ *Calculate CO conversion efficiency of purifier*
- ✓ *Check exhaust backpressure*
- ✓ *Visual inspection of complete system for leaks, cracks, etc*

Deficiencies:

- ⌦ *Low CO conversion efficiency – 20%*
- ⌦ *Bad leaks at exhaust flanges under insulation*

Actions:

- ❖ *Cleaned and serviced purifier – retested and found unsatisfactory*
- ❖ *Replaced purifier*
- ❖ *Repaired leaks in exhaust system – cleaned and resealed*

Figure 33 - Purifier Before Service

Figure 34 - Leaks in Exhaust System

Fuel System

The fuel system evaluation on the 3304T engine clearly showed how critical it is to focus on details with mechanically fuel injected engines. Verification and adjustments were made to idle settings, rack setting, timing and injectors. The adjustment of the intake and exhaust valves was also included, although technically not part of the fuel system.

Checkpoints:

- ✓ *High and Low idle RPM settings*
- ✓ *Pin timing*
- ✓ *Fuel rack setting*
- ✓ *API fuel density*
- ✓ *Water separator*
- ✓ *Pressure group*
- ✓ *Intake and exhaust valves*

Deficiencies:

- ⌧ *High idle off by 200 RPM*
- ⌧ *Rack setting off*
- ⌧ *Valves out of adjustment (tight)*

Actions:

- ❖ *Adjusted and checked RPM*
- ❖ *Re-set rack from 5.50 to 3.50*
- ❖ *Set valves*
- ❖ *Replaced 4 injector nozzles (based on emissions tests)*

Figure 35 - Pin Timing Fuel Pump

Figure 36 - Setting Fuel Rack

Figure 37 - Setting Intake & Exhaust Valves

Cooling System

As mentioned earlier, this vehicle application tends to run at cooler engine temperatures than recommended. This accounts for much of the emissions problem complaints and explains the malfunction of the exhaust DOC. The explanation of the cooling system was a good opportunity to explain how different approaches can control engine temperature problems and what to look for in maintaining cooling systems.

Checkpoints:

- ✓ *Thermostat operation (I.R. temperature gun)*
- ✓ *Air flow through radiator*
- ✓ *Conditioner / Additive level*
- ✓ *Fan and belt adjustment and condition*

Actions:

- ❖ *Demonstrated effectiveness of shutterstats with cardboard restriction for controlling engine temperature*

