

**REVISED FINAL REPORT**

**EVALUATION OF BIODIESEL FUEL AND OXIDATION CATALYST IN  
AN UNDERGROUND METAL MINE**

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## EXECUTIVE SUMMARY

The University of Minnesota (UMN), Inco, CANMET, Michigan Technological University (MTU), ORTECH, and the National Institute for Occupational Safety and Health (NIOSH) evaluated the impact of blended biodiesel fuel and modern diesel oxidation catalyst (DOC) on air quality and diesel emissions. The study was conducted at Inco's Creighton Mine in Sudbury, Ontario in October of 1997. Other organizations participating in the study included: the Manufacturers of Emission Controls Association, the Ontario Soybean Growers' Marketing Board, and the Deutz Engine Company.

The study characterized the concentration of diesel particulate matter (DPM) and exhaust gas emissions in a non-producing test section. During the first week of the evaluation a diesel-powered scoop was operated on low sulfur, number 2 diesel fuel (D2). During the second week the scoop was operated on a 58 % (by mass) blend of soy methyl ester (SME) biodiesel fuel and a low sulfur D2. During both weeks the scoop was equipped with a pair of identical, advanced design diesel oxidation catalysts (DOC). The objective of the evaluation was to determine changes in exhaust emissions and to estimate operating costs of a test vehicle fueled with blended biodiesel.

The results of this study are detailed in three reports. The chemical and biological analyses of particulate matter samples are summarized in the MTU report. Analyses of samples collected with a prototype denuder-difference sampling system for specific polycyclic aromatic hydrocarbons are summarized in the ORTECH report. This report summarizes the body of data collected to determine the difference in gaseous and particulate matter concentrations attributable to the use of a blended biodiesel fuel and catalyst.

Day-to-day variation in emissions was determined using the Emissions Assisted Maintenance Procedure (EAMP). This procedure requires that the test vehicle be operated for a short time under torque stall conditions while undiluted exhaust gas concentrations are measured at the tailpipe at points above and below the DOCs. Data obtained under these conditions are not representative of full-shift time-weighted average emissions, but do indicate the general condition of the engine and DOCs. No major changes in engine emissions were observed and the DOCs performed as anticipated. Carbon monoxide was effectively removed ( $98 \pm 10$  %, D2 fuel and  $99 \pm 11$  % blended fuel) by the DOCs, but there was an increase in  $\text{NO}_2$  concentrations ( $185 \pm 78$  % D2 fuel,  $233 \pm 59$  % blended fuel). At this engine condition blended fuel increased  $\text{NO}_2$  concentrations downstream of the DOCs by  $43 \pm 28$  %.

Air samples collected in the test section demonstrated that the combination of the blended biodiesel fuel and DOCs used in this study decreased total carbon emissions by about  $21.4 \pm 0.98$  %. Elemental carbon was reduced by  $28.6 \pm 0.87$  % and organic carbon was reduced  $6.0 \pm 3.32$  % although the OC reduction was not statistically significant. This is lower than the initial expectation of 30 % - 50 % reduction. There was a slight, but statistically insignificant, increase in  $\text{NO}_2$  concentrations measured at the downwind location and a corresponding decrease in NO emissions, which was also statistically insignificant.  $\text{SO}_2$  levels were low during both

weeks of testing. Reductions in mutagenicity and PAH concentrations are detailed in the MTU report.

Blended biodiesel fuel used in conjunction with a modern DOC offer a passive control option to reduce DPM in an underground mine. The primary limitation to the use of biodiesel fuel is cost. Typical biodiesel fuel ranges in price from \$3.00 - \$3.50/gal U.S. Assuming a cost of \$1.00/gal U.S. of D2 fuel, use of a 50 % blended biodiesel fuel would cost \$2.00 to \$2.25/gal U.S. This cost must be weighed against the cost of installing and maintaining emission control systems based upon filtration or other methods. It is likely that increased production of a renewable energy source, such as biodiesel, will lower costs allow biodiesel fuel to become a more viable DPM control option for underground mines in the future.

## BACKGROUND

Extensive information on the potential health effects from exposure to diesel exhaust is found in publications by the World Health Organization (WHO, 1996), the Health Effects Institute (HEI, 1995), the International Agency for Research on Cancer (IARC, 1989) and the National Institute for Occupational Safety and Health (NIOSH, 1988). A brief overview of the health concerns, chemical composition and physical characteristics of diesel aerosol are presented.

**Health Concerns:** Recent attention has focused on the potential carcinogenicity of DPM and the potential health impact on miners. The American Conference of Governmental Industrial Hygienists (ACGIH, 1995) added DPM to the List of Intended Changes for 1995-96 with a threshold limit value (TLV<sup>TM</sup>) recommendation of 0.15 mg/m<sup>3</sup>. DPM remains on the ACGIH List of Intended Changes for 1998.

**Chemical Composition:** Diesel aerosol consists mainly of highly agglomerated solid carbonaceous material and ash, and volatile organic and sulfur compounds. The structure is illustrated schematically in figure 1. Solid carbon is formed during combustion in locally fuel rich regions. Much of the carbon is subsequently oxidized with the residue exhausted in the form of solid agglomerates. A tiny fraction of the fuel and atomized and evaporated lube oil escape oxidation and appear as volatile or soluble organic compounds (generally described as the soluble organic fraction, SOF) in the exhaust. Most of the sulfur in the fuel is oxidized to SO<sub>2</sub>, but a small fraction is oxidized to SO<sub>3</sub> that leads to sulfuric acid and sulfate aerosol. Metal compounds in the fuel and lube oil lead to a small amount of inorganic ash.

**Physical Characteristics of Diesel Aerosol:** Figure 2 shows the idealized, log-normal diesel aerosol number and mass weighted size distributions (Kittelson, 1998). The distributions are multi-modal and lognormal in form. The concentration of particles in any size range is proportional to the area under the corresponding curve in that range. Most of the particle mass exists in the so-called accumulation mode in the 0.1 to 0.3 μm diameter range. This is where the carbonaceous agglomerates and associated adsorbed materials reside. The nuclei mode typically consists of particles in the 0.005 to 0.05 μm diameter range. This mode usually consists of volatile organic and sulfur compounds that form during exhaust dilution and cooling, and may also contain solid carbon and metal compounds. The nuclei mode typically contains 1-20 % of

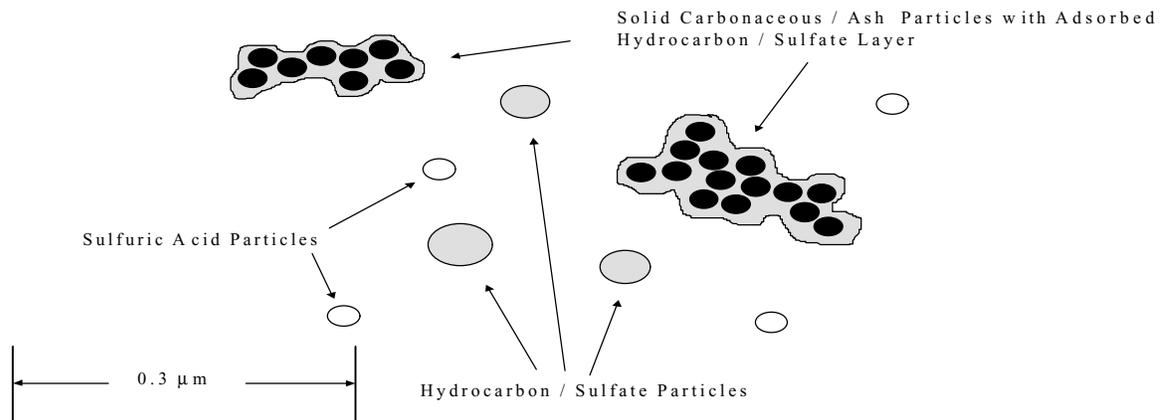


Figure 1 - Typical composition and structure of engine exhaust particles

the particle mass and more than 90 % of the particle number. The coarse mode contains 5-20 % of the particle mass. It consists of accumulation mode particles that have been deposited on cylinder and exhaust system surfaces and later reentrained. Also shown in figure 2 are definitions used to define atmospheric particles: PM<sub>10</sub>, D (diameter) < 10  $\mu\text{m}$ ; fine particles, D < 2.5  $\mu\text{m}$ ; ultrafine particles, D < 0.10  $\mu\text{m}$ ; and nanoparticles D < 0.05  $\mu\text{m}$  or 50 nm. Definitions of fine, ultrafine and nano-particles are not universally agreed upon. Note that by number, nearly all of the particles emitted by a diesel engine are nano-particles

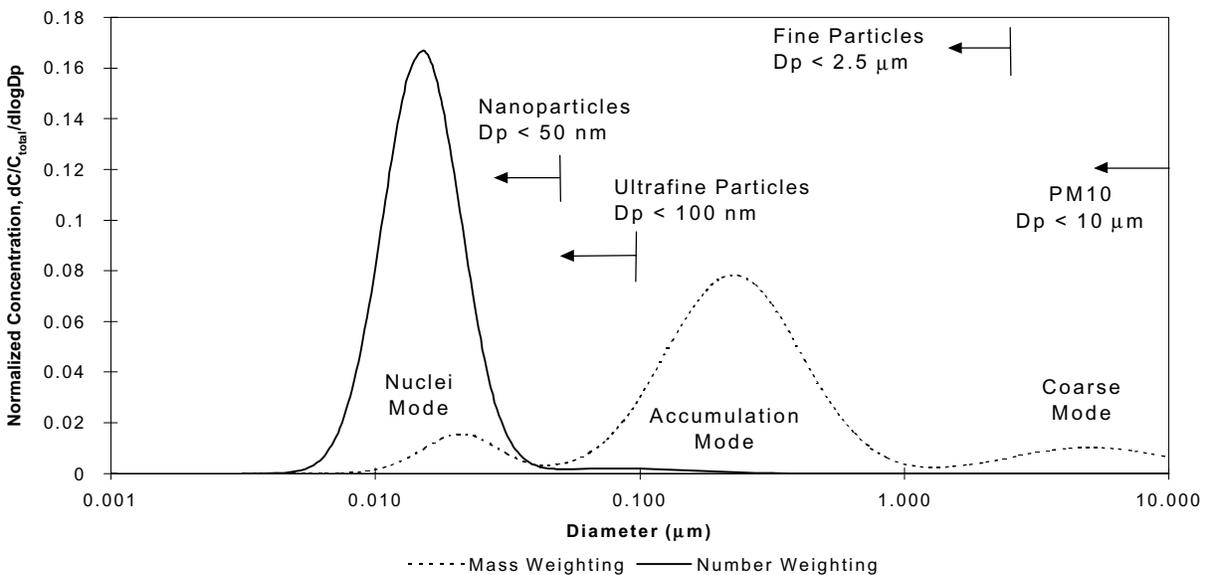


Figure 2 - Typical engine exhaust size distribution both mass and number weightings (Kittelson, 1998).

Figure 3 (Whitby and Cantrell, 1975) shows the mechanisms such as condensation and coagulation that transfer aerosol mass from one size range to another. The smallest of the three modes, 0.001 to 0.08  $\mu\text{m}$ , is the Aitken nuclei range, which consists of primary aerosol from combustion sources such as diesel engines and secondary aerosol formed from coagulation of primary aerosols to form chain agglomerates. The next size range, 0.08 to 1.0  $\mu\text{m}$  is the accumulation range, that contains emissions in this size range plus aerosol accumulated by mass transfer through the coagulation and condensation processes from the nuclei range. The last range, 1.0 to approximately 40  $\mu\text{m}$  is referred to as the coarse aerosol size range. Aerosols within this range generally originate from mechanical processes such as grinding, mechanical fracture and bulk material handling. There is very little exchange of mass from the nuclei and accumulation modes to the coarse particle mode under most conditions.

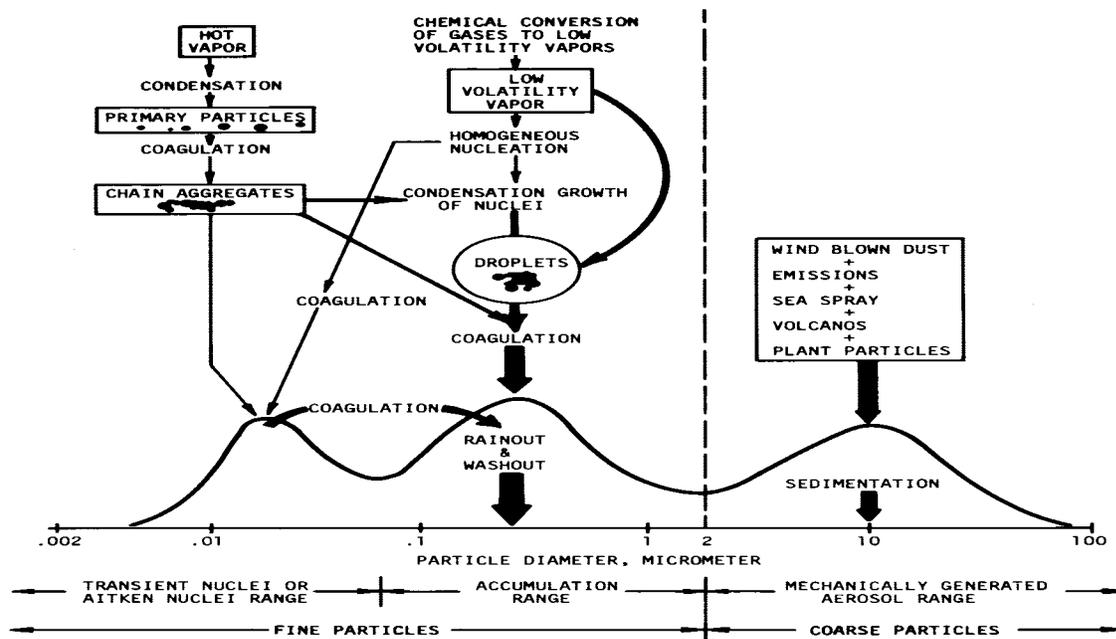


Figure 3 - Idealization of an atmospheric surface area distribution showing the principal modes, sources of mass, and the processes involved in mass transfer and removal (Whitby and Cantrell, 1975).

### PREVIOUS BIODIESEL FUEL RESEARCH

Biodiesel is a generic term that refers to various fatty-acid mono-esters that can be used for diesel fuel. Mono-esters are typically produced by transesterification of triglycerides with a simple alcohol such as methanol, ethanol, butanol, or iso-propanol in the presence of an alkaline catalyst. These fuels contain about 11 % oxygen by mass. Biodiesel fuel reduces the carbon portion of DPM by increasing oxygen availability to locally fuel-rich regions within the cylinder during combustion (Heywood, 1988 and Ladommatos, et al.1996). This increase in oxygen availability may reduce the pyrolysis of unburned or partially burned fuel compounds that is believed to be the primary mechanism of carbon fraction formation during diesel combustion. Biodiesel fuels typically increase the formation of particle-phase volatile organic compounds (Needham and

Doyle, 1985, Last, et al., 1995, Schmidt and Van Gerpen, 1996) and increases in NO<sub>x</sub> have been reported (Liotta and Montalvo, 1993, Ullman, et al. 1994, Last, et al., 1995, Schmidt and Van Gerpen, 1996) but not in all cases (Needham and Doyle, 1985).

Laboratory evaluations of SME biodiesel fuel in conjunction with a DOC showed significant reductions of DPM emissions (McDonald, et al. 1995 and Purcell, et al. 1996). [Organic material from incomplete combustion of biodiesel fuel is more likely to condense to form the SOF of DPM or volatile organic compounds (VOC), than partially burned petroleum diesel fuel compounds. Therefore, to obtain the maximum reduction of DPM possible, an advanced design catalyst is used in conjunction with biodiesel fuels to reduce the organic fraction of DPM.] During this evaluation the biodiesel fuel was used either pure or blended with D2 fuel. The test engine was a Caterpillar 3304 PCNA. When 100 % biodiesel fuel was used with a modern DOC, total DPM emissions were reduced by 50 % when compared with using low sulfur, D2 fuel with a DOC. Particulate and vapor phase extracts of organic material collected from the exhaust stream while the engine was operated using the biodiesel fuel showed greatly reduced mutagenic activity compared to operation on D2. The laboratory evaluation concluded that the combination of biodiesel fuel, either pure or blended with petroleum diesel fuel, could be an effective control strategy to reduce DPM emissions and DPM mutagenic activity from diesel-powered equipment used in underground mines.

