Diesel Emissions Evaluation Program

(DEEP)

Final Report

Prepared by:
W. Addy Majewski
and
Sean McGinn

Toronto, Ontario
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Foreword

Dr. Bruce Conard

Dear Reader,

The use of diesel-powered vehicles in most underground mining operations is a key factor in the safe and economical movement of large tonnages of material. While other sources of energy may be found to be more suitable in the future, the near term clearly indicates that diesel fleets will be with us for some time to come. And while diesels today offer some safety advantages over other types of power, increasing concerns about health effects of diesel particulate matter (DPM) must be confronted.

The Canadian mining industry responded to the challenge of decreasing miners' exposures to diesel particulate matter by forming in 1997 a research consortium consisting of stakeholders from government, industry and labour. The present report constitutes the final communication with stakeholders on the progress made by this consortium. The objective of the Diesel Emission Evaluation Program (DEEP) was to investigate state-of-technology options for reducing DPM emissions from diesel engines. The focus of DEEP was on field testing of technologies that were relatively mature. The criteria for success included effectiveness, reliability, robustness, ease of use and cost (both purchase price and maintenance needs).

Even though it has taken longer to complete the program than any of the stakeholders initially imagined or desired, the work accomplished has been successful in pointing out what works, what doesn't work, and where attention must continue to be applied. There are immediate benefits of the program. For example, improvements in maintenance programs can result in significant reductions in DPM emissions. Biodiesel fuels can offer some benefit. Particulate filters, if carefully chosen to match the vehicle duty cycle, can provide dramatic reductions.

The details of each project conducted are important because therein lie the issues that must be dealt with in successful implementation of any technology or combination of technologies to the environments in which we operate and for the people who work there. The present report gives the summary of results and points the way for the interested reader to obtain further details.

All of this work, of course, has been done by extremely skilled and dedicated people across many companies and fields of expertise. First, at the mine face with operators of vehicles, then with mechanics whose job it is to keep the vehicle and its systems running, then with the scientific investigators where experimental plans were developed and data interpretation occurred, then at the DEEP Technical Committee level, and finally at the DEEP Management Board level. I have been fortunate to have met many of these individuals and have worked along side many of them. My respect for their knowledge, ingenuity and approach in getting the job done is enormous.

DEEP's work needed a significant amount of cash funding and I want to acknowledge the Canadian mining industry and several U.S. companies for stepping forward with the necessary commitment. The role of government has also been noteworthy. In particular, the response from Natural Resources Canada, CANMET-MMSL in providing funding and in-kind support throughout DEEP's work helped it gain both stability and technical sophistication. Also, the assistance of provincial agencies, such as the Ontario Workplace Safety and Insurance Board, in assisting with funding of specific projects is gratefully acknowledged. The support of DEEP's work by two major labour unions was extremely important, not only for the communication they provided to their members, but also for the dedication and vision they brought to helping to manage all the phases of DEEP research.

I congratulate all of the people associated with DEEP. It is never easy to bring people with different backgrounds and expertise together and to end up all pulling in the same direction. In this case it has worked. We need this cooperative spirit to continue as we implement what we have learned. My heartiest best wishes for continued success.

Bruce R. Conard
Chair, DEEP Management Board
Oakville, Ontario

October 18, 2005

Acknowledgements

This report covers nearly eight years of work of the DEEP consortium. A research program of this length and scope required strong collaboration from many organizations and individuals. The following is the list of individuals and organizations who made the DEEP program possible. We also extend our gratitude to hundreds of people who, although their names are not listed, were essential contributors to DEEP research.

DEEP Steering Committee (formed in 1996)

Bruce Conard[*] – Mine Operator Sector – INCO
Charles Graham – Advisory Member – CAMIRO
Joe Stachulak – Mine Operator Sector – INCO
Andrew Hara – Mine Operator Sector – Noranda
Philippe Gaultier – Mine Operator Sector – Noranda
Don Dainty[*] – Research Agency Sector – CANMET-MMSL
Michel Grenier[*] – Research Agency Sector – CANMET-MMSL
Win Watts[*] – Research Agency Sector – University of Minnesota
Andrew King[*] – Labour Movement Sector – USWA
Jennifer Penney – Labour Movement Sector – USWA
Gary Hrytsak – Labour Movement Sector – CAW
Bob Scott[*] – Machine and Engine Manufacturers Sector – Detroit Diesel Canada
Jamie Munn – Machine and Engine Manufacturers Sector – Tamrock
Dale McKinnon[*] – Manufacturers of Emission Controls Sector – MECA
John Vergunst[*] – Mine Inspectorate Sector – Ontario Ministry of Labour
Ken Bee – Fuels Sector – Ontario Soybean Grower's Marketing Board
Fred Brandenburg – Fuels Sector – Ontario Soybean Grower's Marketing Board

DEEP Management Committee

Bruce Conard – INCO (Chair 1997-2005)
Albert Cecutti – Falconbridge (Xstrata)
Andrew Hara – Noranda
Andrew King – USWA
George Botic – CAW
Richard Allan – Barrick
Charles Graham – CAMIRO
Michel Grenier – CANMET
David Cisyk – IMC Kalium
Dale McKinnon – MECA
Bernie Deck – MOL
Allan Moss – Rio Tinto
John O'Grady – TTC
Charles Hazen – Xstrata Nickel
Fred Herman – Assn of Chief Mine Insp.
Louis Dionne – Barrick
Gilles Brousseau – Barrick
Serge Vezina – Cambior
Norm Girard – Falconbridge (Xstrata)
Gordon Hall – Falconbridge (Xstrata)
Peter R. Jones – HBMS
Gary Allen – HBMS
Brent Kristof – IMC Kalium
Tom Olsen – IMC Kalium
Ray Ellington – Morton International
Jim Schnarr – Noranda
Philippe Gaultier – Noranda
Bill Howell – NRCan
Bob Hargreaves – NRCan
Raymond Gaetan – NRCan
Henry Steger – NRCan
Ken Bee – OSBGMB
Fred Brandenburg – OSBGMB
Keith Ferguson – Placer Dome
Keith Marshall – Rio Tinto
Steve Hunt – USWA

[*] Designates original Committee members from March 1996

Don Dainty – CANMET
Heather Langfeld – Falconbridge (Xstrata)
Joanne Aubry – USWA
David Bronkhorst – Williams Operating Corp.