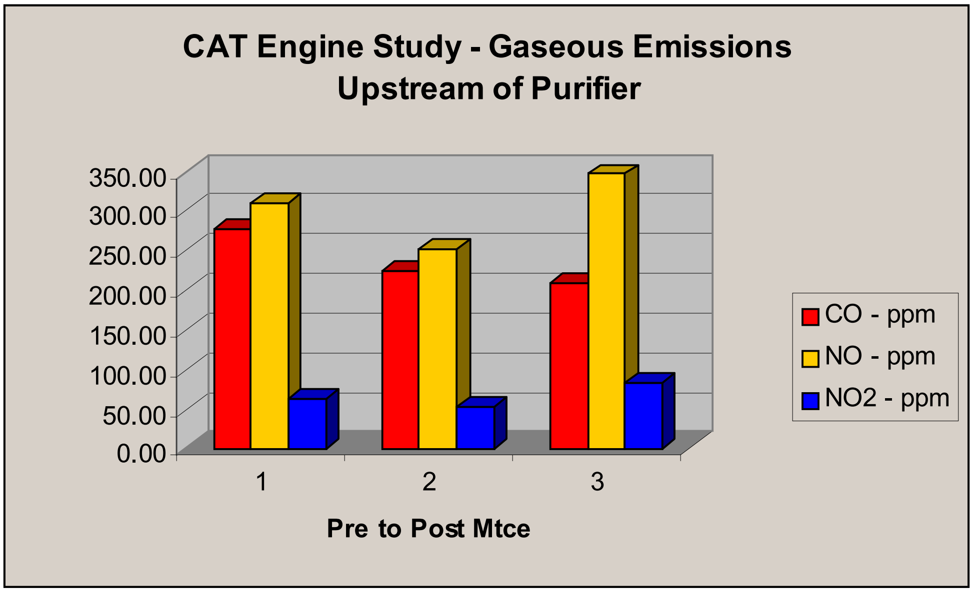
Lubrication System

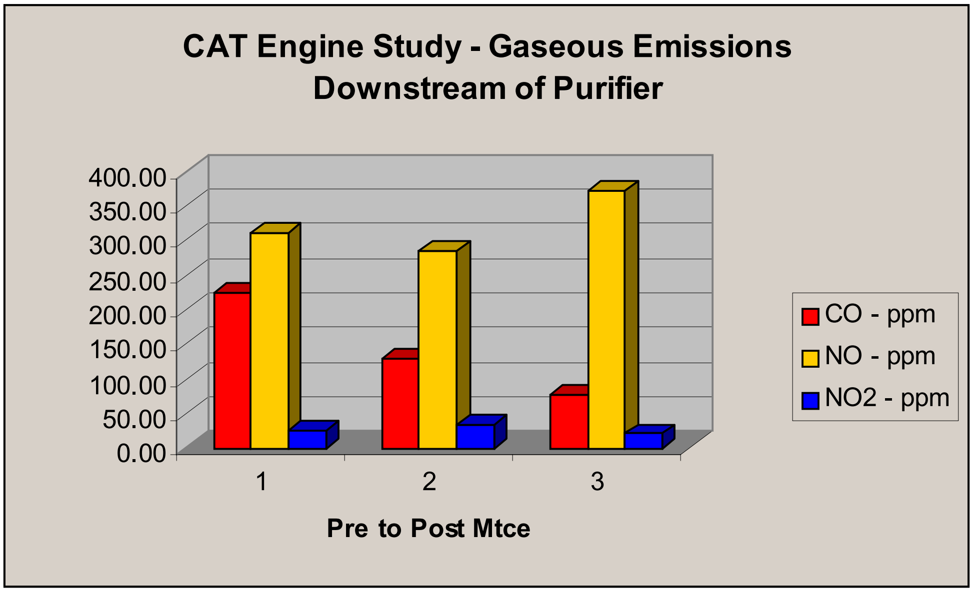
This section was more of a discussion area rather than hands on although of no less importance. One of the often-overlooked points by both operators and mechanics is the importance of maintaining a proper level on the engine oil dipstick. An overfilled crankcase can cause an engine to burn excess oil in the combustion chamber producing higher emissions. Also discussed was the importance of proper replacement of oil filters – and fuel also. The oft used practice of pre filling the filters on the workbench before installing can possibly lead to inadvertent contamination entering the system on the outlet side of the filter. The importance of using clean fill cans and nozzles was also stressed.