A field study (McDonald, et al, 1997) was conducted at the Homestake Mine in Lead, SD. The study evaluated mine air quality in a producing mine section operating a diesel scoop equipped with modern DOCs. The scoop was fueled by either a 100 % biodiesel fuel or a commercial, low-sulfur, D2 fuel. The scoop was a 2.7 m<sup>3</sup> (3.5 yd<sup>3</sup>) Wagner load-haul-dump (LHD) powered by a 10.5 liter, 6 cylinder, naturally aspirated, 100 kW Caterpillar 3306 pre-chambered naturally aspirated (PCNA) diesel engine. The LHD was completely reconditioned, and the engine was rebuilt by the local Caterpillar distributor prior to the start of the field study. No modifications were made to the LHD for operation on biodiesel fuel.

Mine air DPM concentrations were monitored daily for a six week period while the LHD was operated with either the biodiesel fuel or the D2 fuel. DPM concentrations were measured in the section's clean air intake and ventilation exhaust, and on the LHD. Reduction in DPM emissions was determined from the measured difference in DPM concentrations between the clean air intake and the ventilation exhaust. Based upon measurements obtained with the size selective sampler, the biodiesel fuel reduced energy-specific DPM emissions approximately 72 %, from 3.6 ± 1.9 g/kW-hr to 0.99 ± 0.26 g/kW-hr. Time-weighted average DPM exposure, measured near the LHD operator, was reduced from 0.70 ± 0.15 mg/sm<sup>3</sup> to 0.36 ± 0.12 mg/sm<sup>3</sup>, or approximately 49 %, when the biodiesel fuel was used.

## **PROJECT SCOPE AND OBJECTIVES**

Under the auspices of the Diesel Emission Evaluation Program, the UMN, Inco, CANMET, MTU, ORTECH, and NIOSH evaluated the impact of blended biodiesel fuel and modern DOC on air quality and diesel emissions. Other organizations participating in the study included: the

Manufacturers Emission Control Association, the Ontario Soybean Growers' Marketing Board, and the Deutz Engine Company.

The study is similar in many ways to the study conducted by the U.S. Bureau of Mines at the Homestake mine described above (McDonald, et al. 1997). The major differences are:

- A blended rather than pure biodiesel fuel was evaluated,
- An air-cooled as opposed to a water-cooled engine was used,
- The test was conducted in a non-producing test section rather than a producing section,
- Air quality measurements included NO, NO<sub>2</sub>, CO, CO<sub>2</sub> and SO<sub>2</sub>,
- The test protocol included samples to determine gas and particle bound polycyclic aromatic hydrocarbons (PAH),
- Ventilation air flows were constant throughout the study period,
- The engine was instrumented to obtain fuel consumption and power data,
- Exhaust emissions tests were performed daily.

During the first week of the evaluation a diesel-powered scoop was operated on low sulfur, D2 fuel. During the second week the scoop was operated on a blend of SME biodiesel and low sulfur D2. During both weeks the scoop was equipped with a pair of identical, advanced design DOC. The objective of the evaluation was to determine changes in exhaust emissions and to estimate operating costs of operating a test vehicle on a blended SME biodiesel fuel blend with a modern DOC. [There was also one additional day of testing requested and paid for by Inco, in which the DOCs were removed from the scoop and testing was conducted with the blended fuel.]

## TEST PROTOCOL

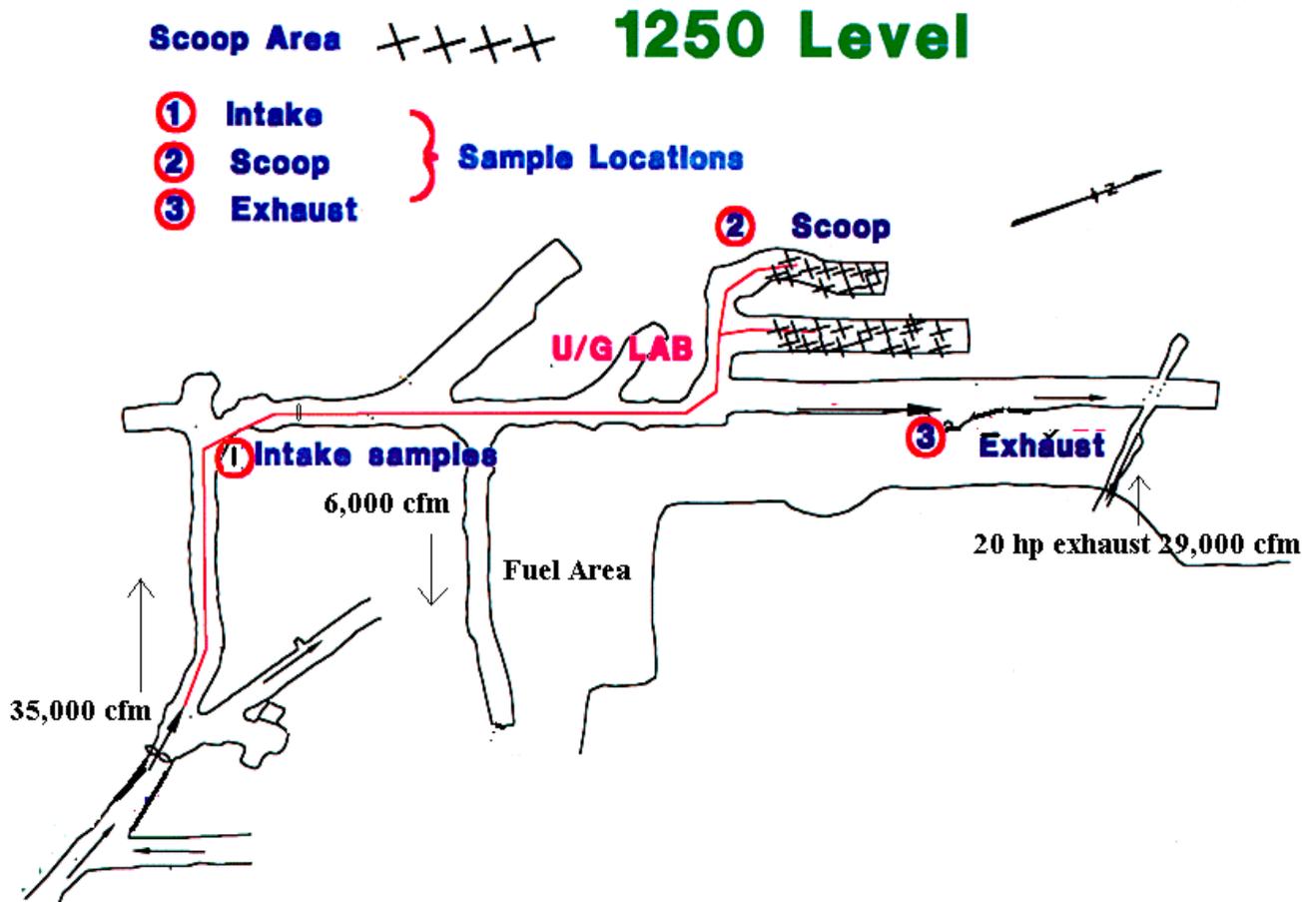
**Mine Test Site:** Inco hosted this project at Creighton Mine #3 in Sudbury, Ontario. The test section was located at the 1250 ft (381 m) level of the mine and was accessed by driving down a ramp from the surface. The layout of the section is shown schematically in figure 4. The scoop moved muck from one drift to the other as marked by the Xs in the figure. Ventilation air entered the section at point 1 and exhausted at point 3. Typically, 35,000 ft<sup>3</sup> (991 m<sup>3</sup>) of air entered the section. This air was used to ventilate the fuel bay (6,000 ft<sup>3</sup> or 170 m<sup>3</sup>) and the mucking area (29,000 ft<sup>3</sup> or 821 m<sup>3</sup>). Separate splits of air were used to ventilate each of the two mucking areas. Air samples were collected at points 1 and 3 and samplers were located on the scoop near the operators location. The scoop operated for about 5 hrs each day, including a 30 min lunch break.

**Test Vehicle And Instrumentation:** The vehicle was a Wagner ST-8a scooptram powered by a Deutz F12L 413FW diesel engine rated at 204 kW at 2400 rpm. The scoop was operated by a senior Inco scooptram operator with previous experience working with the leaders of the research team. Prior to the test, the engine was thoroughly inspected and repaired as required by a qualified Deutz technician. The engine was also evaluated after the tests were concluded. No significant changes were observed.

A critical factor in evaluating the two fuels is engine performance and duty cycle. The engine was instrumented to ensure that the air quality data could be normalized for day-to-day changes in engine performance and duty cycle

The scoop's duty cycle was evaluated by recording engine speed, fuel consumption, and exhaust temperature at 1-s intervals over each sampling period. Data were stored in a Rustrak Ran ger II data logger, which was enclosed in a foam padded aluminum suitcase and strapped to the top of the scooptram with bungee cords.

Figure 4 - Test section layout Creighton Mine number 3 shaft



A Flo-scan fuel flow meter was also enclosed in the suitcase to monitor fuel consumption. Two infrared turbine sensors were mounted in the engine's fuel system: one measured fuel supply flow to the engine, and the other measured fuel return flow to the fuel tank. Signal outputs from these sensors were processed by the flow meter, and a 0-5 V output proportional to net fuel consumption was converted and recorded by the data logger into instantaneous fuel flow in gal/h. The fuel meter and data logger were bench tested in an engine laboratory against a Pierburg Flo-tron fuel measurement system prior to field installation. The portable system was accurate within 4 % of the laboratory standard.

Speed was measured by sensing the frequency of the 12 V waveform frequency from the engine's alternator. A frequency to voltage converter was used to provide a proportional 0-10 V output to the data logger. A factor to convert from alternator speed to engine speed was calculated by measuring the engine crankshaft and alternator pulley diameters and knowing the number of poles in the alternator. The factor was verified by comparing the engine speed recorded by the data logger to the engine speed measured by a photo-tachometer at the crankshaft pulley. Both speed measurements were consistently within  $\pm 5$  rpm at various speeds.

Because the engine was configured with dual exhaust, each exhaust bank was fitted with a 0.125 in (3.2 mm) K-type ungrounded thermocouple at the inlet cone of their respective DOCs. The data logger was configured with two K-type thermocouple-logging channels, and the channels were checked at one point with ice water.

**Daily Emission Testing:** Day-to-day variation in emissions was determined using the EAMP recommended by the U.S. Mine Safety and Health Administration (Spears, 1997). This procedure requires that the test vehicle be operated for a short time under torque stall conditions while undiluted exhaust gas concentrations are measured at the tailpipe at points above and below the DOCs. *Data obtained under these conditions are not representative of full-shift time-weighted average emissions, but do indicate the general condition of the engine and DOCs.* Results from these tests verified that the engine and DOCs were operating properly. The test procedure measured the undiluted exhaust emissions from the Deutz F12L 413 FW diesel engine. Because the V-block engine was configured with dual exhaust and separate DOCs for each exhaust bank, the procedure was repeated at the following four sampling locations each day:

- Left exhaust bank, upstream of the left bank DOC
- Left exhaust bank, downstream of the left bank DOC
- Right exhaust bank, upstream of the right bank DOC
- Right exhaust bank, downstream of the right bank DOC

An Ecom-AC 4-gas electrochemical cell gas analyzer (Ecom America Ltd. Duluth, GA) was used to determine concentrations of CO, CO<sub>2</sub>, NO and NO<sub>2</sub> in the engine's exhaust. The emission concentrations were measured when the engine was operated at a steady-state torque converter stall condition. CO<sub>2</sub> exhaust concentration and an engine speed sensor were used to verify that the torque converter on the LHD consistently stalled along the engine's lug curve at 2250  $\pm$ 30 rpm. Power output for the engine at this condition was 200 kW. Because this full-load engine condition was repeated for each test, emission concentrations could be directly compared.

Each day the test procedure was performed as follows:

1. The gas analyzer was turned on and allowed to warm up for at least 5-min. Each day the instrument sensors were zero calibrated, and on alternate days the sensors were zero and span calibrated using bottled span gases. The span calibration on the CO sensor was only adjusted twice and the NO and NO<sub>2</sub> sensors were adjusted 5 times over the 3-wk testing period.
2. A laptop PC was connected to the gas analyzer and emission measurements were recorded electronically at 1-sec intervals.
3. Exhaust port plugs located upstream of the DOCs were temporarily removed in order to sample the exhaust upstream of the DOCs.
3. Because the engine was always tested after about 3 hrs of operation, the engine did not have to be warmed up prior to testing.
4. The gas analyzer probe was inserted into one of the sampling locations, and the exhaust was sampled continuously for 15-sec before the torque converter stall was initiated.
5. To initiate the torque converter stall, the equipment brakes were applied.
6. The transmission was shifted into high gear.
7. The fuel pedal was then fully depressed for 30-sec\*. The operator closely monitored the torque converter oil temperature during the torque stall. The test was to be aborted immediately if any of the LHD's operating parameters appeared abnormal. If the LHD had begun to move during a test, the test would have been aborted immediately and the LHD's brakes would have been serviced.
8. Sampling continued for the entire torque stall. The instrument technician monitored both CO<sub>2</sub> and CO instrument readings to ensure that the torque converter stall condition had been reached and that emissions were stable.
9. After 30-sec\* the fuel pedal was released, the transmission was shifted out of gear, the brakes were released, and the torque converter was allowed to cool for a few minutes before the test was repeated at the remaining sample locations.
10. At each location sampling continued for 15-sec after the torque stall to ensure that emissions were completely drawn through the sample line and analyzed by the instrument.

11. The analyzer was allowed to sample mine air after each test to purge the instrument of raw exhaust.
12. Data were reviewed to determine test results. By interpreting a graph of CO<sub>2</sub> concentration versus time, the time interval over which the engine was operated under a steady state was determined. The CO, NO, and NO<sub>2</sub> concentrations should also be fairly constant over this interval, and CO, CO<sub>2</sub>, NO, and NO<sub>2</sub> values were averaged over this interval.

\*The torque converter stall time was increased from 30-sec to 1-min when sampling took place downstream of the DOCs. This change in protocol was made because the downstream NO<sub>2</sub> concentration did not stabilize until about 45-sec after the torque stall was initiated. This increase in time required to reach stable NO<sub>2</sub> concentrations was due to the time required for the catalyst to approach a stable temperature.

**Test Fuels and Costs:** The Ontario Soybean Growers' Marketing Board provided 770 gal of biodiesel fuel from the NOPEC Corporation in Lakeland, Fl. The fuel was shipped to Sudbury in 55 gal drums. The low sulfur D2 fuel routinely used by Inco was used in this project. D2 fuel is supplied to Inco by Imperial Fuel, Sudbury, Ontario. The blended fuel was mixed underground and samples were collected for chemical analysis (System Lab Services, Kansas City, KS). Results from the fuel analysis are shown in Appendix 1. Both fuels met test specifications as outlined in the project proposal (Watts, et al, 1997).

Mixing ratios of fuels are affected by temperature and fuel density. D2 fuel was pumped into 250 gal totes (110 gal/tote) while the totes were on the surface. Temperatures on the surface were near freezing. The biodiesel fuel was stored underground where the temperature was about 55 °F (13 °C). This was done to avoid potential problems with surface temperatures being below the cloud point of biodiesel fuel. The more dense biodiesel fuel was then added to the totes after the totes were transported underground. Thus, even though 2 drums (55 gal) of biodiesel fuel were added to each tote the exact percentage of biodiesel fuel was slightly more than 50 % as explained below.

The percentage of biodiesel fuel in the blended fuel was determined from API gravity. The API gravities obtained from the fuel analyses were related to fuel density (Stinson, 1990) and the fuel density ratios were used to determine the percent of biodiesel fuel by volume (55.6 %) and by mass (58.1 %). These values, in conjunction with heat content of the fuels yielded the percent energy contained in the blended fuel by mass or volume. The blended fuel yielded 93.1 % of the energy by mass or 98.1 % of the energy by volume as compared to the D2 fuel. The D2 fuel had a heat content of 19,937 BTU/lb. These values are used later in the power correction factor discussed in the results section.

Biodiesel fuel is more expensive than low sulfur D2 fuel and is currently not produced in large quantities. Recently, Twin Rivers Technologies of Quincy, Massachusetts received U.S. Environmental Protection Agency (EPA) certification for Envirodiesel, a brand of biodiesel fuel

for use in the EPA's Urban Bus Retrofit/Rebuild program. It is expected that this will spur demand and lower future prices.