DEEP Technical Committee

Heather Langfeld – Falconbridge (Chair 1997-1998)
Gary Allen – Hudson Bay Mining & Smelting (Chair 1998-2000)
Michel Grenier – CANMET-MMSL (Chair 2000-2005)
Gilles Brousseau – Barrick Gold
Rick Allan – Barrick Gold
Mike Meadows – Detroit Diesel Canada
Philippe Gaultier – Noranda
Sean McGinn – Noranda
Dale McKinnon – MECA
Jennifer Penney – USWA
Joe Stachulak – INCO
Greg Nault – INCO
John Vergunst – Ontario Ministry of Labor
George Schnakenburg – NIOSH
Aleksander Bugarski – NIOSH
Daniel Vallieres – Cambior
Gary Hrytsak – CAW
Tom Olson – IMC Kalium
Dave Cisyk – IMC Kalium
Sheri Weeks – Noranda
Ray Ellington – Morton Salt
David Bronkhorst – Williams Operating Corp
Bob Dougherty – Toronto Transit Commission
Winn Watts – University of Minnesota
Doug Johnson – Ortech

DEEP Secretary

Bill Howell – CANMET (1997-2000)
Charles Graham – CAMIRO (2000-2005)

DEEP Treasurer

Charles Graham – CAMIRO (1997-2005)

DEEP Members

- Association of Chief Mine Inspectors
- Barrick Gold Corporation
- Cambior Inc.
- Canadian Auto Workers
- CAMIRO - Canadian Mining Ind. Research Org.
- Falconbridge Limited
- Hudson Bay Mining & Smelting
- IMC Kalium
- INCO Ltd.
- Natural Resources Canada, CANMET-MMSL
- New Brunswick Workers Health and Safety Compensation Commission (WHSCC)
- Noranda Mining & Exploration
- Ontario Soybean Growers Marketing Board
- Saskatchewan Canola Dev. Commission
- South Dakota Soybean Promotion Committee
- Toronto Transit Commission
- United Steelworkers of America

Other DEEP Stakeholders

- Morton International - Canadian Salt
- Placer Dome Canada Limited
- Rio Tinto
- Tamrock (Sandvik)
- Williams Operating Corporation
- Detroit Diesel
- Manufacturers of Emission Controls Association (MECA)
- Engine Controls Systems (ECS)
- Ontario's Workplace Safety and Insurance Board (WSIB)
- Manitoba WCB
- Australian Joint Coal Board
- Institut fur Gefahrstoff-Forschung der Bergbau-Berufsgenossenschaft (IGF)
- Mining Diesel Emissions Conference
- National Institute of Occupational Safety & Health (NIOSH)
- ORTECH
- University of Minnesota
- VERT

Acronyms and Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
CAMIRO	Canadian Mining Industry Research Organization
CANMET-MMSL	CANMET-Mining and Mineral Sciences Laboratories
CO	Carbon monoxide
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
DPM	Diesel particulate matter
EAMP	Emissions assisted maintenance procedure
EC	Elemental carbon
HC	Hydrocarbons
LHD	Load-haul-dump (vehicle)
MOL	Ministry of Labour (Canadian Provinces)
MSHA	Mine Safety and Health Administration (US Department of Labor)
NIOSH	The National Institute for Occupational Safety and Health (US Department of Health and Human Services)
NOx	Nitrogen oxides
OC	Organic carbon
PAH	Polycyclic aromatic hydrocarbons
RCD	Respirable combustible dust
SS	Size selective sampling
TC	Total carbon
TLV	Threshold limit value
USBM	US Bureau of Mines

1 DEEP Program Description

1.1 Background

The DEEP program had been formed as an extension of the activities of the Canadian AdHoc Diesel Committee, at a time when the mining industry was faced with significant diesel emission challenges which required the involvement of a wider and more resourceful group of stakeholders.

The AdHoc Diesel Committee was an informal association of agencies having a continuing and specific interest in the efficient, least polluting use of dieselized machinery in underground non-coal mines. It began in 1986 as a successor to the tri-partite international Cooperative Diesel Research Advisory Panel (CDRAP) which included Ontario MOL, CANMET-MMSL and the USBM.

The AdHoc Committee acted as a forum for technology exchange and as a body undertaking cooperative research programs. Extensive R&D supported by the AdHoc resulted in—among others—the development and underground evaluation of ceramic wall-flow DPFs, development of the RCD protocol for underground sampling of ambient particulates, and the development and use of underground environmental assessment instrumentation and protocols.

In 1991, the AdHoc Committee made a recommendation to the Canadian mining industry to limit RCD exposure in underground mines to 1.5 mg/m^3. This exposure limit was subsequently incorporated into some (but not all) provincial mining regulations in Canada.

The immediate catalyst for the formation of DEEP was the proposed TLV limit for DPM published in March 1995 by the ACGIH[1]. The proposed exposure limit was 0.15 mg/m^3—a level that was considered nearly impossible to achieve in view of the diesel engine technology that was used in Canadian and US mines in the 1990's.

In October 1995, MSHA convened a committee to recommend regulatory changes to minimize DPM exposure in underground mines. The committee considered a possible permissible DPM exposure limit of 0.3 mg/m^3 for recommendation. Even though this figure was more relaxed than the ACGIH proposal, it still presented a formidable challenge for the U.S. mining industry in the mid-1990's.

The DPM exposure limits considered for adoption by the ACGIH and by MSHA caused a surge of interest in reducing diesel particulate exposure in underground mines. Investigation of the underlying technical issues—which ranged from DPM exposure measurement to control technologies and included engine-based approaches and aftertreatment, required a close cooperation of the industry with academia and government-based mining research. In November 1995, Bruce Conard (INCO) and Win Watts (USBM) proposed a North American research consortium of underground non-coal mining companies, engine manufacturers, emission control manufacturers, agencies and organizations involved with worker health in underground mine operations. The formation of the consortium, which eventually evolved into DEEP, also allowed for keeping the mining diesel research group, which was transferred from the USBM, a US government agency scheduled for termination at end of 1995, to become a part of the Diesel Research Group at the University of Minnesota in Minneapolis.

The proposed scope of the consortium research was:

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[1] Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices, Notice of Intended Changes for 1995-1996, ACGIH, Cincinnati, Ohio

- Aerosol measurement
- DPM exposure assessment
- Control strategy implementation and evaluation
- Laboratory testing of emission controls

The consortium was envisioned as a 3-year program (1996-98), with a budget funding estimate of $500,000 per year from the industry, which would cover 33% of the total required funds.

In December 1995, Don Dainty and Michel Grenier (CANMET-MMSL) met with Bruce Conard and Joe Stachulak to discuss the INCO/USBM proposal. They submitted a proposal for inclusion of CANMET and the Canadian AdHoc Diesel Committee members as partners in the proposed consortium. CANMET confirmed willingness to assume a leadership and coordinating role in the new consortium.

In February 1996, Bruce Conard made a presentation to ACGIH, outlining the concerns of the mining industry and the perceived shortcomings of the evidence used in the ACGIH process. The ACGIH, however, had no concern for technical feasibility or potential problems of its proposed TLV, which set the stage for organizing the DEEP consortium.

1.2 Early Organizing Work

As a result of the ACGIH proposal and the implied changes to regulatory exposure limits in the USA (MSHA) and Canada, the Canadian AdHoc Diesel Committee convened a meeting, held in March 1996 in Markham, ON which was attended by about 90 delegates representing all groups of stakeholders. Under the leadership of mine operators (companies) and labour (unions), the delegates endorsed the concept of a North American diesel research consortium comprised of several industry sectors. A *steering committee* was formed to prepare the scope of work for what would be called the Diesel Emissions Evaluation Program (DEEP). A DEEP *management board*, consisting of program sponsors, was to be formed to solicit and manage funding, oversee direction, and manage the consortium.

The stated goal of DEEP was to reduce miner exposure to diesel exhaust pollutants and to oil mists, with the following specific objectives:

1. Evaluation of emissions reduction strategies underground to determine effectiveness, technical feasibility and cost
2. Evaluation of diesel exhaust aerosol measurement methodology
3. Expansion of the diesel exhaust and oil mist aerosol exposure database
4. Laboratory evaluations of new, but untested, emission control technologies

In the first draft of the DEEP scope prepared by Win Watts in April 1996, a three year program with a total budget of $1 million per year was envisioned.