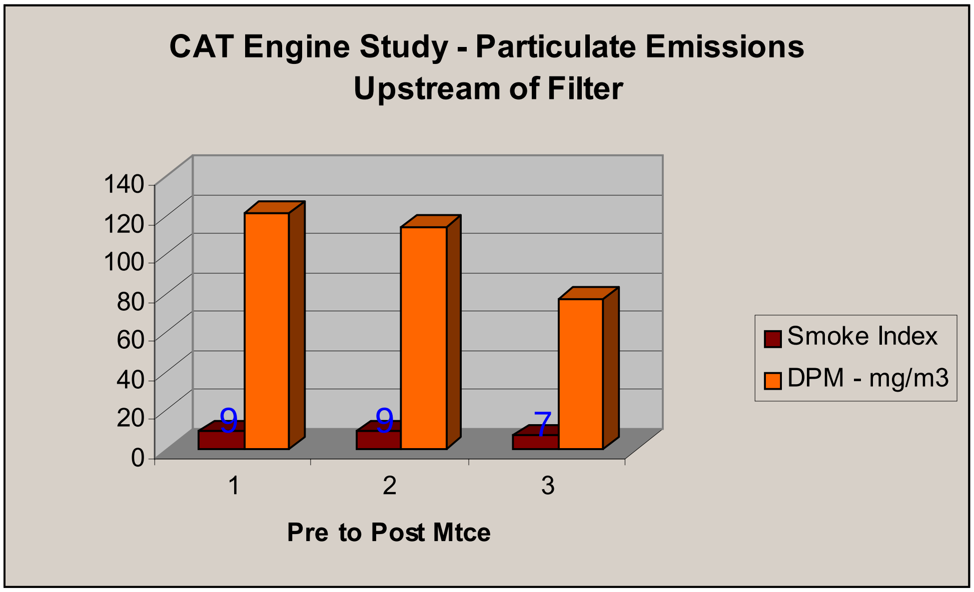
Emissions Results

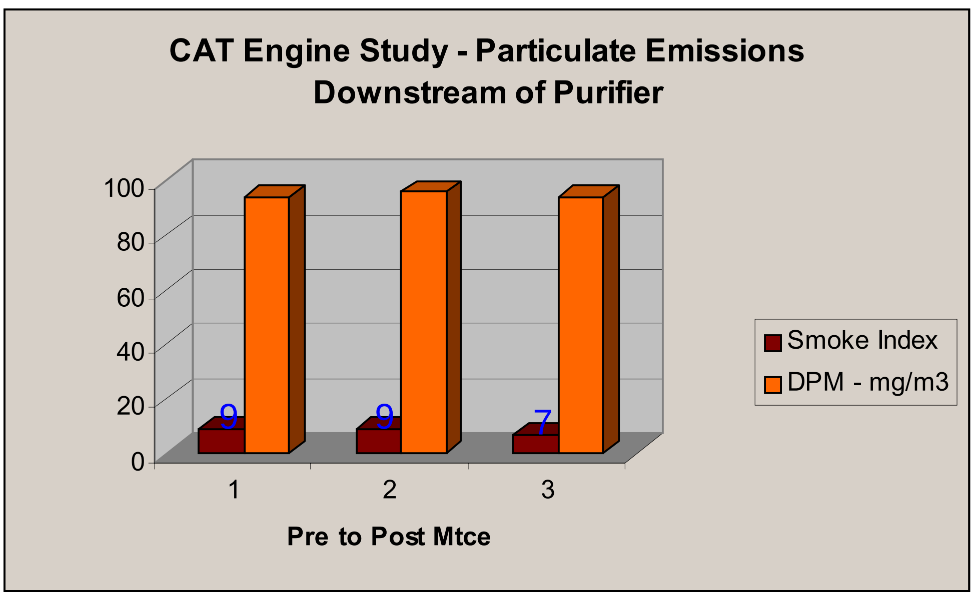
Test	Desc	O2	CO	CO2	NO	NO2	Smoke	DPM
		%	ppm	%	ppm	ppm	index	mg/m3
1	UPSTR-Pre Mtce	14.76	277.46	4.54	309.13	63.08	9	121.67
2	DNSTR-Pre Mtce	14.74	224.77	4.57	310.03	25.55	9	94.17
3	UPSTR- Mid Mtce	15.23	224.53	4.26	252.87	53.76	9	114.17
4	DNSTR-Mid Mtce	15.71	129.91	3.89	283.97	33.97	9	95.83
5	UPSTR-Post Mtce	14.90	208.98	4.50	346.53	82.92	7	77.50
6	DNSTR-Post Mtce	14.92	76.55	4.48	371.60	21.29	7	94.17

Table 11 - CAT Grader Case Study Emissions Data


CAT Engine Study - Gaseous Emissions
Upstream of Purifier
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
1
2
3
Pre to Post Mtce
CO - ppm
NO - ppm
NO2 - ppm


CAT Engine Study - Gaseous Emissions
Downstream of Purifier
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
1
2
3
Pre to Post Mtce
CO - ppm
NO - ppm
NO2 - ppm


CAT Engine Study - Particulate Emissions
Upstream of Filter
140
120
100
80
60
40
20
0
9
9
7
1
2
3
Pre to Post Mtce
Smoke Index
DPM - mg/m3