The biodiesel fuel used during this project cost \$3,913 (U.S.) for 770 gal. This breaks down to \$2,456 for the fuel (\$3.19/gal US), \$280 for 14 - 55 gal drums and \$1,177 for shipping from FL to Sudbury. In addition, the 250 gal totes purchased to store the fuel underground cost \$2,200 and fuel specification analysis cost \$588. Clearly, the cost of the biodiesel fuel could be reduced by purchasing in larger volumes. Low sulfur diesel fuel used in the Sudbury for mining costs about \$ 0.72/gal (U.S.).

For comparison, biodiesel fuel purchased in Minnesota in 1-2,000 gal quantities ranges in cost from \$3.00 - 3.50/gal including tax and shipping costs. Low sulfur D2 fuel for off-highway use purchased in the same quantities costs about \$1.00/gal. Using these costs, a 50:50 blended fuel would range in cost between \$2.00 - 2.25/gal.

**Diesel Oxidation Catalyst:** The 6 identical DOCs used in this evaluation were provided by the Manufacturers of Emission Controls Association and combined an advanced design catalyst with a ceramic flow-through substrate. The exact nature of the catalyst is proprietary but the DOC was certified for use under U. S. Environmental Protection Agency Urban Bus Retrofit and Rebuild requirements (U.S. 1990 Clean Air Act Amendments). Prior tests showed this type of catalyst minimizes the formation of sulfuric acid and other sulfate aerosols, and is compatible with biodiesel fuel.

Four of the DOCs were used, two with each fuel. The other two DOCs were backups and were never used during tests. Each DOC was conditioned by the manufacturer for about 25 h using low S D2 fuel. The DOCs were mounted downstream of the exit to the engine exhaust manifold in an area previously occupied by the scoop's own DOC and muffler. The test DOCs were approximately 15.5 x 28 cm in size, about twice the size of the DOCs normally used on this scoop. [The large size of the DOCs would be expected to enhance performance.]

The engine and DOCs were conditioned prior to the beginning of each week of testing with the two fuels. Originally, each conditioning period was to be about 50 hrs but this was not economically feasible. The low S D2 fuel was evaluated during week 1 and the break-in period was about 8 hrs. The blended fuel was evaluated during the second week and the break-in period was slightly longer, about 10 hrs. [This includes run time on October 24<sup>th</sup> which is not included in the analysis.] Data shown in the results section show these break-in times to be adequate as no apparent trends were seen in the weekly air quality data.

**Aerosol Measurement:** Three methods were used to assess in-mine concentrations of DPM in mg/m<sup>3</sup>; the size selective sampling (SS) method, the respirable combustible dust (RCD) method and the elemental carbon (EC) method. The RCD samples were collected using 0.8 µm silver membrane filters mounted in 25 mm cassettes. Respirable dust samples were collected using 10 mm Dorr-Oliver cyclones and sent to NIOSH for EC/OC analysis. Specific details of these methods are available elsewhere (Cantrell and Rubow, 1990, Maskery, 1998, Birch and Cary, 1996). A comparison of these methods and their limitations can be found elsewhere (Cantrell and

Watts, 1996 and Cantrell, 1996). Correction factors were determined from analysis of sample blanks and used to correct SS, RCD, and EC/OC concentrations.

Arrays of SS, RCD, and EC samplers were co-located in baskets upwind (air intake), downwind (air exhaust) and on the diesel scoop. All samples were collected in triplicate over 10 days for a total of 270 samples (3 samples x 3 sample types x 3 sample locations x 10 days = 270 samples). Twenty additional EC samples were used to assess aerosol stratification at the down wind location. Three laboratories analyzed the EC samples; NIOSH, CANMET and IGF in Germany. NIOSH analyzed every sample while the other two labs analyzed a subset of samples. NIOSH and CANMET used NIOSH method 5040 while IGF used the coulometric method (ZH 1.120/44, 1995) developed by Dr. Dahmann. These investigators will prepare a separate report comparing the inter-laboratory results.

SS, RCD, and SS samplers were operated at a flow rate of 1.7 l/m. Pumps (MSA, Pittsburgh, PA) were calibrated in the test section's underground refuge shelter at the beginning, middle and end of each week. Two Gilibrators (Gillian Instruments, W. Caldwell, NJ) were used for the pump calibrations.

All SS samples were analyzed gravimetrically by the University of Minnesota. The RCD samples were analyzed by Inco using the method developed by Maggs, Grigg, and Maskery in the mid-1970s (Hews and Rutherford, 1973, Rutherford, et al. 1977, Maskery, 1998). All EC samples (137) were analyzed by NIOSH using NIOSH method 5040 (NIOSH, 1996). Particulate matter samples for chemical (polycyclic aromatic hydrocarbons) and biological (Ames assay) characterization were collected using four hi-volume samplers located at the upwind (2) and downwind (2) sampling locations. These samplers were equipped with size selective impactors to split the collected aerosol into super and sub-micron fractions. The hi-vols were calibrated in the laboratory using a gas clock, and were operated underground at 40 ft<sup>3</sup>/min. Approximately 2 upwind and 4 downwind samples were collected each day. Samples were refrigerated by Inco and were delivered on ice to MTU for analysis. Further details are provided in the MTU report.

Aerosol size distributions were obtained using two micro-orifice uniform deposit impactors (MOUDIs) located at the upwind and downwind locations. MOUDI data were obtained to determine if the DPM and respirable dust size distributions were altered by the use of the biodiesel fuel. Changes in the size distribution could effect the interpretation of the size selective sampling data. For each day (except 10/16), one MOUDI sample was collected at the upwind location and two were collected at the downwind location. The sample collection time at the downwind location was about 2 hrs/sample. The MOUDIs were calibrated in the laboratory and were operated underground at 30 l/m. MOUDI data were analyzed by NIOSH.

A real-time aerosol monitor (RAM) equipped with a 1 µm impactor was used at the downwind location to provide the investigators with qualitative, real-time DPM concentrations. RAM data were not recorded electronically, but occasional readings were logged into investigator notebooks by time, date and concentration.

The vapor/particle distribution of selected semi-volatile organic compounds was determined by operating a denuder at the downwind location. Details are provided in the ORTECH report.

**Gas Measurements:** To determine the effect of the fuel + DOC combinations on gaseous emissions, continuous measurements were made at the upwind and downwind locations for CO, CO<sub>2</sub>, NO, NO<sub>2</sub> and SO<sub>2</sub>. These measurements were made by CANMET. A detailed description of the instrumentation and methods is provided in Appendix 2.

## RESULTS

Data were collected for 11 sampling days; five days with each fuel type and one day with blended fuel and no DOCs. October 16<sup>th</sup> and 24<sup>th</sup> are excluded from all analysis. On October 16<sup>th</sup> the scoop had mechanical problems and sampling times were too short for the collection of valid samples. On October 24<sup>th</sup>, ramp heaters were left on upwind of the test site to prevent ice formation resulting in higher background concentrations for some pollutants. In addition, there was limited diesel activity upwind of the test site, which may have affected some data. These problems were addressed by mine management and did not arise on subsequent sampling days.

The remainder of this section presents results obtained from vehicle monitoring and emissions testing, gas analyzers, particulate matter samplers and size distribution measurements. Daily averages are shown; with (mg/m<sup>3</sup>/MW-h) and without (mg/m<sup>3</sup>) normalization on a brake specific basis. Data obtained from the scoop are presented first and discussed in detail because the power correction factor is used in subsequent tables. Observations drawn from the gaseous pollutant data are also summarized because they affected the selection of the ventilation test conditions. A detailed discussion of the particulate matter data is found in the Discussion Section.

**Test Vehicle Monitoring:** At the end of each sampling day, data were downloaded to a laptop PC and saved in a spreadsheet. Instantaneous power was calculated by extrapolating torque, based on speed, fuel flow and the engine manufacturer's brake-specific fuel consumption (BSFC) map (plotted on torque vs. speed coordinates). For the diesel fuel, power calculated from exhaust CO<sub>2</sub> data, speed, BSFC and an assumed volumetric efficiency of 0.85 agreed well with the power calculated from the manufacturer's BSFC and the data logger's fuel and speed data. A correction to the manufacturer's BSFC data was applied to calculate engine energy output when the blended fuel was used. It was assumed that the thermal efficiency of the engine remained the same between fuels for a given speed and load. Therefore, BSFC was increased proportionally across the entire engine map for the blended fuel to account for its lower mass based energy content.

Daily duty cycles were compared by plotting normalized histograms of power output, and by the 1-sec change in power. Figure 5 shows how much time was spent at various loads. Figure 6 shows how much time was spent at a steady operating condition versus a transient operating condition. By analyzing the duty cycles this way, it was discovered that the operator changed the way he operated the scoop after the fuel was switched from diesel to blended fuel. This was confirmed in a phone interview with the operator. The operator was instructed to muck from one dead-end drift to another, and on diesel fuel he operated the scoop by making two advances into the muck pile in order to fully load the bucket. After the fuel was switched to blended fuel, the

operator's personal NO<sub>2</sub> monitor frequently exceeded the 3 ppm level when he was making the second advance into the muck pile. To avoid this he altered his duty cycle by operating the scoop at a higher load on the first advance in order to load the bucket as much as possible using only one advance. This shifted the duty cycle so that a greater fraction of the day was spent at a higher load. Figure 5 illustrates that the average duty cycles on diesel and on blended fuel were different. Figure 6 illustrates that the amount of time spent at steady state and transient conditions remained the same, however.

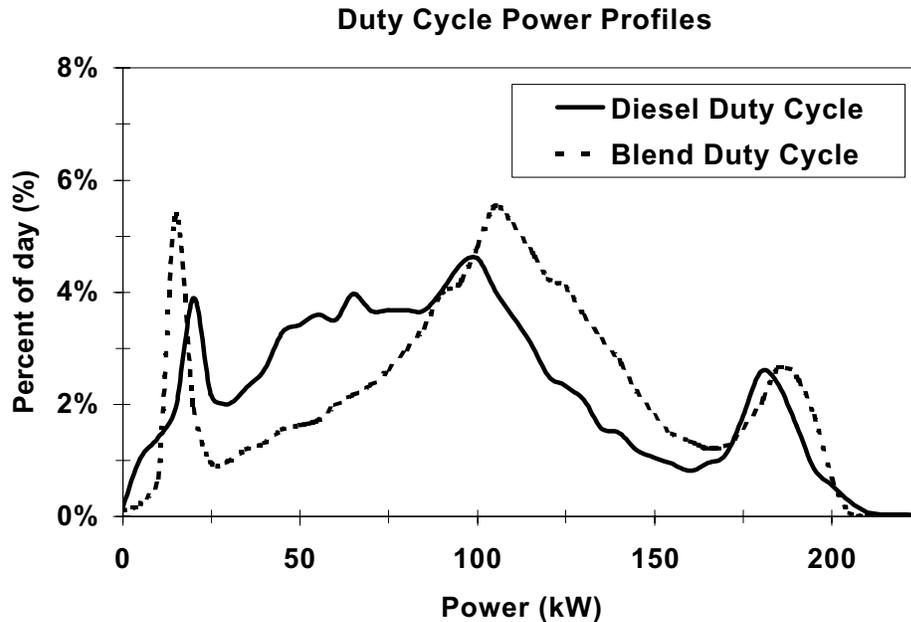


Figure 5 - Duty cycle power profiles

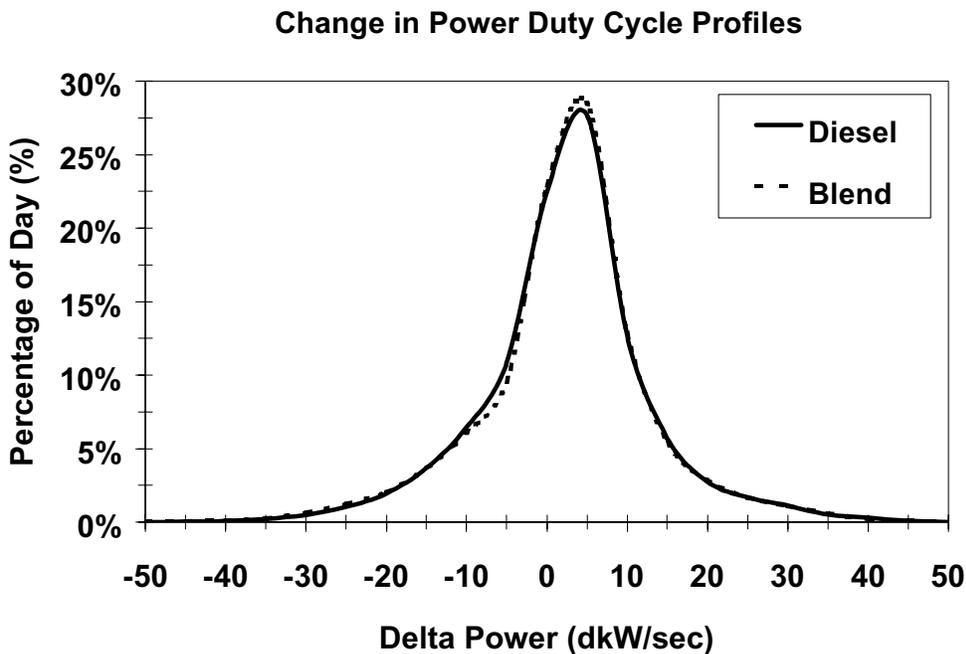


Figure 6 - Change in power duty cycle profiles

Because of the shift in duty cycle, an energy specific (i.e. brake specific) correction factor was established to normalize the emissions data collected over each day. Both fuel and power data were integrated over each sampling period so that comparisons between total fuel consumed and total work performed could be made for each day. Tables 1 and 2 summarize these data.

In Tables 1 and 2 "Engine Output" in MW-h indicates the amount of work performed over each sampling period. This number can be used to compare average daily emissions concentrations on an energy specific basis of engine output. For example DPM concentrations are measured in  $\text{mg}/\text{m}^3$ , but differences in this daily value may be the result of the engine operating for a greater fraction of the sampling period or at a higher power output. Dividing daily emission concentrations by the daily engine output accounts for these differences, and allows comparisons to be made between fuels. The energy specific emissions units for DPM will be  $\text{mg}/\text{m}^3/\text{MW-h}$  and are shown in later tables. The estimated error for these correction factors is 6 %.

<b>Table 1 - Diesel fuel consumption and power totals</b>					
Date	10/16*	10/17	10/20	10/21	10/22
Sampling Time (h)	N/A	6.1	6.2	6.0	6.0
Engine Run Time (h)	N/A	5.4	5.6	5.3	5.5
Down Time (h)	N/A	0.7	0.6	0.7	0.5
Fuel Vol. (gal)	N/A	47.0**	49.0**	46.1	47.8
Fuel Mass (kg)	N/A	144.8	151.0	142.1	147.2
Fuel Energy (MW-h)	N/A	1.87	1.94	1.83	1.90
Engine Output (MW-h)	N/A	0.50***	0.52***	0.50	0.51
*1 <sup>st</sup> day of sampling was cancelled due to mechanical problems.					
**Estimated from fuel supply tank fill lines.					
***A similar overall BSFC was assumed based on days' 4 and 5 data.					

Date	10/24	10/25	10/27	10/28	10/29	10/30*
Sampling Time (h)	6.1	6.0	6.2	5.2	6.0	6.7
Engine Run Time (h)	5.4	5.5	5.6	4.4	5.4	5.7
Down Time (h)	0.7	0.5	0.6	0.8	0.6	1.0
Fuel Vol.. (gal)	55.7	56.7	54.4	44.7	54.3	59.2
Fuel Mass (kg)	179.9	183.0	175.4	144.4	175.4	191.1
Fuel Energy (MW-h)	2.16	2.20	2.10	1.73	2.10	2.29
Engine Output (MW-h)	0.58	0.60	0.57	0.48	0.58	0.62

\*The 6<sup>th</sup> day of blended fuel sampling was performed without DOCs.

**Daily Emission Test Results:** Although emission concentrations did change from day-to-day, none of the results indicated that the engine or catalysts were operating improperly. The effects of DOCs, the blended fuel, and the differences between left and right exhaust banks were analyzed by comparing data collected at the torque converter stall condition. *These data and comparisons are not representative of full-shift, time-weighted average data collected to assess exposure or changes in emissions.*

**Effect of DOCs:** The DOCs had similar effects on emissions regardless of exhaust bank or fuel type. The DOCs effectively oxidized 99 % of the CO, but the DOCs also oxidized NO to NO<sub>2</sub>, which caused a 230 % increase in NO<sub>2</sub> tailpipe concentration. Table 3 summarizes the DOCs' effects on emissions.