In June 1996, Bruce Conard wrote a letter, soliciting mines' interest and participation in the DEEP consortium, and specifying DEEP funding relationships and organization. The basic program structure involving a *management board* (which included the sponsors) and a *technical committee* (composed of stakeholders and technical advisors) was first proposed in that letter.

A formal letter from CANMET-MMSL and DEEP Steering Committee soliciting participation and contribution to DEEP was sent out industry-wide in August 1996.

September 1996 marks the first research effort undertaken at the request of the DEEP steering committee. An engine comparison study at the Kidd Creek mine investigated the effect of converting to electronic engines (DDEC) on emissions and underground mine air quality. It was found that the tailpipe CO levels decreased, but RCD exposures were inconclusive due to a large number of older diesel engines present in the fleet. The study also compared a 6V92 DDEC engine to a Deutz F12L413FR engine. The 6V92 outperformed the Deutz engine in terms of MSHA certified emissions, fuel consumption, capital costs, and maintenance.

Also in September 1996, significant progress was made toward formulating the final scope and organizational structure of the consortium. The steering committee commissioned J. Stachulak (INCO), J. Penney (USWA) and P. Gaultier (Noranda) to make revisions and to peer review the program description. It was suggested that the evaluation of aerosol measurement methods be moved to the front of the program. The rationale was that measurement methods should be established before attempting to control exposures. Two pilot projects were proposed—at INCO and Brunswick Mine—both of which focused on aerosol measurement. Third draft of the DEEP Program Description was finished in the following month.

A number of mines and mining organizations responded to the DEEP solicitation. By September 1996, CAMIRO became the DEEP funding coordinator, and CANMET agreed to assume the secretariat responsibility. Funding commitments were received from INCO, Noranda, Falconbridge, Barrick Gold, Goldcorp, Hudson Bay Mining and Smelting, Placer Dome, and Cambior. Strong interest had been expressed by others.

Contributors had the flexibility of allocating their funds to projects of their choice, as solicited by CAMIRO through DEEP on a project by project basis. The two proposed studies—(1) biodiesel study at INCO with sampling procedures comparison to be done by University of Minnesota, and (2) comparison of sampling and analytical methods in a high sulphide ore mine to be done at BMS—were deemed to be the first two official DEEP projects (the Kidd Creek electronic engine investigation was to be presented at the upcoming November AdHoc meeting, but was not considered a DEEP project).

1.3 DEEP Program Structure

The structure of the DEEP consortium was discussed during the AdHoc Conference held in November 1996 in Toronto, and was finalized in the following months. The organization and the technical scope of DEEP were outlined in two documents: (1) *DEEP Memorandum of Understanding* and (2) *Program Description* (see Appendix A and B), which were adopted in early 1997.

The goal of the program was expressed by the following statement: “The goal of DEEP is to reduce miner’s exposure to diesel exhaust pollutants by systematically testing and evaluating control strategies to reduce emissions at specific mine sites”. The program objectives had been changed to:

1. Evaluation of diesel exhaust and oil mist aerosol measurement methodologies to determine benefits / limitations of each
2. Implementation and evaluation of comprehensive emission control strategies to reduce DPM concentrations to determine efficiency, technical feasibility and costs
3. Measurement of DPM and diesel gaseous pollutants

Specific research priorities included evaluation of DPM aerosol measurement methods, modern engine technology, alternative fuels and additives, emission control technologies, and engine maintenance.

Stakeholders. Inclusion of not only the industry, technical, and manufacturer sectors, but also labour and government had been deemed absolutely essential for the structure of DEEP. The representation of government was especially critical, as it would eventually have the responsibility for adopting DPM exposure regulations.

DEEP had been structured to consist of individual projects to be financed independently. At a modest administration fee, stakeholders were able to join DEEP and participate in project development. Stakeholders including government and labour had the option of allocating their funding to whichever specific projects they deemed most beneficial or appropriate. Stakeholder funding was managed by CAMIRO, acting as DEEP Treasurer.

Management. The organization of DEEP—structured into the Management Committee, the Technical Committee and project teams—has been developed based on similar cooperative research programs: the Mine Environmental Neutral Drainage Program (MEND) and Aquatic Effects Technology Evaluation Program (AETEP).

The DEEP structure is schematically shown in Figure 1.

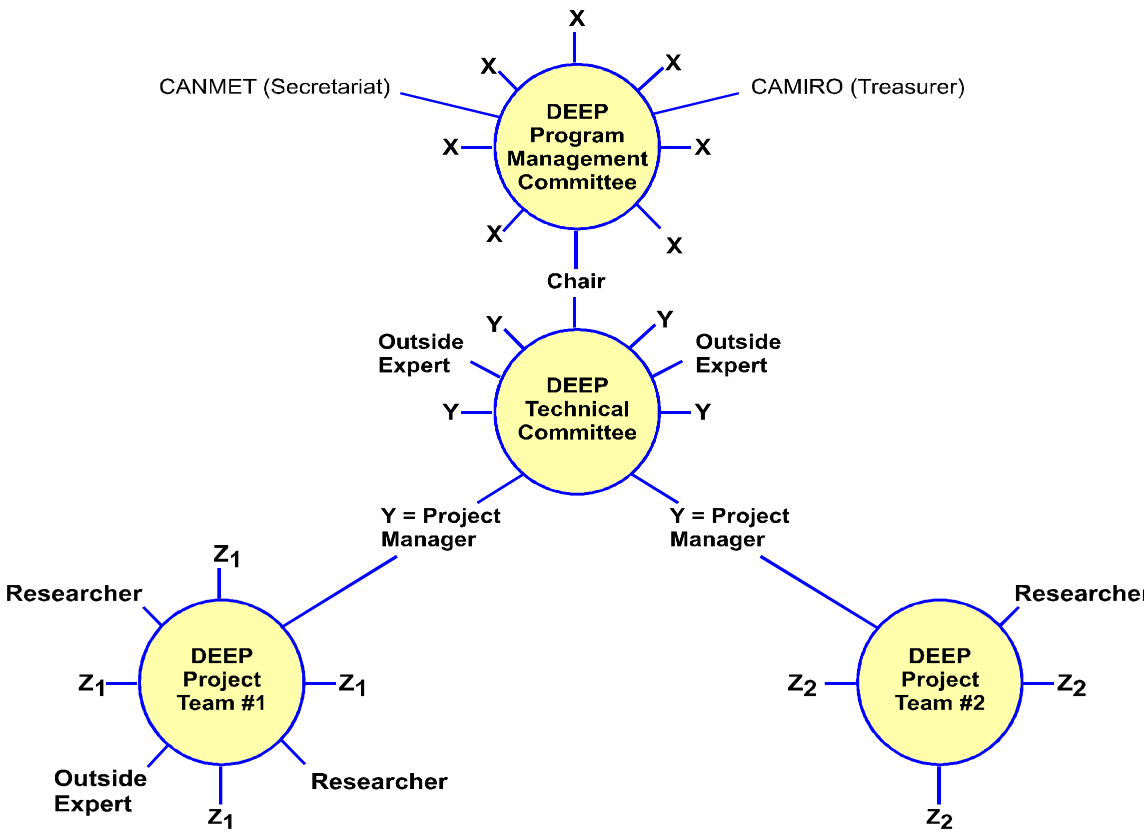


Figure 1. *DEEP Management Structure*

The above structure of the Consortium was outlined in the DEEP Memorandum of Understanding (Appendix A), which also covered:

- Management Board representation, chair and vice-chair
- DEEP Treasurer (CAMIRO)
- DEEP Secretary (CANMET-MMSL)
- Technical Committee: representation and roles
- Project teams: roles and leaders
- Funding policy
- Contracting policy

- Intellectual property agreement

Scope of Research. The major elements of the DEEP philosophy can be summarized as follows:

- There must be collaboration between researchers
- Labour and government must be full partners in the planning, execution and interpretation of projects
- Specific interests of certain mines will be taken into account
- Technology transfer and training of industry personnel in the field is a key benefit

It was also emphasized that DEEP would not fund or conduct research on the health effects of diesel particulate matter.