CAT Engine Study - Particulate Emissions
Downstream of Purifier
100
80
60
40
20
0
9
9
7
1
2
3
Pre to Post Mtce
Smoke Index
DPM - mg/m3

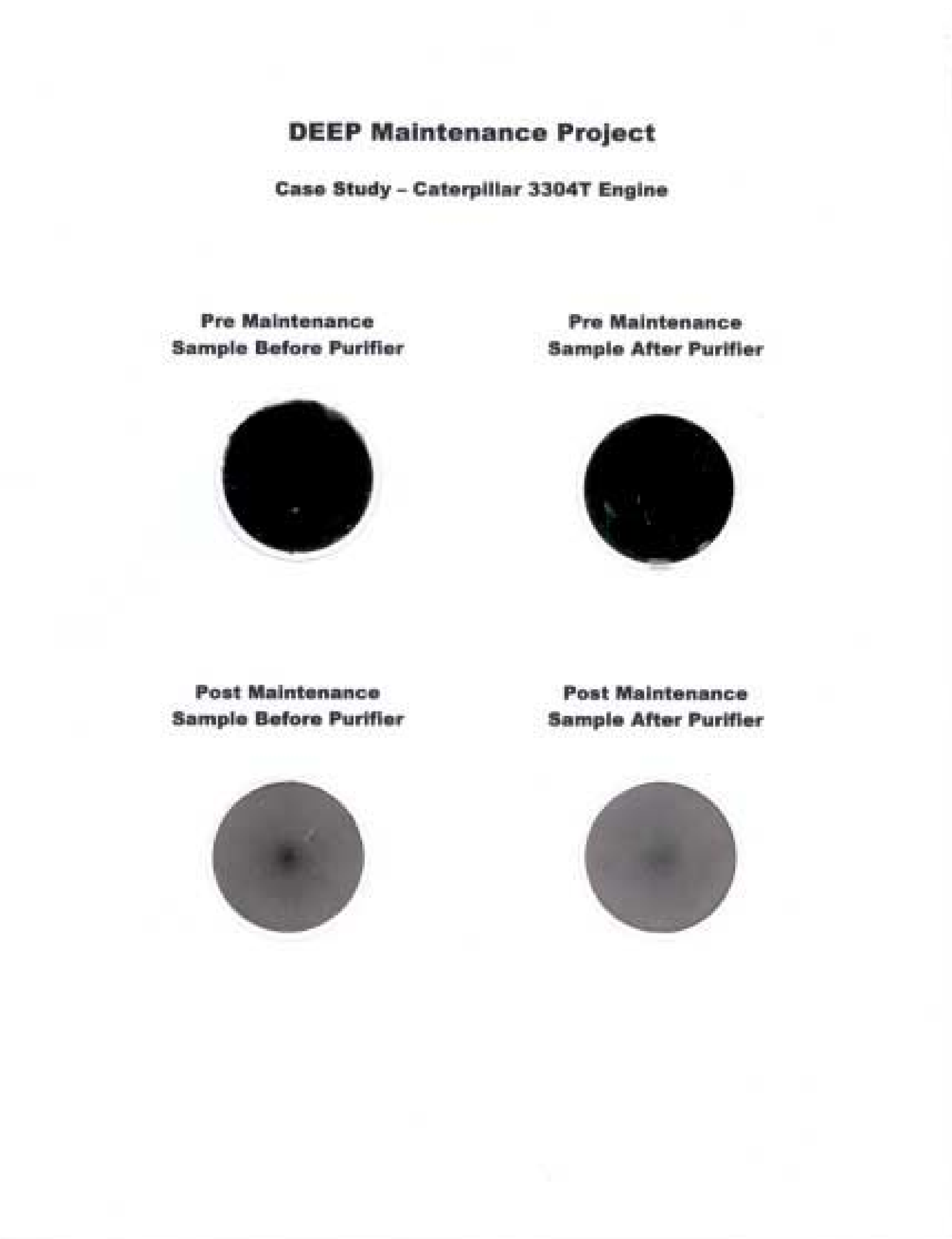


Figure 38 - DPM Samples Before and After

Summary

Of the four case studies the engine in the grader provided the best example of what can be found looking at all of the engine systems. The intake system had leaks, the turbocharger was defective, the exhaust system was in need of service, the fuel injection system was badly out of tune, and the cooling system required modifications. Though each of these problems are significant individually, the maintenance of the fuel injection system made the largest single difference to emissions. This is primarily because the rack setting was so far out of adjustment. This can be seen in the emissions analysis as the associated difference between the 3 sets of tests. The difference between the first and second is attributable to intake and exhaust repairs. The difference between second and third and overall is attributable to the fuel injection system.