Emission	Diesel Fuel			Blended Fuel		
	Upstream	Downstream	% change	Upstream	Downstream	% change
CO, ppm	155	10	↓98±10%	174	2	↓99±11%
CO <sub>2</sub> , %	8.24	8.58	No change	N/A	N/A	N/A*
NO, ppm	596	546	No change	634	526	↓17%±4%
NO <sub>2</sub> , ppm	37	120	↑185±78%	51	171	↑233±59%
NO <sub>x</sub> , ppm	633	666	No change	685	697	No change

\*Due to a sensor failure, blended fuel CO<sub>2</sub> concentrations were not available.

The insignificant change in total NO<sub>x</sub> across the DOC indicates that NO<sub>x</sub> was conserved between measurements.

**Effect of blended fuel:** There was a  $43 \pm 28$  % increase in NO<sub>2</sub> downstream of the DOCs after the fuel was switched from diesel to blended fuel. There were also statistically insignificant trends toward higher exhaust temperatures and concentrations of CO upstream of the catalyst after the fuel was switched to blended fuel, but more data must be collected before any conclusions can be drawn.

**Differences between left and right exhaust banks:** There were no significant differences in exhaust temperature between exhaust banks regardless of fuel. However, differences in emissions were observed. Table 4 summarizes the statistically significant differences in emissions.

<b>Emission</b>	<b>Fuel</b>	<b>DOC</b>	<b>Left Bank</b>	<b>Right Bank</b>	<b>% Difference, Left-to-Right</b>
CO, ppm	Both	Upstream	187	143	↓31% ±12%
NO <sub>2</sub> , ppm	Diesel	Downstream	83	157	↑47% ±18%
NO <sub>2</sub> , ppm	Blended	Downstream	143	200	↑29% ±9%

Even though there were no significant differences between left and right exhaust bank temperatures, the lower CO and higher NO<sub>2</sub> concentrations suggest that some of the right bank cylinders may have been operating at higher temperatures, or at least at a more advanced fuel injection timing. Perhaps some of the right bank fuel injectors were popping at a slightly lower fuel injection pressure.

**Gaseous Pollutants:** Table 5 summarizes the gas data collected by CANMET at the upwind and downwind sampling locations. Table 6 shows data collected at the downwind location normalized on a brake specific basis using the daily correction factors shown in tables 1 and 2. [Data in table 5 are representative of time-weighted average exposure, but data in table 6 are not because of the correction factor used to normalize the daily means.]

Since Creighton Mine #3 was in a non-producing status there was virtually no mining activity or traffic of any type on the ramp above the test section. Gas data collected at the upwind location, and particulate matter data shown later, demonstrate that ventilation air entering the test section was consistently clean throughout the test period. This simplifies later analysis because it is not necessary to correct the vehicle and downwind concentrations for the upwind contribution.

Inco requested that the DOCs be taken off and an additional day of testing be conducted with the blended fuel without the DOCs. This was done on October 30<sup>th</sup>. A single day of testing is insufficient for statistical inferences to be drawn, but it illustrates the general impact of DOCs on exhaust emissions. Ambient measurements adjusted for power output support the findings of the EAMP exhaust emission testing discussed above, and are representative of full-shift, time-weighted average emission levels.

DOCs reduce CO and hydrocarbons but may increase NO<sub>2</sub> and SO<sub>2</sub>. When used with an oxygenated fuel such as the blended biodiesel fuel, the NO<sub>2</sub> increase is greater than that observed with a D2 fuel. Table 6 shows that the mean NO<sub>2</sub> concentration increased by 0.3 ppm from 3.9 to 4.2 ppm from the first to the second week. Conversely, the NO concentrations decreased. When the DOCs were removed, table 6 shows a decrease in NO<sub>2</sub> levels to 1.4 ppm and an increase in NO levels to 10.7 ppm. The SO<sub>2</sub> concentrations were quite low for all conditions. This is attributed to the fuels. The Inco D2 fuel had < 0.02 wt % S and the blended fuel had < 0.006 wt % S.

Table 5 - Gaseous pollutant concentrations

Date	Condition	CO <sub>2</sub>		CO <sup>a</sup>		NO		NO <sub>2</sub>		SO <sub>2</sub>	
		Mean ppm	SD ppm	Mean ppm	SD ppm	Mean ppm	SD ppm	Mean ppm	SD ppm	Mean ppm	SD ppm
Upwind Sampling Location											
10/17/97	D2+DOC	435	9	0.0	0.0	0.2	0.2	0.7	0.0	0.5	0.0
10/20/97	D2+DOC	402	21	0.0	0.0	0.3	0.3	0.3	0.1	0.3	0.0
10/21/97	D2+DOC	397	17	0.0	0.0	0.1	0.2	0.1	0.0	0.1	0.0
10/22/97	D2+DOC	394	14	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.0
10/25/97	BLEND + DOC	485	5	0.0	0.1	0.1	0.1	0.1	0.0	0.1	0.1
10/27/97	BLEND + DOC	398	10	0.2	0.1	0.3	0.2	0.2	0.0	0.2	0.0
10/28/97	BLEND + DOC	438	12	0.0	0.0	0.2	0.2	0.1	0.0	0.1	0.0
10/29/97	BLEND + DOC	425	12	0.0	0.0	0.3	0.2	0.2	0.0	0.2	0.0
10/30/97	BLEND	426	15	0.0	0.0	0.2	0.2	0.2	0.0	0.2	0.0
Downwind Sampling Location											
10/17/97	D2+DOC	1148	247	0.1	0.1	5.6	1.8	1.9	0.6	0.5	0.1
10/20/97	D2+DOC	1087	230	0.1	0.1	5.2	1.6	2.2	1.0	0.6	0.1
10/21/97	D2+DOC	1073	255	0.2	0.2	5.2	1.9	1.9	0.7	0.5	0.1
10/22/97	D2+DOC	1093	267	0.2	0.1	5.3	1.9	2.0	0.7	0.5	0.1
10/25/97	BLEND + DOC	1345	286	0.3	0.1	5.4	1.8	2.6	0.9	0.5	0.1
10/27/97	BLEND + DOC	1109	286	0.3	0.2	4.9	1.8	2.3	0.9	0.6	0.1
10/28/97	BLEND + DOC	1122	291	0.4	0.2	4.4	1.7	2.1	0.8	0.4	0.1
10/29/97	BLEND + DOC	1251	341	0.0	0.1	5.0	2.0	2.4	1.0	0.5	0.1
10/30/97	BLEND	1164	356	1.3	0.6	6.6	3.0	0.8	0.2	0.7	0.1

<sup>a</sup>Negative values set to 0.0

SD standard deviation

Table 6 - Downwind gaseous pollutant concentrations normalized on a brake specific basis

Date	Condition	CO <sub>2</sub>		CO <sup>a</sup>		NO		NO <sub>2</sub>		SO <sub>2</sub>	
		Mean ppm/MW-h	SD ppm/MW-h								
Downwind Sampling Location											
10/17/97	D2+DOC	2296	513	0.1	0.1	11.1	3.6	3.8	1.2	1.0	0.2
10/20/97	D2+DOC	2090	461	0.1	0.2	10.0	3.1	4.1	1.9	1.1	0.2
10/21/97	D2+DOC	2146	525	0.3	0.4	10.4	3.8	3.8	1.4	1.0	0.2
10/22/97	D2+DOC	2144	540	0.5	0.2	10.3	3.8	4.0	1.5	1.0	0.2
10/25/97	BLEND + DOC	2242	495	0.5	0.2	8.9	3.1	4.3	1.5	0.8	0.2
10/27/97	BLEND + DOC	1945	516	0.5	0.4	8.5	3.2	4.0	1.6	1.1	0.2
10/28/97	BLEND + DOC	2337	623	0.8	0.4	9.3	3.6	4.4	1.8	0.9	0.1
10/29/97	BLEND + DOC	2156	602	0.0	0.2	8.6	3.5	4.1	1.7	0.8	0.1
10/30/97	BLEND	1878	586	2.2	1.0	10.7	4.9	1.4	0.4	1.2	0.2

<sup>a</sup>Negative values set to 0.0

SD standard deviation

Table 6 shows the normalized gaseous data for the two fuels with the DOCs and for the blended fuel without the DOCs. [As an example, to obtain the normalized NO<sub>2</sub> concentration for October 25<sup>th</sup> (4.3 ppm/MW-h), the corresponding NO<sub>2</sub> concentration in table 5 (2.6 ppm) was divided by the October 25<sup>th</sup> correction factor in table 2 (0.60).]

The original test plan called for a reduction in the required amount of ventilation air so that DPM concentrations could be raised to about 0.8 mg/m<sup>3</sup>. This increase in DPM would assist in the statistical interpretation of the DPM data. In anticipation of the need to reduce ventilation air flow, Inco engineers set the initial air flow to approximately 30,000 ft<sup>3</sup>/m in the test section. This air flow is about 75 % of the regulated level. At this flow rate the average NO<sub>2</sub> concentrations at the downwind location (table 5) approached 3 ppm, which is the permissible exposure limit in Ontario, and increased slightly during the second week when the blended fuel was used. The increase in the ambient NO<sub>2</sub> concentrations was statistically insignificant. A portable gas analyzer worn by the scoop operator gave a warning when the 3 ppm standard was exceeded. These warnings were frequent enough to support a decision not to further reduce ventilation air flow even though the operator's time-weighted average exposure was < 3 ppm.

**Daily Respirable Dust and DPM:** As described previously, respirable dust and DPM data were collected at three locations; upwind, scoop and downwind. Results from individual samples were excluded from further analysis when a pump prematurely stopped or failed to maintain calibrated flow rates, when a sample was mishandled or when a concentration was more than twice as high as the other two. Less than 10 pct of the samples were excluded.

**Size Selective Samples:** The UMN analyzed the SS samples and tables 7 and 8 summarize the SS results. The power correction factors used in table 8, are only applied to the < 0.8 μm fraction of the SS sample, because this fraction consists primarily of DPM. The error of the power weighted concentrations in table 8 [and in all tables where the power weighted concentration is shown] is the propagated error of the daily means and power correction factor (Taylor, 1982).

Table 7 - Size selective sampler daily means and standard deviations

Date	Condition	>0.8 um		<0.8 um		Total Respirable Dust	
		Mean mg/m <sup>3</sup>	SD mg/m <sup>3</sup>	Mean mg/m <sup>3</sup>	SD mg/m <sup>3</sup>	Mean mg/m <sup>3</sup>	SD mg/m <sup>3</sup>
Upwind Sampling Location							
10/17	D2+DOC	0.01	0.01	0.00	0.00	0.01	0.01
10/20	D2+DOC	0.01	0.01	0.01	0.01	0.01	0.01
10/21	D2+DOC	0.01	0.01	0.02	0.02	0.03	0.01
10/22	D2+DOC	0.02	0.03	0.01	0.02	0.03	0.02
10/25	BLEND+DOC	0.00	0.01	0.01	0.02	0.01	0.01
10/27	BLEND+DOC	0.01	0.01	0.00	0.00	0.01	0.01
10/28	BLEND+DOC	0.02	0.02	0.02	0.01	0.04	0.03
10/29	BLEND+DOC	0.01	0.01	0.01	0.02	0.03	0.01
10/30	BLEND-NO DOC	0.03	0.00	0.01	0.01	0.04	0.01
Vehicle Sampling Location							
10/17	D2+DOC	0.25	0.00	0.35	0.04	0.60	0.04
10/20	D2+DOC	0.28	0.01	0.35	0.04	0.63	0.02
10/21	D2+DOC	0.24	0.02	0.39	0.01	0.63	0.02
10/22	D2+DOC	0.28	0.00	0.43	0.00	0.70	0.01
10/25	BLEND+DOC	0.29	0.02	0.36	0.03	0.66	0.04
10/27	BLEND+DOC	0.32	0.00	0.34	0.02	0.66	0.02
10/28	BLEND+DOC	0.22	0.00	0.41	0.03	0.63	0.03
10/29	BLEND+DOC	0.30	0.02	0.50	0.01	0.79	0.01
10/30	BLEND-NO DOC	0.26	0.04	0.50	0.05	0.76	0.09
Downwind Sampling Location							
10/17	D2+DOC	0.16	0.03	0.35	0.01	0.51	0.03
10/20	D2+DOC	0.15	0.02	0.38	0.00	0.54	0.02
10/21	D2+DOC	0.17	0.03	0.41	0.01	0.58	0.02
10/22	D2+DOC	0.14	0.01	0.45	0.03	0.60	0.04
10/25	BLEND+DOC	0.18	0.01	0.37	0.02	0.55	0.01
10/27	BLEND+DOC	0.17	0.01	0.36	0.05	0.53	0.05
10/28	BLEND+DOC	0.14	0.01	0.39	0.02	0.53	0.02
10/29	BLEND+DOC	0.18	0.02	0.46	0.05	0.65	0.07
10/30	BLEND-NO DOC	0.20	0.01	0.58	0.04	0.78	0.05

Table 8 - Size selective sampler daily means and standard deviations normalized on a brake specific basis

Date	Condition	<0.8 um	
		Mean mg/m <sup>3</sup> /MW-h	SD mg/m <sup>3</sup> /MW-h
Vehicle Sampling Location			
10/17	D2+DOC	0.70	0.09
10/20	D2+DOC	0.67	0.08
10/21	D2+DOC	0.78	0.05
10/22	D2+DOC	0.84	0.05
10/25	BLEND+DOC	0.61	0.06
10/27	BLEND+DOC	0.60	0.05
10/28	BLEND+DOC	0.85	0.08
10/29	BLEND+DOC	0.85	0.05
10/30	BLEND-NO DOC	0.80	0.10
Downwind Sampling Location			
10/17	D2+DOC	0.71	0.04
10/20	D2+DOC	0.74	0.04
10/21	D2+DOC	0.81	0.05
10/22	D2+DOC	0.89	0.08
10/25	BLEND+DOC	0.62	0.05
10/27	BLEND+DOC	0.64	0.10
10/28	BLEND+DOC	0.81	0.07
10/29	BLEND+DOC	0.80	0.10
10/30	BLEND-NO DOC	0.93	0.09

**Respirable Combustible Dust Data:** Inco provided the RCD filters preloaded into cassettes to the field team. After the samples were collected the cassettes were returned to the Inco laboratory for analysis. Summary results are presented in tables 9 and 10. The correction factors used in table 10 are only applied to the RCD portion of the measurement because this is the portion assumed to consist of DPM.

Table 9 - RCD and total respirable dust daily means and standard deviations

Date	Condition	RCD		Total Respirable Dust	
		Mean mg/m <sup>3</sup>	SD mg/m <sup>3</sup>	Mean mg/m <sup>3</sup>	SD mg/m <sup>3</sup>
Upwind Sampling Location					
10/17/97	D2+DOC	0.01	0.01	0.02	0.00
10/20/97	D2+DOC	0.02	0.02	0.05	0.00
10/21/97	D2+DOC	0.02	0.01	0.02	0.01
10/22/97	D2+DOC	0.00	NA	0.00	NA
10/25/97	BLEND+DOC	0.01	0.01	0.02	0.00
10/27/97	BLEND+DOC	0.00	0.00	0.02	0.00
10/28/97	BLEND+DOC	0.00	0.00	0.02	0.01
10/29/97	BLEND+DOC	0.01	0.01	0.02	0.00
10/30/97	BLEND-NO DOC	0.01	0.00	0.03	0.01
Vehicle Sampling Location					
10/17/97	D2+DOC	0.33	0.08	0.61	0.09
10/20/97	D2+DOC	0.32	0.01	0.62	0.03
10/21/97	D2+DOC	0.40	0.12	0.68	0.13
10/22/97	D2+DOC	0.49	0.13	0.80	0.15
10/25/97	BLEND+DOC	0.31	0.06	0.73	0.04
10/27/97	BLEND+DOC	0.30	0.03	0.65	0.04
10/28/97	BLEND+DOC	0.32	0.01	0.60	0.04
10/29/97	BLEND+DOC	0.46	0.14	0.78	0.13
10/30/97	BLEND-NO DOC	0.49	0.04	0.73	0.04
Downwind Sampling Location					
10/17/97	D2+DOC	0.34	0.01	0.51	0.00
10/20/97	D2+DOC	0.37	0.02	0.53	0.01
10/21/97	D2+DOC	0.37	0.01	0.53	0.02
10/22/97	D2+DOC	0.37	0.01	0.56	0.02
10/25/97	BLEND+DOC	0.34	0.02	0.56	0.02
10/27/97	BLEND+DOC	0.33	0.01	0.54	0.01
10/28/97	BLEND+DOC	0.34	0.02	0.45	0.05
10/29/97	BLEND+DOC	0.37	0.03	0.54	0.02
10/30/97	BLEND-NO DOC	0.54	0.02	0.69	0.03

Note: Only 1 valid upwind RCD sample was obtained on 10/22 because 2 samples were mistakenly reused.