From the beginning of the program, DEEP activities were coordinated with the relevant European research. In May 1997, DEEP (J. Stachulak and B. Howell) made contact with Dr. Dirk Dahmann of Germany to discuss developments and perspectives on elemental carbon analysis, regulatory limits, and German approaches to control of DPM. At a later time, cooperation was started with the Swiss VERT program, which was focused on the reduction of DPM exposure in tunnel construction.

A three year plan of the program—covering the period from 1 April 1997 to 31 March 2000—was adopted in August 1997. The DEEP explicit working objectives were described as follows:

1. DEEP seeks reliable, economic means of reducing DPM levels in non-coal mines to intermediate levels (0.3 mg/m^3) and target levels (0.15 mg/m^3) suggested by regulatory or reference groups without causing undue increases in other diesel emissions.
2. The implementation pathways for an effective and economic reduction of DPM to target levels should be developed and confirmed for selected mine sites. A guideline for reducing DPM at other operations that accounts for local conditions, should also be developed based on the experience with DEEP.
3. Sampling/analytical techniques will be verified as to their operational, maintenance and bench test suitability for the target DPM levels under a variety of mine environments that may pose special interferences, and in the context of their suitability for a potential 0.15 mg/m^3 regulatory standard. This implies that accuracy of 0.0015 mg/m^3 is the target and 0.05 mg/m^3 is the minimum acceptable performance of sampling/analysis techniques.
4. The ability to distinguish oil mist from DPM is an objective, but only as long as the Elemental Carbon approach is NOT adapted.
5. Results of the previous working objectives are to be disseminated throughout the Canadian mining community, with a minor emphasis on exchanges with international organizations and mining operations.

DEEP project priorities were defined by a special planning group meeting:

1. Measurement Methodologies Program Area
    a) Comparison of existing measurement methods for DPM—RCD/SS/EC
    b) Identify the effects of potential interferences on RCD/SS/EC
    c) Differentiation of oil mist and DPM in the U/G environment
    d) Real time monitoring of DPM exposure levels
    e) Evaluate or develop new methods of determining DPM
    f) Non-mass characterization of DPM

2. Emissions Reduction Program Area
    a) Engine maintenance

b) System integration/combination/control strategies
c) Engine technology
d) Operating practices
e) Alternative fuels, conventional fuel upgrading
f) Ventilation
g) Aftertreatment devices
h) Awareness of new technologies

3. Measurement Use Program Area
   a) Data banking—industry-wide emissions information for inter-operation benchmarking
   b) Development of a standard evaluation tool/approach for underground environment baselining and data banking
   c) Baselining—collection of information clearly describing the current state of an operation in order to assess the impact of changes

Fundraising. The total funding of the DEEP program over its entire duration amounted to $2.5 million. The sources of funding are illustrated in Figure 2. Relative DEEP expenditures on the particular research projects are shown in Figure 3.

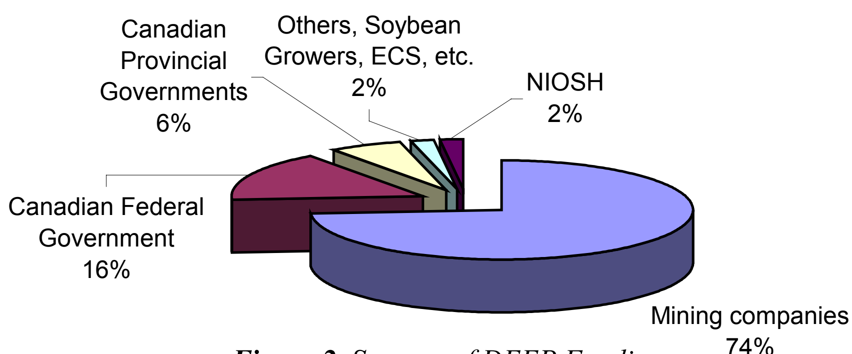


***Figure 2**. Sources of DEEP Funding*

2 DEEP Research Projects

2.1 Summary of Projects

Over the duration of the DEEP program, 8 research projects (out of 24 that were under consideration) have been accepted and completed. The list of all projects, completed or not, is given in Table 1. Projects that were accepted and received DEEP funding are listed in **bold typeface**.

Table 1. DEEP Research Projects

Project	Investigator	Comments
Mine Air Quality Impact of Low Emissions Engines	INCO, UMN	Pilot project completed in 1996, not funded under DEEP
Evaluation of Biodiesel Fuel and a Diesel Oxidation Catalyst in an Underground Metal Mine	UMN, INCO at INCO Creighton mine	Completed in 1998
Evaluation of Existing Diesel Particulate Matter Sampling and Analysis Methods at a High Sulphide Ore Mine	CANMET-MMSL at Noranda mine	Completed in 2000
Sampling in High Graphite Mines	HBMS	Not accepted
Impact of Diesel Fuel Quality on Emissions	ESI International	Not Accepted
Diesel Particulate Characterization	NIOSH	Not Accepted
The Relationship Between Diesel Engine Maintenance and Exhaust Emissions	Noranda	Completed in 2002
Laboratory Evaluation of Control Technologies	CANMET-MMSL	Not Accepted
A-55 Water Emulsion Fuel	Noranda	Not Accepted
Fluorescence Technique for Oil Mist Determination	Ortech	Not Accepted
Contribution of Light-Duty Vehicles to the Underground Atmosphere Diesel Emissions Burden	CANMET-MMSL at Falconbridge Kidd Creek mine	Completed in 2005
Canadian RCD Database	CANMET-MMSL	Not Accepted
PAH Content of Commercial Pneumatic Oils	CANMET-MMSL	Not Accepted
Methodologies for Monitoring	Ortech	Not Accepted
Diesel Particulate Matter Sampling Methods: Statistical Comparison	UMN	Completed in 2000
Characterization of Diesel Emissions	Health Canada	Not Accepted
Fuel Ionization Catalyst	Comtec	Not Accepted
Ceramic Engine Coatings	CAMIRO	Not Accepted

Project	Investigator	Comments
Review of DPM Control Strategies for Underground Mines	ESI International	Completed in 1999
Diesel Fuel Additives	Carvern Petrochemical	Not Accepted
Emissions Control Strategies	Ecopoint	Not Accepted
Flameless Thermal Oxidation	Thermatrix	Not Accepted
Noranda Brunswick Mine DPF Field Study	Noranda	Completed in 2004
Evaluation of Diesel Particulate Filter Systems at Stobie Mine	INCO	Completed in 2006

The two largest DEEP projects—consuming a combined 47% of DEEP budget—included the evaluation of diesel particulate filter technologies at Noranda and INCO mines. The allocation of DEEP funding to all research projects is schematically shown in Figure 3.