The gaseous emissions show a reduction on the upstream side of the purifier of 25% and on the downstream side 66%. This is primarily due to the servicing of the aftertreatment system. The particulate emissions show a reduction on the upstream side from 121 mg/m3 to 77 mg/m3 or 37% total. The graphic in Figure 38 demonstrates visually the real impact on particulates. The scanned images are of the actual silver membrane filters with loaded DPM from the first and third set of tests.

PROJECT RECOMMENDATIONS AND CONCLUSION

RECOMMENDATIONS BASED ON FINDINGS

When looking back at the work done within this project it becomes obvious that it was really more of a review in proving what was already known than a demonstration of new technology or philosophy. With the exception of a few of the new tools that were introduced, the work described in this report brings together a lot of what the heavy-duty mechanics and shop foremen in our mining industry have known for many years. What is new here is that much (but not all) of the knowledge has been pulled together and applied as a uniform strategy without exception. The project mandate forced us to be consistent with the new strategy and not slip back to the more familiar and comfortable ways of the past. The ultimate goal of reduced emissions in applying this strategy has been proven with the data. A possible bonus that was never included in the scope of the project was the strongly suspected improvement in the bottom line for the mine in operating cost savings.

As the first level of control in reducing diesel exhaust emissions, the following recommendations for improved diesel engine maintenance can be adopted as the first steps in achieving reduced emissions.

❖ **Recommendation # 1**

Build a team focussed on implementing an improved maintenance strategy. The team should have members including mechanics, supervision, planning, and management from the mine. Responsibilities can be delegated according to an implementation plan and followed up through a report and meeting structure. Ensure that sufficient resources are made available to the team with respect to time, tools, and training.

❖ **Recommendation # 2**

Construct an engine maintenance audit program using the model provided in this report as a template. Select an auditing team from both internal and external to the mine maintenance system. Sometimes it takes an unaccustomed eye to uncover what is obvious and overlooked by someone closer to home. A good audit program has follow up mechanisms built in to it and should be conducted at least annually.

❖ **Recommendation # 3**

Utilize the *Guidelines and Best Practices* included in this report along with the six system approach to engine maintenance as a foundation in building a strategy for improving existing maintenance practices.

❖ **Recommendation # 4**

Put a program together for testing undiluted tailpipe emissions on underground vehicles. Integrate the program into the existing scheduled maintenance program with set action limits on emissions to ensure response to problems. The critical factor in the emissions testing program is not so much in the technology used to measure but in the structured protocol in taking the tests. In order to be useful the emissions must be compared against a known baseline at a known operating state consistently.

- **Recommendation # 5**

Make use of the suppliers of diesel engines and related equipment for training and follow up with new tools and other developments. The best way for an engine supplier to improve the relationship with the mine is to provide solutions to problems. The best way to do this is to have service representatives come to the mine and provide hands on instruction with small groups or one on one as described in the case studies for this project.

CONCLUSION

The DEEP maintenance project brought together resources from every corner of the mining industry to participate in some way however large or small. This in itself could be seen as the greatest success factor in the project. Every person who participated in the project gained valuable knowledge on the issue of diesel engine maintenance that so many continue to believe to be a non-issue. At the end of the project it is clear to all of us who participated that improved maintenance practices on diesel engines is the first line of control to reductions in emissions. The challenge now ahead is to pass this knowledge on to others in the mining industry. With all of the new technologies and developments that are presented to the mining industry it sometimes becomes difficult to look back to the fundamentals before moving ahead. Before the mining industry adopts new technologies as bolt on solutions it must ensure first that it understands the technology it already has and can maintain it to an acceptable level of performance.