Table 10 - RCD daily means and standard deviations normalized on a brake specific basis

Date	Condition	RCD	
		Mean mg/m <sup>3</sup> /MW-h	SD mg/m <sup>3</sup> /MW-h
Vehicle Sampling Location			
10/17	D2+DOC	0.67	0.17
10/20	D2+DOC	0.62	0.04
10/21	D2+DOC	0.79	0.24
10/22	D2+DOC	0.96	0.27
10/25	BLEND+DOC	0.51	0.11
10/27	BLEND+DOC	0.52	0.06
10/28	BLEND+DOC	0.67	0.05
10/29	BLEND+DOC	0.79	0.25
10/30	BLEND-NO DOC	0.79	0.08
Downwind Sampling Location			
10/17	D2+DOC	0.69	0.05
10/20	D2+DOC	0.71	0.05
10/21	D2+DOC	0.74	0.05
10/22	D2+DOC	0.73	0.05
10/25	BLEND+DOC	0.57	0.05
10/27	BLEND+DOC	0.59	0.04
10/28	BLEND+DOC	0.71	0.06
10/29	BLEND+DOC	0.64	0.07
10/30	BLEND-NO DOC	0.87	0.06

***Elemental and Organic Carbon Data:*** All samples were analyzed for EC, organic carbon (OC) and total carbon (TC) by NIOSH and selected samples were also analyzed by CANMET and IGF in Germany. Summary results from the NIOSH analysis are shown in tables 11 and 12. A subsequent paper, to be prepared by NIOSH, CANMET and IGF will compare results from the three laboratories.

Sixteen samples were collected at the downwind location to determine the degree of aerosol stratification. It was determined that no stratification existed and results from these samples are also included in the calculation of the daily means.

Table 11 - Elemental, organic and total carbon daily means and standard deviations

Date	Condition	Organic carbon		Elemental carbon		Total Carbon		Elemental Carbon	
		Mean mg/m <sup>3</sup>	SD mg/m <sup>3</sup>	Mean mg/m <sup>3</sup>	SD mg/m <sup>3</sup>	Mean mg/m <sup>3</sup>	SD mg/m <sup>3</sup>	Mean %	SD %
Upwind Sampling Location									
10/17	D2+DOC	0.02	0.01	0.01	0.0	0.03	0.01	24.2	8.9
10/20	D2+DOC	0.01	0.00	0.03	0.0	0.04	0.00	67.2	2.6
10/21	D2+DOC	0.01	0.00	0.02	0.0	0.03	0.00	56.5	5.9
10/22	D2+DOC	0.02	0.00	0.01	0.0	0.03	0.01	44.6	13.4
10/25	BLEND+DOC	0.01	0.00	0.00	0.0	0.01	0.00	10.9	1.0
10/27	BLEND+DOC	0.01	0.00	0.01	0.0	0.02	0.01	28.5	12.3
10/28	BLEND+DOC	0.02	0.01	0.01	0.0	0.03	0.01	39.2	6.1
10/29	BLEND+DOC	0.02	0.00	0.01	0.0	0.02	0.00	34.8	10.5
10/30	BLEND-NO DOC	0.02	0.00	0.01	0.0	0.02	0.00	31.2	2.5
Vehicle Sampling Location									
10/17	D2+DOC	0.07	0.01	0.15	0.0	0.22	0.03	66.4	2.9
10/20	D2+DOC	0.08	0.01	0.15	0.0	0.23	0.02	66.1	8.9
10/21	D2+DOC	0.08	0.00	0.14	0.0	0.22	0.01	63.9	1.7
10/22	D2+DOC	0.08	0.02	0.12	0.0	0.20	0.06	61.5	2.9
10/25	BLEND+DOC	0.10	0.02	0.14	0.0	0.23	0.02	58.7	3.9
10/27	BLEND+DOC	0.10	0.02	0.15	0.0	0.26	0.03	59.9	1.2
10/28	BLEND+DOC	0.12	0.03	0.15	0.0	0.27	0.04	55.7	3.8
10/29	BLEND+DOC	0.12	0.02	0.15	0.0	0.28	0.03	54.9	0.5
10/30	BLEND-NO DOC	0.22	0.02	0.14	0.0	0.37	0.04	38.8	1.0
Downwind Sampling Location									
10/17	D2+DOC	0.08	0.01	0.19	0.0	0.27	0.01	71.6	2.4
10/20	D2+DOC	0.09	0.02	0.19	0.0	0.27	0.02	68.4	5.7
10/21	D2+DOC	0.08	0.01	0.17	0.0	0.24	0.01	68.0	1.9
10/22	D2+DOC	0.09	0.01	0.16	0.0	0.24	0.03	64.6	2.4
10/25	BLEND+DOC	0.09	0.01	0.15	0.0	0.25	0.01	62.0	1.6
10/27	BLEND+DOC	0.08	0.00	0.14	0.0	0.22	0.02	61.8	1.9
10/28	BLEND+DOC	0.12	0.01	0.13	0.0	0.25	0.01	52.7	2.4
10/29	BLEND+DOC	0.12	0.01	0.15	0.0	0.28	0.01	55.0	2.4
10/30	BLEND-NO DOC	0.22	0.05	0.12	0.0	0.34	0.08	36.0	2.7

Table 12 shows the EC/OC daily means and standard deviations normalized on a brake specific basis. The correction factors were applied to EC, OC and TC concentrations because DPM consists of both EC and OC, and the primary source of EC and OC in the test section was diesel exhaust from the scoop. However, there were short periods (< 30 min) during the course of the study when aerosol was contributed from other sources other than the tailpipe and affected the results. This sample contamination is discussed below at length because it affects the interpretation of the particulate data described in the Discussion section of the report.

The daily event log maintained by Ortech (Appendix 3) documents that on October 28<sup>th</sup> and 29<sup>th</sup> clouds of blue smoke were apparent. On the 28<sup>th</sup> the scoop had a fueling problem and the fuel filter was replaced and a loose wire on the fuel shutoff was repaired. Immediately after the repairs were completed, the scoop operator and others noted a period of intense smoke occurring before but not after lunch. An effort to identify the problem failed. After fueling and startup on the 29<sup>th</sup>

the same problem occurred. The real-time aerosol monitor (RAM) operated at the downwind location recorded submicron aerosol levels  $> 0.6 \text{ mg/m}^3$  during these periods of excess smoke and numerous people commented on the “smoky conditions”. After a second investigation of the scoop, the investigators concluded that the fuel tank vent/overflow hose was directing fuel onto the surface of the hot exhaust line and DOC on operator’s side of the vehicle. Fuel apparently spilled out of the short hose when the tank was full and the scoop operated at a steep incline. The hose was not in a fixed position and was probably unintentionally moved by personnel when repairs were made to the scoop or by project personnel placing or removing instruments on the scoop. Spillage occurred for a short period of time because the level of fuel in the fuel tank was reduced as the day progressed and because the scoop was not always operated at a steep angle. The problem was identified and fixed on October 29<sup>th</sup>.

The fuel spill combined with high engine operating temperatures and resulting high surface temperatures on the exhaust pipe and DOC resulted in excess smoke. It is likely that this smoke was organic in nature because the temperature on the surface of the DOC (estimated to range between 250 - 350 °C) was insufficient to form EC. This smoke would be detected by all three aerosol methods but is not part of the EC fraction as shown in table 12. This introduces an error into the measurements, which will be discussed further in the Discussion section.

Table 12 - Elemental, organic and total carbon daily means and standard deviations normalized on a brake specific basis

Date	Condition	Organic carbon		Elemental carbon		Total carbon	
		Mean mg/m <sup>3</sup> /MW-h	SD mg/m <sup>3</sup> /MW-h	Mean mg/m <sup>3</sup> /MW-h	SD mg/m <sup>3</sup> /MW-h	Mean mg/m <sup>3</sup> /MW-h	SD mg/m <sup>3</sup> /MW-h
Vehicle Sampling Location							
10/17	D2+DOC	0.15	0.03	0.29	0.04	0.44	0.06
10/20	D2+DOC	0.15	0.03	0.29	0.06	0.43	0.05
10/21	D2+DOC	0.16	0.01	0.28	0.02	0.43	0.03
10/22	D2+DOC	0.15	0.03	0.24	0.08	0.39	0.11
10/25	BLEND+DOC	0.16	0.03	0.23	0.02	0.39	0.04
10/27	BLEND+DOC	0.18	0.03	0.27	0.04	0.45	0.07
10/28	BLEND+DOC	0.25	0.06	0.32	0.04	0.57	0.09
10/29	BLEND+DOC	0.21	0.03	0.26	0.03	0.48	0.06
10/30	BLEND-NO DOC	0.36	0.05	0.23	0.03	0.59	0.08
Downwind Sampling Location							
10/17	D2+DOC	0.15	0.02	0.39	0.03	0.54	0.04
10/20	D2+DOC	0.17	0.04	0.36	0.02	0.53	0.05
10/21	D2+DOC	0.16	0.01	0.33	0.02	0.49	0.03
10/22	D2+DOC	0.17	0.03	0.31	0.04	0.47	0.07
10/25	BLEND+DOC	0.16	0.01	0.26	0.02	0.41	0.03
10/27	BLEND+DOC	0.15	0.01	0.24	0.03	0.39	0.04
10/28	BLEND+DOC	0.25	0.02	0.28	0.02	0.53	0.04
10/29	BLEND+DOC	0.21	0.02	0.26	0.03	0.48	0.04
10/30	BLEND-NO DOC	0.35	0.09	0.20	0.05	0.54	0.14

**Micro-Orifice Uniform Deposit Impactor Size Distribution:** MOUDI data were analyzed by NIOSH and table 13 summarizes the results. Figures 7-10 show the composite size

distributions for upwind, and downwind for both weeks and for the last day of testing. These distributions were obtained by averaging the respective data. Note that the y-axis scales differ by more than an order of magnitude between plots.

The upwind particulate matter concentrations were quite low and some stages of the MOUDI collected insufficient particulate matter for gravimetric analysis even though the upwind MOUDI was operated for the entire test period (about 5 h/day). Two MOUDI samples were collected each day at the downwind location, with each sampling period being about 2 h in duration. Due to the low concentrations, the upwind MOUDI data were not subtracted from the downwind data.

The fine and coarse mode data shown in table 13 refer to the fractions illustrated in figure 3. The fine mode includes aerosol  $< 1.0 \mu\text{m}$ , which includes the nuclei and accumulation modes. Nearly all the mass in the fine mode is composed of accumulation mode particles, but by particle number nearly everything is in the nuclei mode (figure 2). The coarse mode includes aerosol  $> 1.0 \mu\text{m}$ , which are primarily generated by mechanical actions such as grinding. These definitions differ somewhat from those in figure 2, which are taken from the atmospheric literature where the fine mode includes particles  $< 2.5 \mu\text{m}$ .

It is clear from the fine particle mass median diameter (MMD) at the downwind location and from the three composite size distributions that there was no change in the diesel aerosol size distribution caused by changing fuel (mean MMD D2 fuel  $0.128 \mu\text{m}$  and MMD blend fuel  $0.124 \mu\text{m}$ ) or removal of the DOC (MMD  $0.11 \mu\text{m}$ ). However, the downwind coarse mode MMD decreased in size from  $3.5 \mu\text{m}$  to around  $2.0 \mu\text{m}$ . The coarse mode is composed primarily of dust aerosol generated by the scoop during mucking. Since the scoop mucked the same material throughout the test period, smaller and smaller particles were generated by the grinding action of the tires, bucket and rock, thus the declining trend in the MMD of the coarse aerosol fraction.