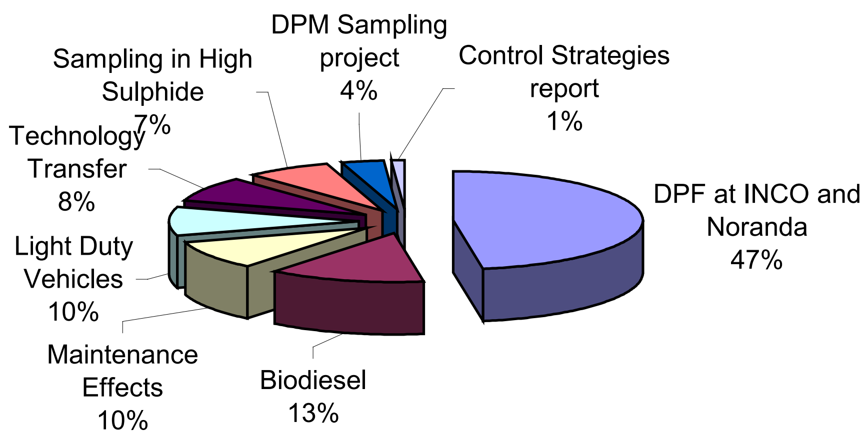


***Figure 3**. DEEP Expenditures*

The most important research projects funded by DEEP are discussed in the following sections. The reader is also referred to the 'plain language' 2-page summaries (generated under the Technology Transfer program) of all DEEP projects and their results, which can be found in the CD-ROM accompanying this report.

2.2 Evaluation of Biodiesel Fuel and a Diesel Oxidation Catalyst in an Underground Metal Mine

This project was a pilot study that evolved during the formation of DEEP. It was approved for funding in May 1997, started in October 1997, and was completed in September 1998. Researchers from the UMN, INCO, CANMET-MMSL, Michigan Technological University, ORTECH, and NIOSH participated in the project. The experimental work was conducted in a non-producing section of the INCO's Creighton Mine in Sudbury, ON.

The objectives of the project were:

1. Measure changes in exhaust emissions, especially DPM, from a test vehicle equipped with a diesel oxidation catalyst (DOC) when operated on a blended biodiesel fuel in a test section of an underground mine.
2. Estimate costs of operating a test vehicle fueled with blended biodiesel fuel.

The field evaluation was conducted in two one-week long phases. During the first week, a diesel-powered LHD 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 fuel. During both weeks the LHD was equipped with a pair of identical DOCs.

The results of the study were detailed in three reports. The primary report summarized the body of data collected to evaluate the difference in gaseous and particulate matter concentrations attributed to the biodiesel and the D2 fuels used in conjunction with the DOCs. Two other reports summarized results associated with the chemical composition and mutagenicity of the collected samples.

Three methods were used to assess in-mine concentrations of DPM: the SS method, the RCD method and EC method. Continuous monitoring instrumentation was used to determine NO, NO_2, CO, CO_2 and SO_2 concentrations. Samples were also collected to determine gas and particle bound polycyclic aromatic hydrocarbons (PAH), and the particle phase mutagenicity.

The scooptram engine was instrumented to obtain fuel consumption and power data. Engine exhaust emissions were tested using the emissions assisted maintenance procedure (EAMP).

When DPM data were normalized on a brake specific basis, the combination of the blended biodiesel fuel and DOCs was shown to decrease total carbon emissions by 21.4 ± 0.98%. Elemental Carbon was reduced by 28.6 ± 0.87%, and organic carbon (OC) was reduced 6.0 ± 3.32%. The OC reduction was not statistically significant. There was a slight increase in NO_2 concentration and a corresponding decrease in NO concentration. Both were found to be statistically insignificant. Mutagenicity was reduced by about 75% and although large reductions were measured for PAH compounds only reductions for pyrene were statistically significant due to large day-to-day variation.

The study concluded that blended biodiesel fuel used in conjunction with a modern DOC offered a passive control option to reduce DPM in an underground mine, concluded the study. The primary limitation to the use of biodiesel fuel was its cost. In 1997, the typical cost of biodiesel fuel ranged from $3.00 - $3.50/gal. A 50 % blended biodiesel fuel would range in cost from $2.00 to $2.25/gal assuming a cost of $1/gal for D2 (US$ and US costs). It is likely that increased production of a renewable energy sources, such as biodiesel, will lower costs and allow biodiesel fuel to become a more viable DPM control option for underground mines in the future.

The most important benefits of the biodiesel project were:

1. It was the second project ever to evaluate the use of biodiesel fuel in a North American underground mine, and the first of its type in a Canadian mine. Since 1997 the U.S. MSHA and NIOSH have collaborated with the U.S. mining industry to conduct similar pilot studies. Several U.S. mines use 100% biodiesel fuel or a blended biodiesel fuel on a regular basis. Successful demonstration projects such as these, combined with economic incentives, can assist in the introduction of new technologies that can improve the mine environment.
2. Results from this project and other projects that used a variety of methods to assess DPM levels in metal and non-metal mines contributed to the decision by the U.S. MSHA to adopt the EC method as the basis for regulating DPM concentrations underground.

A significant technical challenge in conducting the project was to analyze the emission data on a brake specific basis. On a electronically controlled engines, with electronic control modules (ECM), this was a relatively simple task. However, on vehicles with mechanical engines that took part in the project, this task proved to be more difficult than anticipated.

From today's perspective, the project could have been expanded and/or improved in a number of ways:

- A complete test matrix would have included the evaluation of each fuel with and without a DOC to apportion and compare the results between fuels and the DOCs. Due to cost restraints only one day of testing was done without the DOCs. A better protocol would have allowed for one week of testing for each of the four test conditions.
- Early consultation with a statistician would have improved the project plan and assisted in data analysis. It would have been very useful to have a consulting statistician available on the steering committee.
- Routine and advanced methods for monitoring exhaust constituents were combined in the project. Including additional measurements allows for a better evaluation and helps to ensure that no new known hazardous substances are introduced into the mine environment with the introduction of new emission control technology. However, it also adds to the complexity making it more important to limit the influence of uncontrolled variables. In the future, a consideration should be given to conducting this type of test in an underground mine with a dedicated, isolated zone used only for research purposes, and supported by a consortium of mining companies and government institutions.

2.3 Evaluation of Existing Diesel Particulate Matter Sampling and Analysis Methods at a High Sulphide Ore Mine

This project was one of the two pilot initiatives that were proposed in July 1996, before the actual formation of the DEEP Consortium and its management structure. It was approved by the DEEP Management Board in February 1997. The study was performed by CANMET at Noranda's Brunswick Mine in Bathurst, NB, and was completed in December 1998.

The study had three objectives:

1. To evaluate the three analytical methods—including respirable combustible dust (RCD), size-selective sampling (SS) and the thermal-optical method —available at the time to measure the exposure of miners to diesel particulate matter.
2. To investigate the potential interference of airborne sulphide dust in the ashing process used in the RCD method.
3. To provide additional RCD (DPM) exposure data for Brunswick mine personnel.

The RCD method is a simple ashing process where dust samples collected on silver membrane filters are placed in a furnace at 400˚C for a period of 2 hours. The mass loss on ashing is the RCD mass and is a measure of exposure to DPM.