To simply re-state the objectives of the project and how the work has achieved success on each point would be further repetition of what would by now be obvious. The final judgement should be left to those who actually did the work with this project and continue to carry on with the monitoring of emissions and practicing improved engine maintenance long after the project has been completed. During the case studies in the project the mechanics were asked to provide feedback as to their thoughts on the new maintenance practices and the future. The thoughts from the mechanics from 3900 shop at Strathcona Mine in the following appendix serve as the best gauge of success for the DEEP Maintenance Project.

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Acknowledgement

Thank you to the following for their assistance in making the DEEP Maintenance Project a success!

Project Funding

The contributing members of the Diesel Emissions Evaluation Program (DEEP) and the Workers Compensation Board of Manitoba

Technical Panel for Guidelines and Best Practices

Bob Huzij – INCO Ltd.
Barry Huston - Williams Operating Corp.
Mike Meadows – Detroit Diesel Canada
Gaston Auclair – Deutz Canada

Diesel Engine Maintenance Audit Model

Philippe Gaultier - Compañía Minera Antamina
Sheri Weeks – Nexfor Inc.
Jennifer Penney – USWA

Implementation of Improved Maintenance and Case Studies

Peter Prince – Deutz Canada Sudbury
Brent Rubeli – DCL International
Mike Meadows – Detroit Diesel Canada
Tom Serpell – Harper Detroit Diesel Sudbury
Bob Whitcher – Toromont Caterpillar Sudbury
Robert Lafond – Toromont Caterpillar Sudbury

Emissions Measurement and Analysis

Michel Grenier and the group at NRCan – CANMET laboratories in Sudbury, Ontario
Dr. Mahe Gangal and the group at NRCan – CANMET laboratories in Bells Corners. Ontario

The management and employees of Hudson Bay Mining & Smelting - Ruttan Mine

Falconbridge Ltd. – Strathcona Mine

Heather Langfeld, Parviz Farsangi, Rick Allair, Tom Semadeni, and Tim Hinds

and most importantly…..the mechanics from 3900 Shop!

Scott Chisolm, Paul Chouinard, Ron DeCou, Phil Dube, Al Jones, Mike Lalonde, Denis Laplante, Bruce Lapping, Norm Leger, Maurice Mainville, Paul Marcoux, Mike Robinson, Blair Sagle, Paul Serpell, Pat Sweeney, and Larry Thompson

Appendix I – Mechanic Feedback

The following is a sample of written feedback from Strathcona Mine mechanics who participated in the case studies. They were asked to respond to the questions below following the completion of the case study.

How has the training changed your approach towards engine maintenance?

" Particulates is everyone's concern for health reasons. It is interesting to see training courses like this offered when the mechanic's feedback will be looked at or addressed. We should succeed by monitoring emissions on a monthly basis with the help and technology and cooperation."

" Last two days showed us how we can make improvements in our daily maintenance with very little effort or cost to use"

" My approach to engine maintenance and emissions will change now by having a better idea of what is involved in the emissions and knowing that I can play a role in the reduction of emissions for my own benefit and that of others. By understanding the maintenance of diesel engines and other devices at our disposal we can measure and reduce emissions greatly."

Will you continue to use the new knowledge and approach after this course?

"Yes, especially the controls devices section. Again, the only limitation to using this information may be a time factor but this is an area where I would be able to see an actual difference. I need to contribute to the quality of the environment down here."

" We must continue to use our new found knowledge if we are to continue running equipment U/G due to the new laws coming into effect, and to help reduce maintenance costs."

"Yes, for health reasons."

" I think I will, but the company will have to allow the time and not let it go by the way side."

Appendix II – Maintenance Audit Template

The template for auditing diesel engine maintenance has been attached as a separate document.

APPENDIX III – GUIDELINES AND BEST PRACTICES

The Guidelines and Best Practices for Diesel Engine Maintenance have been attached as a separate document.