Figure 7 - Upwind composite size distribution

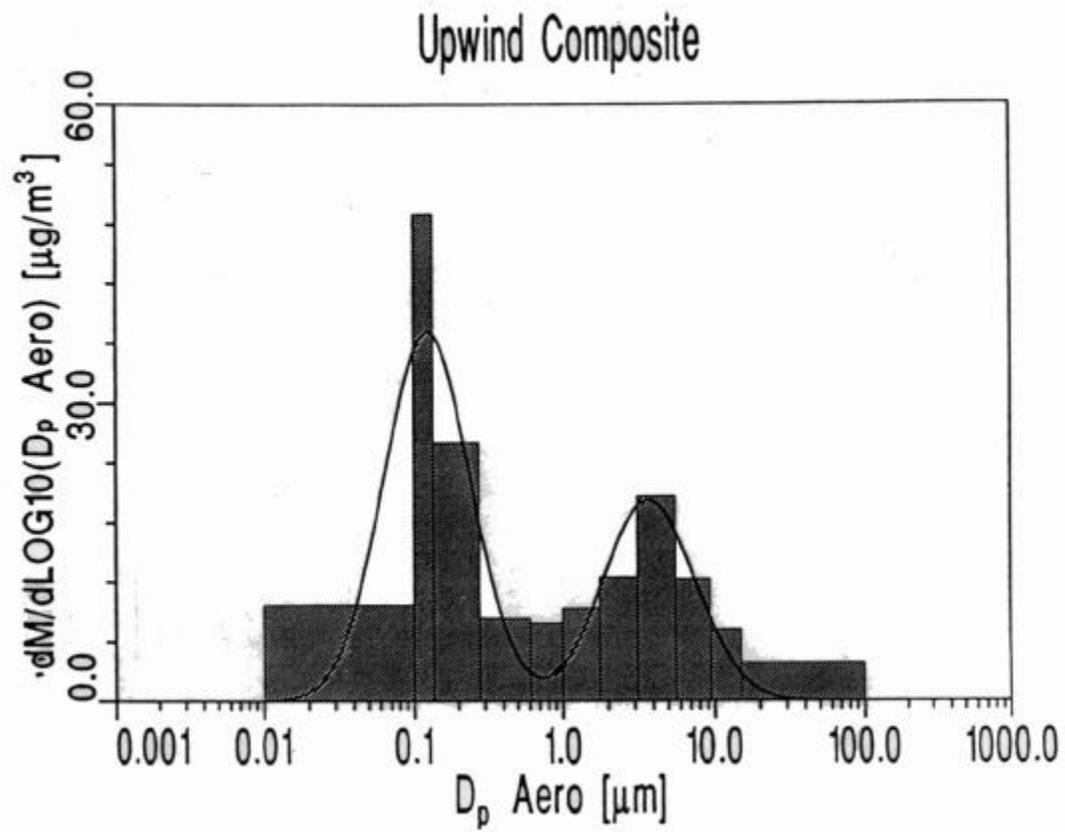


Figure 8 - Downwind composite size distribution for D2 fuel with catalyst

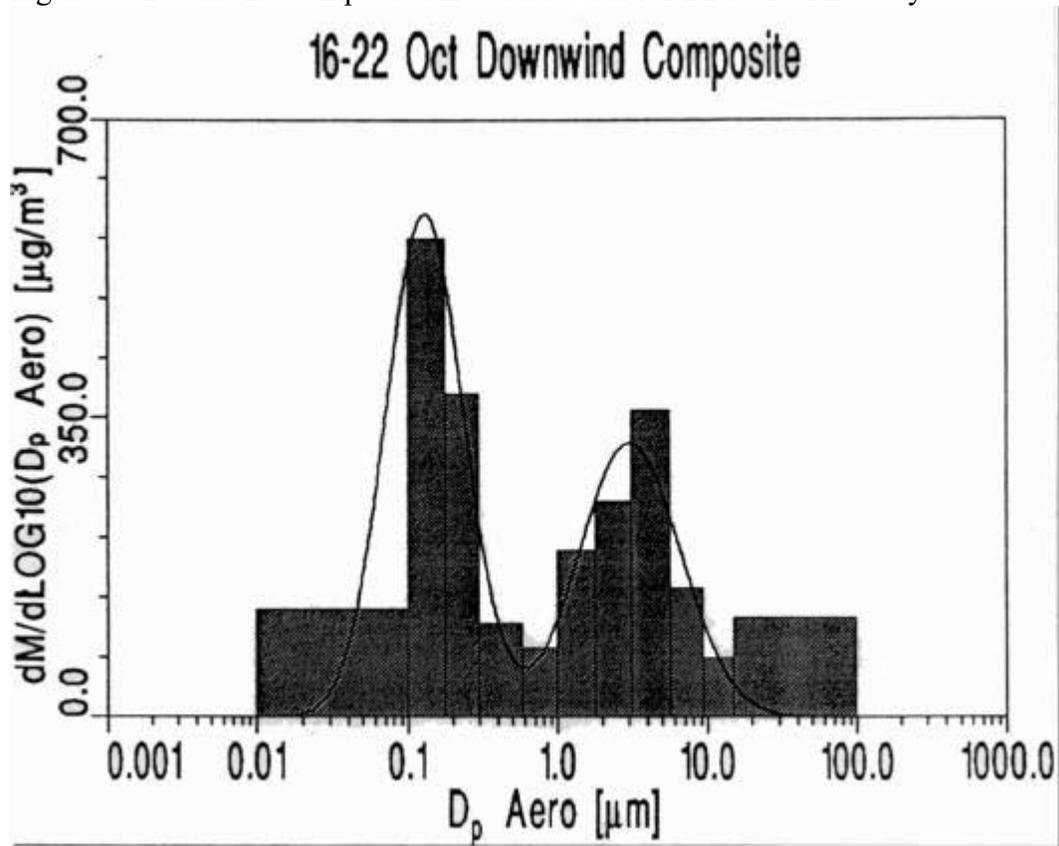


Figure 9 -Downwind composite size distribution for blended fuel with catalyst

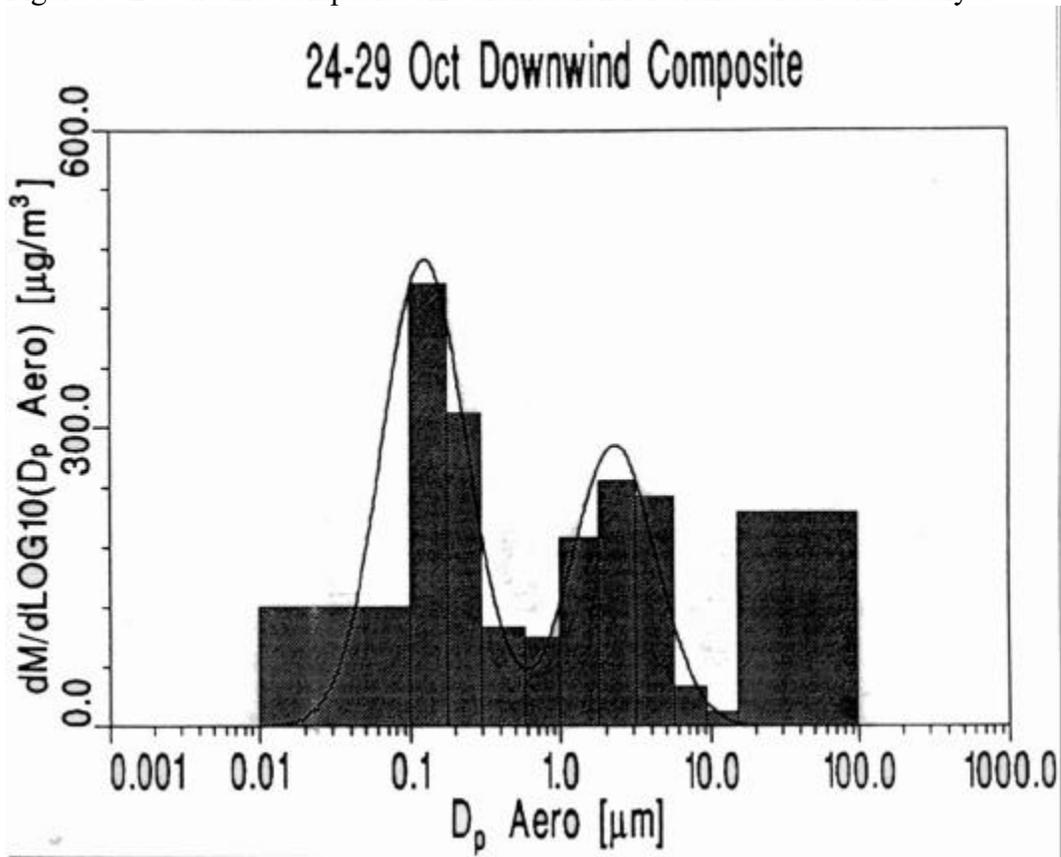


Figure 10 - Downwind composite size distribution for blended fuel without catalyst

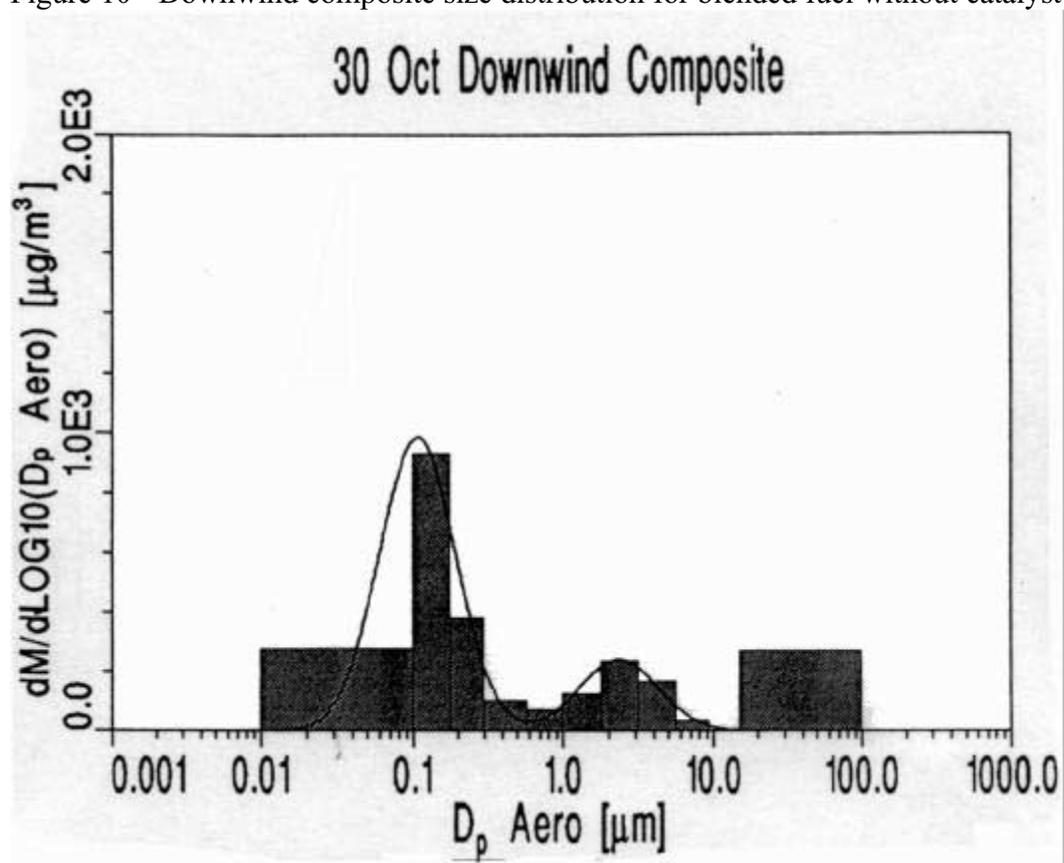


Table 13 - Summary results from the MOUDI samples

Date	Condition	Fine			Coarse		
		Mass conc. ug/m <sup>3</sup>	MMD um	Sigma G	Mass conc. ug/m <sup>3</sup>	MMD um	Sigma G
Upwind Sampling Location							
10/16	D2+DOC	57	0.16	1.67	29	4.0	2.00
10/17	D2+DOC	21	0.16	2.30	12	3.7	2.08
10/20	D2+DOC	35	0.12	1.69	17	2.5	3.01
10/21	D2+DOC	33	0.11	1.54	16	3.6	2.31
10/22	D2+DOC	25	0.11	1.45	18	2.6	2.93
10/24	BLEND+DOC	46	0.11	1.79	28	3.1	2.11
10/25	BLEND+DOC	9	0.08	2.44	12	3.5	2.84
10/27	BLEND+DOC	24	0.17	3.93	8	4.8	1.73
10/28	BLEND+DOC	20	0.12	1.72	13	3.5	2.85
10/29	BLEND+DOC	25	0.13	2.19	14	3.9	2.00
10/30	BLEND-NO DOC	25	0.13	1.85	26	6.3	3.62
Downwind Sampling Location							
10/16	D2+DOC	414	0.14	2.00	402	3.5	2.20
10/17	D2+DOC	404	0.13	1.85	314	3.3	2.39
10/17	D2+DOC	366	0.14	1.72	361	3.6	2.35
10/20	D2+DOC	371	0.12	1.85	291	3.1	2.07
10/20	D2+DOC	346	0.13	1.98	188	2.6	1.91
10/21	D2+DOC	383	0.12	1.96	228	2.9	2.00
10/21	D2+DOC	359	0.14	1.67	197	2.6	2.06
10/22	D2+DOC	428	0.13	1.79	233	2.7	2.10
10/22	D2+DOC	391	0.13	1.77	231	2.9	2.15
10/24	BLEND+DOC	401	0.13	1.69	209	2.4	1.96
10/24	BLEND+DOC	252	0.14	3.11	184	2.6	1.70
10/25	BLEND+DOC	339	0.11	1.82	216	2.3	1.93
10/25	BLEND+DOC	273	0.11	2.18	213	2.4	1.83
10/27	BLEND+DOC	298	0.11	2.03	192	2.3	1.86
10/27	BLEND+DOC	345	0.12	1.88	245	2.3	1.88
10/28	BLEND+DOC	384	0.13	1.77	196	2.2	1.94
10/28	BLEND+DOC	268	0.12	1.97	144	2.2	1.87
10/29	BLEND+DOC	486	0.14	1.71	182	2.0	1.94
10/29	BLEND+DOC	391	0.13	1.65	146	2.0	1.94
10/30	BLEND-NO DOC	717	0.11	1.77	170	2.1	1.86
10/30	BLEND-NO DOC	529	0.11	1.85	127	2.9	1.57

Mass conc. - mass concentration  
MMD - mass median diameter  
Sigma G - geometric standard deviation

## DISCUSSION

The primary objective of this field investigation was to determine the impact of a blended biodiesel fuel and DOC on DPM emissions. The vehicle was a Wagner ST-8a scooptram powered by a Deutz F12L 413FW diesel engine rated at 204 kW at 2400 rpm operated by a senior Inco driver. Standard Inco D2 fuel is a high quality, low sulfur fuel. The test fuel was a

blended biodiesel fuel, mixed on site, and determined to have 55.6 % biodiesel by volume (58.1 % by mass).

The results section presented the daily sampling data. Data shown in tables 14-16 show the weekly averages by sample location and type. This allows comparisons to be made between the two test conditions, D2 + DOC (week 1) and blend + DOC (week 2). Data for the single day of sampling, blend no DOC, are included in the tables, however limited statistical inferences can be drawn from a single day of testing. The weekly data summaries are followed by a section which draws statistical inferences from these data.

**Weekly Upwind Samples:** Table 14 summarizes the upwind data. These data show very low concentrations of aerosol entering the test section with very little day-to-day variation. These data are very consistent with the gas data presented in table 5. The decision was made not to correct for these low background levels because such a correction would not affect subsequent analyses.

Table 14 - Average weekly upwind aerosol concentrations

Sampler	Fraction	Number of days	Mean mg/m <sup>3</sup>	SD mg/m <sup>3</sup>
D2 + DOC				
SS	> 0.8	4	0.01	0.02
SS	< 0.8	4	0.01	0.01
SS	TRD	4	0.02	0.01
RCD	RCD	4	0.01	0.01
RCD	TRD	4	0.02	0.00
EC	OC	4	0.02	0.01
EC	EC	4	0.02	0.00
EC	TC	4	0.03	0.01
BLEND+DOC				
SS	> 0.8	4	0.01	0.01
SS	< 0.8	4	0.01	0.01
SS	TRD	4	0.02	0.02
RCD	RCD	4	0.00	0.01
RCD	TRD	4	0.02	0.00
EC	OC	4	0.01	0.02
EC	EC	4	0.01	0.00
EC	TC	4	0.02	0.01
BLEND NO DOC				
SS	> 0.8	1	0.03	0.00
SS	< 0.8	1	0.01	0.01
SS	TRD	1	0.04	0.01
RCD	RCD	1	0.01	0.00
RCD	TRD	1	0.03	0.01
EC	OC	1	0.02	0.00
EC	EC	1	0.01	0.00
EC	TC	1	0.02	0.00

Sampler refers to the methods: SS - size selective sampler; RCD - respirable combustible dust; EC - elemental carbon

Fraction refers to the respective fractions measured by each method: for the SS method > 0.8 μm, < 0.8 μm and TRD - total respirable dust fractions; for the RCD method RCD - respirable combustible dust and TRD - total respirable dust fractions; and the elemental carbon method OC - organic carbon, EC - elemental carbon and TC - total carbon fractions.

**Weekly Vehicle Samples:** Table 15 summarizes the average weekly aerosol concentrations for the vehicle samples. These data provide an estimate of operator exposure, and are thus not shown normalized on a brake specific basis. There is reasonable agreement between the samplers for the diesel aerosol estimate (SS < 0.8 µm fraction, the RCD fraction and the total carbon provided by the EC/OC method). For instance, 0.38, 0.39, 0.22 mg/m<sup>3</sup> respectively for the week testing the D2 and DOC, and 0.40, 0.35, 0.26 mg/m<sup>3</sup> respectively for week the week testing the blend and DOC. Exposure was higher when the DOC was removed.

Table 15 - Average weekly vehicle aerosol concentrations

Sampler	Fraction	Number of days	Mean mg/m <sup>3</sup>	SD mg/m <sup>3</sup>
D2 + DOC				
SS	> 0.8	4	0.26	0.01
SS	< 0.8	4	0.38	0.03
SS	TRD	4	0.64	0.02
RCD	RCD	4	0.39	0.10
RCD	TRD	4	0.68	0.11
EC	OC	4	0.08	0.01
EC	EC	4	0.14	0.03
EC	TC	4	0.22	0.03
BLEND+DOC				
SS	> 0.8	4	0.28	0.01
SS	< 0.8	4	0.40	0.02
SS	TRD	4	0.69	0.03
RCD	RCD	4	0.35	0.08
RCD	TRD	4	0.69	0.07
EC	OC	4	0.11	0.02
EC	EC	4	0.15	0.02
EC	TC	4	0.26	0.03
BLEND NO DOC				
SS	> 0.8	1	0.26	0.04
SS	< 0.8	1	0.50	0.05
SS	TRD	1	0.76	0.09
RCD	RCD	1	0.49	0.04
RCD	TRD	1	0.73	0.04
EC	OC	1	0.22	0.02
EC	EC	1	0.14	0.02
EC	TC	1	0.37	0.04

Samplers located on top of a scoop's engine compartment are not sampling a well mixed, stable aerosol. As noted in the event log (Appendix 3) the scoop had a number of problems that would affect aerosol concentration. Hydraulic fluid leaks caused the samplers, which were located close to the hydraulic hoses to occasionally be covered by oil. Some of the aerosolize oil may have penetrated the 10 mm cyclones. These samplers were directly exposed to aerosols created from spillage of fuel or other fluids onto hot surfaces. Additionally, the orientation of these samplers changed in relation to the ventilation air flow, so at times, the samplers were oriented in the exhaust stream while at other times the exhaust was directed away from the samplers. For these reasons, vehicle data are not suitable for determining control efficiencies.

**Weekly Downwind Samples:** Samplers located at the downwind location sample a well mixed, stable aerosol. This is demonstrated by samples collected to determine the presence or absence of

stratification. These samples showed that aerosol concentrations throughout the drift were constant at this location. Thus, these data, normalized on a brake specific basis, are used to determine control efficiency.

As previously discussed, the duty cycle shifted from week one to week two to avoid unnecessary operator exposure to NO<sub>2</sub>. Because of the shift in duty cycle, daily correction factors were calculated to normalize the diesel aerosol data. Normalization of diesel aerosol data to determine control efficiency has been done before in underground mine studies (Watts, et al., 1995, and McDonald, et al. 1997). In this study, both fuel and power data were integrated over each sampling period so that comparisons between total fuel consumed and total work performed could be made for each day. Failure to account for daily differences in power output can lead to faulty conclusions, because the daily time-weighted average aerosol concentrations are directly affected by engine power output. Dividing daily emission concentrations by the daily engine output accounts for these differences, and allows comparisons to be made between fuels.

Table 16 shows weekly means and standard deviations normalized on a brake specific basis for the two fuel types. Data are arranged in the table so that the two conditions (D2 +DOC and Blend + DOC) can be compared by sampling method. Four days of sampling from each week were averaged to obtain the weekly means. The 18.8 % increase in organic carbon was unexpected and has adversely affected the comparison. This increase cannot be explained by previously published data. The investigators believe that this increase is an artifact that was caused by the fuel spillage, which occurred on October 28-29<sup>th</sup>. Table 17 shows the comparison with these days removed and the OC fraction decreases by 6.0 %.