The SS method uses a pre-separator downstream of a 10-mm nylon cyclone to remove dust larger than 0.8 micron in diameter. The mass of DPM in this case is also obtained gravimetrically.

The thermal-optical method (also referred to as the EC method) is a newer, two-stage process, where the sample is submitted to high temperatures under oxygen-free and oxygen-rich atmospheres to determine the amount of organic carbon (OC) and elemental carbon (EC) respectively. This technique has been standardized by NIOSH as the 5040 method.

In the first phase of the project, the three methods were compared under conditions where mineral dust was suppressed as much as possible during a simulated load-haul-dump cycle. In the second phase, in order to evaluate the impact of ore-borne sulphide components, the same process was repeated while handling dry, high-sulphide ore. The number of samples and repeat tests were optimized in order to support a statistical analysis of results. Variable-pressure scanning electron microscopy (VP-SEM), thermogravimetric (TG) analysis, differential thermal analysis (DTA) and Fourier transform infrared (FTIR) analysis were used to investigate the impact of sulphide ore dust on the RCD method.

The study showed that the RCD and SS methods compared favourably with the more precise and accurate thermal-optical method. The RCD method was found to be adequate for higher concentration DPM measurements. For regulatory purposes, the RCD method could support legislation where DPM exposure would be limited to 0.6 mg/m^3 or above. Below this limit, alternatives such as the thermal-optical methods are strongly suggested.

The oxidation of sulphides to sulphates during the RCD ashing process could not be linked directly to interference during the analysis. The original hypothesis was that mass increases in the sulphide portion during oxidation could counter mass losses of the organic and elemental portion during ashing. TG and DTA analysis showed that SO_2 emanations and subsequent interaction with the silver from the filter used in the RCD method caused a definite mass increase of the silver membrane filter. The source of the SO_2 could be the sulphide ore or even the organo-sulphates found in the diesel fuel.

The study concluded that using a small pore-size silver membrane filter (0.8 micron) limited the amount of mineral dust and DPM which collected inside the filter matrix, thereby reducing the interaction between evolved SO_2 and the silver in the filter, and reducing the chance of mass increases of the actual filter membrane.

The project recommendations were:

1. The RCD method was still appropriate to measure exposure to DPM.
2. As workplace DPM concentrations decrease, gravimetric approaches such as the RCD and SS methods will have to be replaced by the thermal-optical method.
3. For concentrations less than 0.3 mg/m^3 (legislated limits of exposure of less than 0.6 mg/m^3) the gravimetric methods should not be used.
4. For the RCD method, the use of smaller pore-size silver membrane filters are recommended as they seem to reduce the mass gains associated with the interaction of evolved SO_2 with the silver in the filter.

The significance and the major benefits of the project were:

- It was one of the first projects to compare the RCD method commonly used in Canada to a possible new and improved method. As such it served to make the mining industry aware of the alternative thermal-optical method.
- The knowledge acquired in the study was used in the development of more progressive regulations in Canadian provinces.

The most significant challenge in conducting the project was to coordinate the different research teams and applying/adapting the selected analytical tools (VP-SEM, TG, DTA and FTIR) to the experimental conditions and requirements.

After completing the project, the following improvements have been suggested:

1. More scrutiny on the chemical and physical processes that take place during ashing of sulphide ores would have been useful.
2. More time and more samples, as well as better initial planning in regards to data collection would have helped with the statistical analysis.

2.4 Diesel Particulate Matter Sampling Methods: Statistical Comparison

The project, the University of Minnesota—was proposed in September 1998, approved in November 1998, and completed in August 2000. Based on the final DEEP report, a paper was published in the June 2003 issue of the American Industrial Hygiene Association Journal.

Three sampling methods used in mines to determine the DPM concentration were investigated: the size selective (SS) method, the respirable combustible dust (RCD) method, and the elemental carbon (EC) method. The objectives of the project were:

1. To review existing information on interferences, sampling and analytical biases, limits of detection, and other limitations of the existing methods for measuring DPM concentrations;
2. To assemble available data and compare the methods with respect to their specificity, sensitivity and detection limits, and accuracy;
3. To recommend appropriate conditions for and uses of each method, and to identify needs for further research.

DPM consists of nonvolatile carbon, EC, adsorbed or condensed hydrocarbons referred to as organic carbon (OC), sulfates, and trace quantities of metallic compounds. Total carbon (TC) includes both the elemental and organic carbon, EC + OC.

Each of the sampling and analytical methods that are most commonly used to determine DPM concentrations in the workplace measures only a portion of the overall DPM exposure:

- RCD is composed of all combustible materials collected on a filter, including non-diesel OC, thus only a portion of RCD is attributable to diesel exhaust aerosol.
- The SS method utilizes particle size as the basis for separating diesel from non-diesel aerosol. However, the method is subject to interferences from the collection of non-diesel submicrometer particles.
- EC is a product of combustion and is considered a specific marker of DPM in many occupational settings where other combustion aerosols are not present. However, as in the RCD method, the OC portion of the aerosol is subject to interferences from OC from non-diesel sources.

Replicated simultaneous samples of DPM aerosols using the above methods have been gathered as part of research projects conducted for various purposes. Data were assembled from three of these studies to statistically compare these methods. This constituted a meta-analysis of the available data and provided information over a broader range of mining conditions and DPM concentrations than any of the individual studies.

The variability in weighing associated with the SS method was found to be almost twice that of the RCD technique. The imprecision of the EC-TC method was a function of the mass loading, and EC had a lower imprecision than TC. The RCD, SS, and EC-TC methods exhibited substantial levels of interference, leading to much higher minimum concentrations that could be measured by these methods. Of the three, the SS method had the highest level of interference, primarily from non-diesel submicron material.

The following lower concentrations were recommended for each method: RCD = 100 $\mu g/m^3$, SS = 200 $\mu g/m^3$, and TC = 100 $\mu g/m^3$. These were determined by adding the maximum estimated interference + the lower limit of detection + a 25 % error factor and rounding upward to the nearest 100 µg.

The study concluded that the most sensitive and specific marker of DPM was EC, but TC provided the best estimate of total DPM exposure (because EC accounts for only about 50% of the total DPM). However, unless care is taken to correct the OC measurement for non-diesel sources by including the use of dynamic blank samples to determine the OC adsorbed by the filter, the OC carbon and subsequent TC measurements will be inflated.

2.5 Contribution of Light-Duty Vehicles to the Underground Atmosphere Diesel Emissions Burden

The DEEP light-duty vehicle study was conducted at the Falconbridge Kidd Creek Mine, a copper/zinc operation located in Timmins, Ontario, Canada.

The study was conducted by the CANMET-MMSL Laboratories in cooperation with the mine operator, Falconbridge Limited. A detailed description of the study is available in two documents:

- Phase I Report, completed in 2000
- Final Report (Phase II), completed in 2003

The objective of the study was to estimate the relative contributions of DPM exhaust emission from LD and HD vehicles in an underground metal mine. This was achieved through direct DPM emission measurement from a sample group of LD and HD vehicles and extrapolation of the results onto the entire diesel vehicle population in the mine.

The study was divided into two phases. Issues examined during Phase I included mine selection and selection criteria, characterization of the mine's diesel fleet, duty cycle assessment method, raw exhaust DPM sampling issues and determination of the cross-section of the fleet to be tested during Phase II.

The Phase II—covering the actual field study—was further divided into two parts. Part one focused on DPM sampling from five HD vehicles. Part two focused on DPM measurement from eight LD vehicles.

In the study, vehicles (regardless of horsepower) that were not used in regular production cycles were categorized as LD units. Higher horsepower units involved regularly in ore, waste or fill handling were considered HD vehicles.

The Kidd Mine diesel equipment fleet is comprised of 156 underground vehicles. It was technically feasible to test a mixed LD/HD sample fleet of vehicles representing about 10% of the entire fleet.

Perhaps the most important task in the study was to determine the amount of DPM produced by selected diesel vehicles over a specified sampling period and, indeed, during a full-shift period. The mass of DPM produced during the sampling period was calculated as the product of the exhaust DPM concentration—as measured by the DPM sampling apparatus—and the total exhaust gas volume produced over the sampling period.

Vehicle duty cycles were also evaluated in the study to provide insight into the utilization for each vehicle and vehicle type. On electronically controlled engines (such as those in all tested HD vehicles), the percent engine load was recorded from the engine control unit data stream. In mechanically controlled engines (such as in most of the tested LD vehicles), duty cycle data was determined based on the engine speed, exhaust gas flow and temperature.

At the beginning of each testing day, CANMET personnel installed the in-exhaust DPM sampling system, data loggers and ambient DPM and dust monitors on each tested vehicle. Each operator wore a personal sampling pump for NIOSH 5040 analysis of total/elemental carbon exposure. The vehicle would then proceed to its normal working area to perform its normal duties during the shift. The duty cycle would be interrupted briefly (1-2 minutes) to change the DPM sample filter as required. After a sufficient number of duty cycles were recorded, the vehicle would return to the shop area where the sampling system was removed.

The results of the study clearly showed that the LD contribution to DPM exposures was significant. In one instance, a 27 hp tractor with suspected engine problems produced as much DPM as an 8-yard LHD with approximately 300 hp.

The sample fleet results were extrapolated, taking a number of assumptions, onto the entire underground vehicle fleet in the mine. Based on the equipment utilization rates (in hrs/yr), DPM burdens was calculated (in kg/yr) for each vehicle type. The relative contributions from different vehicle categories are shown in the following chart.

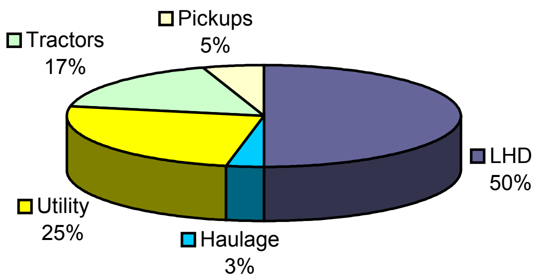


Figure 4. DPM Sources at Kidd Creek Mine

For the entire model fleet, HD vehicles (LHDs and haulage trucks) were responsible for 53% of the total underground DPM burden. LD vehicle (tractors, pickups, utility) were responsible for 47% of the DPM burden.

The study concluded that the underground DPM burden was fairly evenly split between the HD and LD vehicles. While LHDs remained major DPM emitters, LD contribution accounted for nearly half of DPM emission, due to high vehicle numbers and—in some cases—high emission rates. Therefore, LD vehicles must be a part of any DPM control strategy.

2.6 The Relationship Between Diesel Engine Maintenance and Exhaust Emissions

The project was performed by a team from Noranda Technology Centre, Pointe Claire, Quebec. Project objectives included developing a model for auditing mine maintenance procedures and facilities, a guideline for good maintenance practice with emphasis on reducing emissions, implementing good maintenance practice in a mine, and evaluating its effects on diesel emissions. The implementation and evaluation were conducted in Falconbridge's Strathcona Mine in Sudbury, Ontario.

Three documents were developed during the project and submitted to DEEP in 2000:

- Diesel Engine Maintenance Audit Plan,
- Maintenance Guidelines and Best Practices for Diesel Engines in Underground Mining,
- Final Report.

Special emphasis should be put on the "Maintenance Guidelines" document, which has been designed as a practical tool to educate and train mine personnel on the importance of maintenance for reducing diesel emissions.

To accomplish the project objectives, the project plan was broken into five stages, as follows:

1. Preparation of an audit model for engine maintenance operations; application of the audit at two mine sites; selection of a host site for the project;
2. Development of guidelines and best practices for engine maintenance to reduce diesel emissions;
3. Emissions testing to acquire baseline emission values for mobile equipment included in the study;
4. Implementation of improved engine maintenance strategy through changes to process, tools and training;
5. Analysis of the impact of improved maintenance practices on emissions and formulation of recommendations resulting from fieldwork.

Diesel Engine Maintenance Audit Plan. Building on an existing health and safety audit framework, the researchers developed a model for auditing mine site diesel engine maintenance. The audit protocol was based on previous research, which identified the six diesel engine systems that most affect emissions. It allowed the researchers to evaluate both scheduled and unscheduled maintenance activities. The completed model was tested at two mine sites, and the results of the audit reviewed with mine personnel at both sites. The audits allowed the researchers to identify problems in maintenance facilities and practices that could give rise to increased diesel emissions, and also helped identify a good candidate site for implementing and evaluating an improved maintenance program. Mine personnel at the host site agreed that the audit process was effective in identifying strengths and weaknesses in their maintenance program.

From the two mines that were audited, Strathcona Mine was ultimately selected as the host site for the project.

Maintenance Guidelines and Best Practices. A five person panel, including technical personnel from the diesel engine industry, mine maintenance staff and diesel emissions researchers, was recruited to work together to construct guidelines for ensuring that maintenance practices were effective in reducing diesel emissions. The panel drew from a combination of previous research, proprietary reference materials, personal and industry experience.

The guide is divided into two categories: (1) operational issues which cover the general practices of both mechanics and operators concerning diesel engines; (2) the system specific section which recommends best practices for maintaining the six primary engine systems that affect diesel emissions, including:

- Intake system – evaluating the installation and sizing of intake system components; testing and maintaining piping, filter housing, gaskets, connections and seals; installation of appropriate gauges; appropriate servicing intervals; detection and correction of problems.
- Exhaust system – monitoring exhaust backpressure and emissions; evaluating installation and damage of exhaust system components; monitoring the condition and performance of aftertreatment devices.
- Fuel Injection System – diagnosing problems; scheduling checks of primary fuel pressure; selecting and examining filters; verifying air/fuel ratio; checking fuel temperature and air in fuel; using filtered vents on fuel tanks; adjustment and replacement of components.
- Cooling System – scheduling maintenance and cleaning of cooling systems; important service practices; verifying operating condition of gauges and alarm sensors; diagnosing and correcting problems.
- Fuel Quality and Handling – proper storage, transfer of fuels, filtration and cleanliness.
- Lubrication System – operation fundamentals, oil and filter service practices, and used oil analysis techniques.

Emissions testing equipment used in the study consisted of a gaseous emissions test system from Noranda Technology Centre called the Undiluted Gas Analysis System (UGAS) and a particulate emissions test system from CANMET-MMSL called the Undiluted Particulate Sampling System (UPSS). The two systems were situated on a maintenance shop floor in the mine as a tool for mechanics.