Table 16 - Weekly means and standard deviations normalized on a brake specific basis  
4 day vs. 4 day comparison at the downwind sampling location

Sample type	Condition	Number of test days	Mean mg/m <sup>3</sup> /MW-h	SD mg/m <sup>3</sup> /MW-h	Percent change	Standard error
SS < 0.8 μm	D2 + DOC	4	0.79	0.03		
SS < 0.8 μm	BLEND+DOC	4	0.72	0.07	-9.0	0.98
RCD	D2 + DOC	4	0.72	0.02		
RCD	BLEND+DOC	4	0.63	0.04	-12.5	0.42
TC	D2 + DOC	4	0.51	0.05		
TC	BLEND+DOC	4	0.45	0.04	-11.2	1.18
OC	D2 + DOC	4	0.16	0.03		
OC	BLEND+DOC	4	0.19	0.02	18.8	5.62
EC	D2 + DOC	4	0.35	0.03		
EC	BLEND+DOC	4	0.26	0.02	-25.2	0.91

SS < 0.8 μm - Size selective fraction < 0.8 μm in size

RCD - Respirable combustible dust

OC - Organic carbon determined by the thermal optical method

EC - Elemental carbon determined by the thermal optical method

TC - Total carbon determined by the thermal optical method

Table 17 - Weekly means and standard deviations normalized on a brake specific basis  
4 day vs. 2 day comparison at the downwind sampling location

Sample type	Condition	Number of test days	Mean mg/m <sup>3</sup> /MW-h	SD mg/m <sup>3</sup> /MW-h	Percent change	Standard error
SS < 0.8 μm	D2 + DOC	4	0.79	0.03		
SS < 0.8 μm	BLEND+DOC	2	0.63	0.07	-20.0	0.94
RCD	D2 + DOC	4	0.72	0.02		
RCD	BLEND+DOC	2	0.58	0.03	-19.0	0.25
TC	D2 + DOC	4	0.51	0.05		
TC	BLEND+DOC	2	0.40	0.03	-21.4	0.98
OC	D2 + DOC	4	0.16	0.03		
OC	BLEND+DOC	2	0.15	0.01	-6.0	3.32
EC	D2 + DOC	4	0.35	0.03		
EC	BLEND+DOC	2	0.25	0.02	-28.6	0.87

SS < 0.8 μm - Size selective fraction < 0.8 μm in size

RCD - Respirable combustible dust

OC - Organic carbon determined by the thermal optical method

EC - Elemental carbon determined by the thermal optical method

TC - Total carbon determined by the thermal optical method

***Statistical Analysis:*** T-tests were performed to test the null hypothesis, that the means of the parent populations (weekly aerosol means SS, RCD, EC, OC and TC shown in table 17) are equal. A more rigorous statement of the null hypothesis follows:

$$(1) H_o : \mu_1 - \mu_2 = 0$$

Where  $\mu_1$  is the population mean of one distribution and  $\mu_2$  is the population mean of the other.

The t-test assumes that the population distribution of the sampling method is approximately normal, though the underlying physical distribution need not be normal.

The populations characterized by  $\mu_1$  and  $\mu_2$  were sampled to provide estimates of  $\mu_1$  and  $\mu_2$ . These estimates are the sample means,  $x_1$  and  $x_2$  respectively. Associated with these sample means are their respective sample standard deviations of the mean,  $s_1$  and  $s_2$ .

Since  $x_1$  and  $x_2$  (estimates of  $\mu_1$  and  $\mu_2$ ) have associated, non-negligible, and non-equal standard deviations, it is appropriate to use the pooled form of the t-test. The pooled t-test takes into account the unequal uncertainties both sample means when calculating t, the test statistic. Further, since no assumption is made about the relationship of  $\mu_1$  to  $\mu_2$  in an alternative hypothesis, the two-tailed, pooled t-test is used.

For the two-tailed, pooled t-test with the above null hypothesis (eq. 1), the t test statistic is

$$(2) t = \frac{x_1 - x_2}{\sqrt{s_p^2 \left( \frac{1}{n_1} + \frac{1}{n_2} \right)}}$$

calculated as follows.

Where  $n_1$  and  $n_2$  are the number of samples used to calculate  $x_1$  and  $x_2$  respectively.

The t critical value ( $t_c$ ) is calculated from the two-tailed t distribution for a given confidence level

$$(3) \quad s_p^2 = \left( \frac{n_1 - 1}{n_1 + n_2 - 2} \right) s_1^2 + \left( \frac{n_2 - 1}{n_1 + n_2 - 2} \right) s_2^2$$

$(1-\alpha)$  and the pooled degrees of freedom,  $df = n_1 + n_2 - 2$ . For  $|t| < t_{\text{critical}}$ , the null hypothesis cannot be rejected. For  $|t| > t_{\text{critical}}$  the null hypothesis is rejected and one of two alternative hypotheses is formulated.

For  $|t| > t_c$ , the alternative hypothesis is  $\mu_1 \neq \mu_2$ . More specifically, for  $t < -t_c$ ,  $\mu_1 < \mu_2$  and for  $t > t_c$ ,  $\mu_1 > \mu_2$ .

Table 18 summarizes the results of the t-tests performed on the means in table 17.

Table 18 - T-tests comparing weekly aerosol means from table 17

Method	T-value	Statistically significant difference <sup>1</sup>
Size selective	2.90	Yes
Respirable combustible dust	3.31	Yes
Total carbon	2.83	Yes
Organic carbon	0.45	No
Elemental carbon	3.96	Yes

<sup>1</sup> $t_c = 2.78$ ,  $\alpha = 0.05$ , 4 degrees of freedom

Each of the three aerosol methods shows that there was a statistically significant difference between the two fuels. As shown in table 17, the percent reduction for diesel aerosol when the blended fuel and DOC were used was  $-20.0 \pm 0.94$  % for the SS method,  $-19.0 \pm 0.25$  % for the RCD method, and total carbon was reduced by  $-21.4 \pm 0.98$  % as determined by the EC method. Elemental carbon was reduced by  $28.6 \pm 0.87$  % and organic carbon was reduced  $6.0 \pm 3.32$  % although the OC reduction was not statistically significant.

The results obtained from this study using a blended SME fuel are lower than expected but reasonable when compared to similar studies conducted using a 100 % biodiesel fuel. A laboratory study evaluated the impact of 100 % SME fuel combined with a PTX-10 DOC manufactured by Engelhard, on a Caterpillar 3304 PCNA 7 l, 4 cylinder naturally aspirated, indirect injection engine and demonstrated reductions of DPM ranging from 26 to 57 % when compared to D2 + DOC (McDonald, et al., 1995). A field investigation conducted by the same investigators showed a reduction of between 49 and 80 % when a similar fuel was evaluated depending upon the method of measurement (McDonald, et al., 1997).

The level of DPM reduction in the field will vary depending upon how the engine is operated. A heavier duty-cycle produces higher exhaust temperatures and higher engine load conditions. Under these conditions DPM is composed of more elemental carbon and less organic carbon. Oxygenated fuels like SME biodiesel fuel would be expected to have a greater effect on elemental carbon, because the proportion of oxygen in the combustion chamber due to fuel oxygenation increases with the fuel-to-air ratio and thus with the engine load. Laboratory evaluations of various oxygen enriched fuels have shown a nearly linear reduction in elemental carbon emissions with increasing fuel oxygen content (Liotta and Montalvo, 1993, Ullman et al., 1994). The amount of total carbon composed of OC, normalized on a brake specific basis, increased from 32 % to 39 % with the blended fuel.

### SUMMARY

The UMN, Inco, CANMET, MTU, ORTECH, and NIOSH evaluated the impact of blended biodiesel fuel and modern DOC on air quality and diesel emissions. The study characterized the concentration of DPM and exhaust gas emissions in a non-producing test section. During the first week of the evaluation a diesel-powered scoop was operated on low sulfur, D2 fuel. During the second week the scoop was operated on a 58 % (by mass) blend of SME biodiesel fuel and a low sulfur D2. During both weeks the scoop was equipped with a pair of identical, advanced design DOCs. The objective of the evaluation was to determine changes in exhaust emissions and to estimate operating costs of operating a test vehicle on a SME biodiesel fuel blend with a modern DOC.

The results of this study are detailed in three reports. The chemical and biological analyses of particulate matter samples are summarized in the MTU report. Analyses of samples collected with a prototype denuder-difference sampling system for specific polycyclic aromatic hydrocarbons are summarized in the ORTECH report. This report summarizes the body of data collected to determine the difference in gaseous and particulate matter concentrations attributable to the use of a blended biodiesel fuel and catalyst.

Day-to-day variation in emissions was determined using the EAMP. This procedure requires that the test vehicle be operated for a short time under torque stall conditions while undiluted exhaust gas concentrations are measured at the tailpipe at points above and below the DOCs. Data obtained under these conditions are not representative of full-shift time-weighted average emissions, but do indicate the general condition of the engine and DOCs. No major changes in engine emissions were observed and the DOCs performed as anticipated. As expected, CO was effectively removed ( $98 \pm 10$  %, D2 fuel and  $99 \pm 11$  % blended fuel) by the DOCs, but there was an increase in NO<sub>2</sub> concentrations ( $185 \pm 78$  % D2 fuel,  $233 \pm 59$  % blended fuel). At this engine condition blended fuel increased NO<sub>2</sub> concentrations downstream of the DOCs by  $43 \pm 28$  %.

Air samples collected in the test section demonstrated that the combination of the blended biodiesel fuel and DOCs used in this study decreased total carbon emissions by about  $21.4 \pm 0.98$  %. Elemental carbon was reduced by  $28.6 \pm 0.87$  % and organic carbon was reduced  $6.0 \pm 3.32$  %.

% although the OC reduction was not statistically significant. This is lower than the initial expectation of 30 % - 50 % reduction. There was a slight, but statistically insignificant, increase in NO<sub>2</sub> concentrations measured at the downwind location and a corresponding decrease in NO emissions, which was also statistically insignificant. SO<sub>2</sub> levels were low during both weeks of testing. Reductions in mutagenicity and PAH concentrations are detailed in the MTU report.

Blended biodiesel fuel used in conjunction with a modern DOC offer a passive control option to reduce DPM in an underground mine. The primary limitation to the use of biodiesel fuel is cost. Typical biodiesel fuel ranges in price from \$3.00 - \$3.50/ gal U.S. Assuming a cost of \$1.00/gal U.S. of D2 fuel use of a 50 % blended biodiesel fuel would cost \$2.00 to \$2.25/gal U.S. This cost must be weighed against the cost of installing and maintaining emission control systems based upon filtration or other methods. It is likely that increased production of a renewable energy source such as biodiesel will lower costs allowing biodiesel fuel to become a viable DPM control option for underground mines.

### **ACKNOWLEDGEMENTS**

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## APPENDIX 1 - FUEL ANALYSIS

### 100 % D2 Fuel Analysis

Test	Results
D93 Flash, Pensky Martens	157 °F
D445 Viscosity, Kinematic	1.721 cSt @40 °C
D2622 Sulfur	0.0186 wt. %
D613 Cetane Number	44.2
D2500 Cloud Point	-44 °C
D240 Heat of Combustion	19,937 BTU/lb
D287 API Gravity	41.5 °
D1319 Aromatics, FIA	16.5 % vol.
D86R Distillation Points	
IBP	370.6 °F
10 % rec.	401.6 °F
20 % rec.	413.8 °F
50 % rec.	443.2 °F
90 % rec.	493.5 °F
EP	539.4 °F
Recovery	98 ml
Residue	1.3 ml
Loss	0.7 ml

### Blended Fuel Analysis

Test	Results
D93 Flash, Pensky Martens	173 °F
D445 Viscosity, Kinematic	2.669 cSt @40 °C
D2622 Sulfur	0.0055 wt. %
D613 Cetane Number	48.9
D2500 Cloud Point	-12 °C
D240 Heat of Combustion	18,567 BTU/lb
D130 Corrosion	1A
D287 API Gravity	34.6 °
D664 Acid Number by Potentiometric Titration	0.19 mg KOH/g
D86R Distillation Points	
IBP	378.2 °F
10 % rec.	424.6 °F
20 % rec.	447.1 °F
50 % rec.	558.9 °F
90 % rec.	645.1 °F
EP	659.3 °F
Recovery	98.4 ml
Residue	1.6 ml
Loss	0.0 ml

### 100% Biodiesel Fuel

Test	Results
D93 Flash, Pensky Martens	265 °F
D445 Viscosity, Kinematic	4.147 cSt @40 °C
D2622 Sulfur	0.0000 wt. %
D613 Cetane Number	53.5
D2500 Cloud Point	-0 °C
D130 Corrosion	1A
D287 API Gravity	28.2 °
D664 Acid Number by Potentiometric Titration	0.21 mg KOH/g
D1796 Sediment	0.00%
D189 (bio) Carbon Residue Conradson 100% as 10 %	0.001 wt. %
D874 Sulfated Ash	0.002 mass %
Impurities in Biodiesel	
Methyl Esters	
Gly	0.006 Free Glycerin wt. %
Mono	0.549 Monoglycerides wt. %
Di-	0.096 Diglycerides wt. %
Tri-	0.091 Triglycerides wt. %
Tglyc	0.172 Total Glycerin wt. %

Laboratory Analysis  
Systems Lab Services  
1090 A Sunshine Rd.  
Kansas City, KS 66115  
913-621-3603

## Appendix 2 - SIL Multi-Gas Analyzer - provided by CANMET Staff

### **Technical Description:**

#### **Physical Properties:**

Instrument size is (for 12Amps/hr units) 42 x 28 x 22cm and (for 1.2Ahr units) it is 42 x 28 x 15cm. Instrument weight in both cases is less than 15 Kg. The instrument case is fiberglass (for 12Ahr units) or metal (for 1.2Ahr units) and both types are RFI shielded and are type MIL-C-4150 for shock/water resistance.

#### **Operating Parameters:**

Operating temperature range is from 0 to 50 °C, with a range of 0 to 99% RH non-condensing. The pressure range is 800 to 1200 mbars. The instrument continually runs off the built in 12-volt gel cell. AC mains serves only to charge the battery. Operating time on battery only is 45 minutes on 1.2 Ahr battery and 8 hours on 12 Ahr battery.

#### **Data Collection:**

Instrument sampling rate is a maximum of once every 10 seconds using ICS (Instrument Control Software) to once per hour in 10-second increments. The capacity is 1520 samples with a logging period determined by the number of samples times the sample rate. Data retention is indefinite. Instrument to computer communication is via RS-232 at 9600Baud, 8bits, no parity with 1 start and stop bit. Data can be collected in a maximum of 32 sample runs. The ICS can download individual or specific runs. A standard PC is used to communicate with the unit using the supplied communication cable. Instrument parameters such as sample rate, calibration etc., can be done either from the computer or the instrument keypad. The log file generated is a CSV (comma delimited) file.

#### **Principles of Operation:**

Air is drawn into the unit through the input dust filter by an internal sampling pump (~ 0.5 – 1.3 lpm) and through a series of sensors. The sensors are of the electro-chemical type manufactured by CITY Technology Ltd. and the CO<sub>2</sub> sensor is an infrared gun manufactured by Vaisala Ltd. The sample air is passed through another filter and exhausted from the instrument. The signal from the sensors is in millivolts and this is processed by micro-processors to a PPM (parts per million) value. All the sensors, to varying degrees, are affected by temperature, pressure and other interfering gases, as well as, aging and short-term drift. SIL uses a number of strategies to try and reduce these errors.

Short-term drift can be corrected by doing frequent calibrations. Because of characteristics that are particular to each unit, frequency of calibration can vary from once or twice a day to once a week. Often, a zero or spike may be done to check the accuracy. Depending on the range of gas used, for example an error of 2 out of 40 ppm would be considered excellent and calibration would not be required. Zeroing of the instrument is also very important so that the response to low contaminant levels is not affected. Each sensor has an inherent resolution, due to noise and baseline drift depending on the instrument. Also interfering gases may mask or add to readings. Note, that depending on the sensor the baseline drift may vary from 0.5 to 4 ppm.

Calibration gases are purchased in bulk with each cylinder being certified by the supplier. Gases from Matheson or Praxair are exclusively used. Gases from the certified cylinders are decanted into small ~1litre aluminum cylinders which are then used to calibrate the gas sensors on site. The flow rate of the gas injection into the sensor is adjusted to about 1 lpm for a maximum of about 3 minutes for zero and span.

### **Test Procedure:**

## **Pre-Test Preparation:**

Four SIL instruments were used, two from Ottawa and two from the Sudbury Laboratory. The units were essentially identical except the Ottawa instruments were the larger 12 Ahr type. All four units were returned to SIL for a service check and to replace all 4 electro-chemical cells (CO, NO, NO<sub>2</sub> and SO<sub>2</sub>). As well, the batteries on all 4 units were replaced. Prior to being used at the DEEP site the units were operated at the lab for several weeks to see if there were any problems and also to familiarize the operators with the characteristics of each individual instrument.

Because of the value of resources placed upon this survey, SIL were asked to provide us with extra technical help in case there were problems with any of the units. SIL provided us, for one week, with an engineer who had worked on the development of the Multi-Gas Analyzers, plus a spare SIL instrument.

The test site was divided into an intake and exhaust area. At the intake two SIL's were used. One was located directly underneath the fan on the vent tube and the other unit, because of concerns about re-circulation, was moved about 30 meters upstream, near the University of Minnesota sample site. Re-circulation was indeed observed and therefore, for the final results, only data from the upstream unit was used. At the upstream site a Bruel & Kjaer model 1302 Multi-gas monitor which was configured to sample CO<sub>2</sub>, CO and SO<sub>2</sub> was also used, however, due to technical and environmental problems (temperature too low), any data was unreliable and the instrument was removed. The intake site was monitored for the first week by the SIL engineer and for the remaining two weeks by a CANMET technologist. This monitoring consisted of downloading data, spiking the instrument with zero and span gases, calibrating the instruments (when necessary), and noting any unusual conditions or changes. Because of limited space on the man carrier, the intake site technologist wasn't able to go underground with the first group and therefore by the time he arrived, often, there was insufficient time to download and calibrate the instruments before the actual test began.

The exhaust site had two CANMET SIL's plus the SIL loaned to the project test by SIL. All three instruments were generally placed in the same area just behind the University of Minnesota site. Two SIL's were located on a palette on the ground immediately behind the U of M dust samplers and the other was placed on a table against the wall. Along with the SIL on the table there was another a Bruel & Kjaer model 1302 Multi-gas monitor. This instrument monitored the same three gases as the one at the intake side plus formaldehyde. Unfortunately, this instrument also suffered reliability problems and therefore the data wasn't seriously considered in the final analysis. At this site, calibration was usually done before the test started for the day. At the end of each day, data was downloaded to a computer and then the instrument was restarted and sampled/logged overnight. The following morning the data was dumped to a PC but because this data transfer was slow and the dust sampling group didn't require as much preparation, the test sometimes started before all 3 SIL's were ready.

The data for each instrument after being downloaded to a PC was also copied to a fresh diskette every day with the diskette being kept in a secure location in case the hard drive failed

Data processing was done in Microsoft Excel and any unusual data such as zero or span spikes or noise were manually removed. At the intake side data from both instruments was looked at and compared; however because of the concern over recirculation only the data from the instrument upstream from the vent tubing was used. For data from the exhaust side, the CO and CO<sub>2</sub> values for the two CANMET instruments was averaged and for the remaining three gases NO, NO<sub>2</sub> and SO<sub>2</sub>, results from the loaned gas monitor from SIL was also incorporated.

### Appendix 3 - Event Log Compiled by ORTECH

DATE/TIME	COMMENT
1997-10-14	set-up day
1997-10-14 07:15	on site
1997-10-15 08:10	in mine
1997-10-16 06:55	on site, 1st test day, scoop operating on D-2, DOC installed,
1997-10-16 08:20	in mine
1997-10-16 12:15	scoop in drift, mucking started
1997-10-16 12:31	GAP sampling initiated
1997-10-16 12:40	power to all samplers off (blown main fuse), mucking continued
1997-10-16	possible scooptram problems, (transmission oil leak?)
1997-10-16 13:40	fuses replaced power restored
1997-10-16 13:46	GAP restarted
1997-10-16 14:30	scooptram shut down, oil line failure
1997-10-16 14:42	stop test, GAP off., test aborted
1997-10-16 19:30	mechanic replaced broken oil line, line repaired, scoop operating
1997-10-17 07:00	on site, 2nd day of testing, scoop operating on D-2, with DOC
1997-10-17 08:00	in mine
1997-10-17 09:18	scoop started
1997-10-17 09:43	GAP started
1997-10-17 11:15	scoop out of drift, drift ventilation off
1997-10-17 11:19	engine emission test performed
1997-10-17 11:30	scoop engine off, (operator lunch break)
1997-10-17 12:00	ventilation in drift on, scoop back mucking
1997-10-17 13:05	scoop out of drift
1997-10-17 13:07	scoop idling, discussions with operator
1997-10-17 13:10	resume mucking
1997-10-17 15:14	scoop engine off, total 144 buckets, 6.8 hours of operation, 6. hours of mucking, scoop to the surface for maintenance
1997-10-17 15:30	GAP sampler off
1997-10-20 06:45	on site, 3rd test, scoop operating on D-2, with DOC
1997-10-20 08:00	in mine, scoop driven from surface to mine
1997-10-20 09:00	engine on, scoop in drift mucking, note scoop operator adjusting technique to reduce NO2 spikes, emissions test to be performed at lunch
1997-10-20 09:29	GAP operating
1997-10-20 11:26	scoop out of drift, ready for emissions test
1997-10-20 11:30	drift ventilation off
1997-10-20 12:19	scoop back in drift mucking, ventilation on
1997-10-20 15:06	scoop out of drift
1997-10-20 15:20	scoop engine off, total 145 buckets, 6.6 hours of operation, 6.0 hours of mucking, scoop fuel flow sensor relocated
1997-10-20 15:30	GAP off
1997-10-21 06:50	on site, 4th test, scoop operating on D-2, with DOC
1997-10-21 08:30	in mine
1997-10-21 09:00	scoop engine on
1997-10-21 09:05	scoop in drift mucking

1997-10-21 09:25	GAP sampling initiated
1997-10-21 11:15	scoop out of drift, ventilation off
1997-10-21 11:25	scooptram engine off
1997-10-21 12:07	scoop engine on, ventilation on
1997-10-21 15:15	scoop out of drift
1997-10-21 15:24	ventilation off
1997-10-21 15:30	scooptram engine off, total 144 buckets, 6.1 hours of operation, 6.0 hours of mucking
1997-10-21 15:40	GAP off
1997-10-22 07:00	on site, 5th test, scoop operating on D-2, with DOC
1997-10-22 07:50	in mine
1997-10-22 08:52	scooptram engine on
1997-10-22 08:55	GAP sampling initiated
1997-10-22 08:58	scooptram in drift mucking
1997-10-22 11:15	scooptram out of drift for emission test
1997-10-22 11:16	drift ventilation off
1997-10-22 11:36	scooptram engine off, note small leak on the scooptram, possible hydraulic oil leak
1997-10-22 12:07	scooptram engine on, back in drift
1997-10-22 12:07	ventilation on
1997-10-22 12:42	RAM reading .33 mg/m <sup>3</sup> downwind site
1997-10-22 14:46	scooptram out of drift
1997-10-22 15:06	ventilation to drift off, scoop to fueling area
1997-10-22 15:10	scooptram engine off, 147 buckets
1997-10-22 15:20	GAP off
1997-10-22	scooptram fuel tank emptied, refueled with 50%D2 50% bio-diesel, scooptram driven to surface for installation of new DOC
1997-10-23	scooptram on surface, new catalyst refitted, scooptram back to mine and 3 hours of catalyst break-in driving up and down ramp
1997-10-24 07:00	on site, 1st test, scooptram fueled with 50%D2 50% bio-diesel, new DOC installed. note that mine air heaters, direct fired, natural gas, used to heat the ventilation air to prevent the buildup of ice on the ramp
1997-10-24 08:00	in mine
1997-10-24 08:50	scooptram engine on
1997-10-24 08:51	GAP on
1997-10-24 08:56	scooptram engine off
1997-10-24 09:14	scooptram engine on
1997-10-24 09:20	scooptram in drift and mucking started
1997-10-24 09:40	noted higher visible dust at downwind site (may be a dry muck pile)
1997-10-24 09:50	Inco measured ambient NO <sub>2</sub> at downwind location, high NO <sub>2</sub> reading observed (4.5 ppm NO), Inco advised team to limit their exposure to no more that 15 minutes in a 60 minute interval at the downwind site
1997-10-24 10:15	continued high NO <sub>2</sub> levels at downwind site, INCO opened up an ore pass (approximately 35 meters upwind from the downwind site) to create a downcast, in an attempt to reduce the "roll back" of emissions to the under ground laboratory this affects the flow rate as follows: total 48k cfm, 38k exiting at downwind site and 10k exiting the fuel area
1997-10-24 11:17	scooptram out of drift, mucking stopped
1997-10-24 11:29	scooptram emissions test
1997-10-24 11:34	scooptram engine off
1997-10-24 11:38	ventilation to drift off

1997-10-24 12:15	scooptram engine on, in drift mucking
1997-10-24 12:15	ventilation in drift on
1997-10-24 12:50	cover to ore pass reinstalled, observed that there is no further draw, suspect that other operations in #3 shaft may be affecting draw
1997-10-24 13:25	note that ambient gas concentrations are returning to previous test conditions (i.e. lower concentrations), possible that other mucking operations (on other levels) may have had an affect on the ambient levels as the ramp door was left open, possibly affecting the ventilation and ambient background concentrations
1997-10-24 15:25	scooptram out of the drift, mucking stopped
1997-10-24 15:34	scooptram in fuel area, scooptram engine off 145 buckets, 5.8 hours mucking
1997-10-24 15:36	ventilation to drift off
1997-10-24 15:45	GAP off
1997-10-25 07:00	on site 2nd test, 50% bio-diesel, 50% D2 with DOC, mine air heaters are off for this test
1997-10-25 08:00	in mine
1997-10-25 09:04	scooptram engine on
1997-10-25 09:05	GAP on
1997-10-25 09:10	scooptram in drift and mucking
1997-10-25 09:13	scooptram out of drift (engine still on)
1997-10-25 09:15	scooptram back in drift and mucking
1997-10-25 10:10	subjective observation, the air is visibly cleaner (i.e. less particulate) than in previous mornings
1997-10-25 11:17	scooptram out of drift, engine on, emissions test, ventilation off
1997-10-25 11:36	scooptram engine off
1997-10-25 12:06	scooptram engine on, ventilation on
1997-10-25 12:07	scooptram in drift mucking
1997-10-25 15:06	scooptram out of mine, ventilation to drift off
1997-10-25 15:15	scooptram in fueling area
1997-10-25 15:20	scooptram engine off 145 buckets, 6.0 hours mucking
1997-10-27 06:00	NOTE CHANGE TO STANDARD TIME (all time values henceforth are standard time), on-site, 3rd test 50% D2 50% bio-diesel with DOC, air heaters off, early start as operator required for other duties in the afternoon
1997-10-27 06:41	in mine
1997-10-27 07:29	scooptram engine on
1997-10-27 07:30	GAP on
1997-10-27 07:33	scooptram in drift and mucking
1997-10-27 08:47	scooptram out of drift, engine off, electrical short on vehicle, ventilation off
1997-10-27 08:48	scooptram engine on
1997-10-27 08:56	electrical problem repaired, ventilation on, scooptram in drift and mucking
1997-10-27 10:16	scooptram out of drift, ventilation off
1997-10-27 10:38	scooptram engine off
1997-10-27 11:09	scooptram engine on
1997-10-27 11:13	scooptram back in drift mucking
1997-10-27 13:42	scooptram out of drift, ventilation off
1997-10-27 13:51	scooptram in fueling area, 146 buckets, ~5.9 hr. mucking
1997-10-27 14:00	GAP off
1997-10-28 06:45	on-site, 4th test 50% D2 50% bio-diesel with DOC, air heaters off
1997-10-28 07:38	in mine

1997-10-28 08:35	scooptram engine on
1997-10-28 08:37	scooptram in drift and mucking
1997-10-28 08:39	GAP on
1997-10-28 09:25	scooptram engine off, apparent fueling problems (i.e. no fuel to engine)
1997-10-28 09:35	GAP off
1997-10-28 09:54	scooptram engine on, fuel filters changed on engine
1997-10-28 10:00	scooptram back in drift mucking
1997-10-28 10:10	scooptram out of drift, engine off, apparent malfunction of fuel shut off solenoid, possible loose ground wire on solenoid, connection repaired
1997-10-28 10:20	scooptram back in drift mucking
1997-10-28 10:30	GAP on
1997-10-28 11:04	carbonyl sampling initiated
1997-10-28 11:15	scooptram out of drift, ventilation off
1997-10-28 11:30	scooptram off, operator noted occasional bursts of blue smoke so intense that the back end of the scooptram was obscured from view
1997-10-28 12:13	scooptram on, checked engine blow-by pressure: 1" H2O at torque stall and high idle, .25" H2O at idle
1997-10-28 12:22	scooptram back in drift and mucking, observed mucking operation (approx. 5 buckets), no visible blue smoke
1997-10-28 13:28	scooptram in drift, mucking stopped, torque converter oil low, engine off, added approximately 35 litres
1997-10-28 13:46	ventilation to drift off, torque pressure low (55 psi maximum), contacted surface mechanic suggested possible air lock in system, system bled
1997-10-28 13:53	scooptram engine on, ventilation on
1997-10-28 14:01	GAP off, all sampling stop to wait for scooptram repair
1997-10-28 14:04	scooptram engine on, back in drift and mucking
1997-10-28 14:05	GAP on
1997-10-28 15:24	scooptram out of drift, drive shaft disk brake malfunction, engine off, ventilation off, surface mechanic called 137 buckets
1997-10-28 15:37	GAP off, end of test, mechanic will come down for repair, end of testing for today
1997-10-29 07:00	on-site, 5th test 50% D2 50% bio-diesel with DOC, air heaters off
1997-10-29 08:43	scooptram engine on
1997-10-29 08:45	GAP on
1997-10-29 08:49	carbonyl sampling train on
1997-10-29 08:50	scooptram in drift and mucking
1997-10-29 09:30	noted blue smoke from scooptram (big clouds of blue smoke)
1997-10-29 10:01	scooptram out of drift, noted that the fuel tank vent/overflow tube was directing raw fuel near the catalyst, fuel spilled out of this vent tube when either the tank was overfilled or the scooptram was on a sharp incline (bucket up) and the tank was full or near full. When the scooptram was mucking the angle of the scooptram combined with the high load high temperature of the catalyst shell caused the pooled fuel to smoke. The fuel vent/overflow tube was redirected over the fire wall and away from the exhaust system, no further smoking observed. The intermittent smoking problem was observed in some of the previous tests and on marked occasions.
1997-10-29 10:04	scooptram back in drift and mucking
1997-10-29 10:50	scooptram out of drift, ventilation off, ventilation duct fell down, scooptram engine off
1997-10-29 11:02	ventilation duct repaired, scooptram in drift and mucking
1997-10-29 11:16	scooptram out of drift
1997-10-29 11:31	scooptram engine off

1997-10-29 12:08	scooptram engine on, ventilation on, back in drift and mucking
1997-10-29 14:45	scooptram out of drift
1997-10-29 14:52	ventilation to drift off
1997-10-29 14:58	scooptram in fueling area, 142 buckets
1997-10-29 15:08	GAP off
1997-10-29	scooptram to surface for removal of DOC
1997-10-30 06:45	on-site, 6th test 50% D2 50% bio-diesel, DOC catalyst removed, air heaters off, scooptram not ready
1997-10-30 08:05	in mine
1997-10-30 09:57	scooptram in mine, idling in front of underground laboratory
1997-10-30 10:10	GAP on
1997-10-30 10:17	scooptram engine at high idle condition, INCO checking operator emission levels
1997-10-30 10:30	scooptram off high idle, in drift and mucking
1997-10-30 10:41	scooptram out of drift, engine off, hydraulic leak
1997-10-30 10:47	GAP off
1997-10-30 10:49	mechanic called
1997-10-30 14:00	INCO mechanic replaced hydraulic hose, scooptram functioning
1997-10-30 14:10	scooptram A-OK
1997-10-30 14:12	scooptram engine on
1997-10-30 14:15	GAP on scooptram in drift and mucking
1997-10-30 17:18	scooptram out of drift, ventilation off
1997-10-30 17:22	scooptram engine off
1997-10-30 18:22	scooptram engine on
1997-10-30 18:23	scooptram in drift mucking, ventilation on
1997-10-30 20:43	scooptram out of drift, engine off, ventilation off, 168 buckets
1997-10-30 20:53	GAP off