The equipment was first used to collect data on emissions before the new maintenance program was initiated. In total 16 mechanics were trained to use the equipment, and 13 vehicles were tested over the baseline stage of 3 months.

Mechanics were trained in the improved maintenance process. Afterwards, its effectiveness was evaluated by conducting case studies on four vehicles. For each vehicle, emissions were measured at the start of the day, before any changes or maintenance activity. Then improved maintenance procedures were applied. Emissions were measured again when the vehicle was ready to return to work.

Results from the case studies showed that gaseous and particulate emissions could be significantly reduced through maintenance procedures. Emission reductions of up to 65% were demonstrated for gases (CO), and up to 55% for DPM.

The following recommendations for improved diesel engine maintenance were made in the study's Final Report:

- Build a team focused on implementing an improved maintenance strategy. Team members should include mechanics, operators, supervision, planning, and management from the mine. Ensure that sufficient time, tools, and training resources are available to the team.
- Construct an engine maintenance audit program. The model provided by the study could serve as a template. The audit should be conducted at least once per year.
- Create and implement a strategy for improving existing maintenance practices to reduce diesel emissions, drawing on the Maintenance Guidelines and Best Practices.
- Test undiluted tailpipe emissions on underground vehicles. Set action limits on emissions to ensure an adequate response to problems. Establish clear action requirements once action limits are reached.
- Make use of the suppliers of diesel engines and related equipment for training and updating maintenance personnel. Suppliers improve their relationships with mine staff by working with them hands-on to find solutions to problems, as described in the case studies for this project.

Since 2001, the recommendations and maintenance practices based on this project have been adopted by several mining companies in Canada, United States and Australia, including BHP Billiton which is the largest mining company in the world with more than 100 operations worldwide. Feedback from operations following this methodology indicates that the emissions reduction potential is as high as what was demonstrated during the project at Strathcona.

The most significant challenges in completing the project included:

- Finding the site to conduct the research
- Conducting the project activities at the site for 8 months amidst regular production and maintenance priorities
- Obtaining project approval and conducting it despite some opposition and doubt as to the value of this research

Suggested modifications and improvements of this project included:

- A parallel study on ambient DPM concentrations with both personal and area sampling to attempt to correlate the engine maintenance emissions reductions and ambient concentrations
- Investing more time and resources on the raw DPM sampling unit
- Streamlining of both the project proposal and final reporting stages—even with the tri-partite nature of the consortium the proposal and final report phases should have gone a lot smoother and quicker than they did
- Better communication—the only knowledge that the site team and the DEEP technical committee had of each other was what was communicated or reported to each by the project manager.

2.7 Noranda Brunswick Mine DPF Field Study

The Brunswick Mine Diesel Particulate Filter Study was one of the final DEEP projects. It was conducted at Noranda's Brunswick Mine in Bathurst, NB by Noranda crews with the cooperation of CANMET-MMSL, NIOSH, VERT, and particulate filter suppliers.

The study was started in early 2000. Field evaluations continued for 20 months. The final report was submitted to DEEP in the autumn of 2003.

The objective of the Noranda's Brunswick Mine project was to determine the effectiveness and economic maintainability of current generation DPF technologies as applied to underground mining operations.

The project team selected four heavy production vehicles to be tested with DPFs over a period of 4000 hours. Two of the vehicles were ST8-B scooptrams—vehicles that operate as front-end loaders to dig into a pile of ore, tram the load over a distance, dump it to a transfer point, and return to the load point to repeat the cycle. The other two vehicles were MT436-B haulage trucks—machines designed to haul large loads over longer distances, typically loaded either by an LHD or at an overhead chute. All four vehicles were powered by electronically controlled DDC Series 60 engines rated at 242 kW (325 hp) in scooptrams and at 278 kW (375 hp) in trucks.

Request for proposals was submitted to particulate filter manufacturers, which included detailed descriptions of the vehicles and their duty cycles, including recordings of exhaust gas temperatures. Based on this information, the emission control manufacturers produced proposals for particulate filter systems for each application. The filter systems finally chosen for the project were:

- ECS catalyzed passive DPF (ST8-B Scooptram)
- ECS/Unikat fuel additive based passive system (MT436-B Truck)
- DCL catalyzed filter w/electric heater (ST8-B Scooptram)
- Oberland Mangold glassfiber filter w/fuel additives (MT436-B Truck)

Performances of the DPF systems during the project were evaluated by:

1. Qualitative feedback information, logged from vehicle operators, mechanics, maintenance crew, and mine management, and
2. Quantitative measurements, including (1) raw exhaust emissions, (2) ambient concentrations of pollutants, and (3) vehicle and DPF operating statistics.

Instruments and methods were developed to accommodate the day to day monitoring, as well as more precise scientific evaluations done at regular intervals. Three instrument setups were used through the project for measuring undiluted emissions, mostly based on the Ecom gas analyzer (electrochemical measuring cells) and the NanoMet diesel particulate characterization system—an instrument incorporating a diffusion charger (DC) and a photoelectric aerosol (PAS) sensor.

Sampling and analysis was also conducted through the project for ambient concentrations of diesel particulate matter. The samples were taken with both the Respirable Combustible Dust (RCD) method and the NIOSH 5040 method for organic and elemental carbon.

The DPF systems were monitored for basic operating statistics. The engine control modules (ECM) provided data for actual operating hours, fuel consumption, idling hours, and operating profiles with engine rpm and load versus time. In addition, datalogging of exhaust temperature and filter pressure drop were performed to evaluate DPF regeneration.

The experience with the DPF systems can be summarized as follows:

- **ECS Catalyzed Filter:** The ECS filter was a fully passive system utilizing a cordierite wall-flow monolith coated with a base metal catalyst. This filter performed well in all aspects (emissions, regeneration) during the study. It accumulated a total of 4053 operating hours.
- **ECS (Unikat) Filter with Fuel Additive:** The Unikat filter utilized two parallel silicon carbide (SiC) substrates with oxidation catalysts in the upstream position. The filter was passively regenerated using Octimax 4804 iron/strontium (Fe/Sr) based fuel additive by Octel. The additive was blended to the fuel in a separate fueling system maintained for vehicles with additive-assisted DPFs. The concentration of metals in the fuel was 20 ppm, with a 16:4 Fe:Sr ratio. After an initial period of satisfactory operation, this filter started building excessive pressure drop due to slow regeneration, despite high exhaust gas temperatures. After some time the filter substrate failed due to uncontrolled regeneration of the overloaded filter. A replacement unit was also damaged due to uncontrolled regeneration. The first filter unit performed over 2500 hours, the second unit over 1620 hours.
- **DCL Catalyzed/Electric Filter:** The DCL filter utilized platinum-catalyzed SiC substrate, as well as a 600 V electric heater at the inlet face of the filter. In order to regenerate with the electrical heating system, it was planned that the vehicle would be brought to the shop and connected to shore power and a source of compressed air at the end of each shift (an inconvenient requirement opposed by the mine crew). Initially, the electrical regeneration system caused considerable technical and safety (electrical fault) problems. As became apparent during the project, the filter was able to passively regenerate due to the Pt catalyst. The electrical regeneration system was thus deemed redundant. The filter system performed well over 4260 hours.
- **Oberland Fiber Filter with Fuel Additive:** This filter utilized cartridges with knitted fiberglass filter media. Filter regeneration was facilitated using the same Fe/Sr fuel additive (and vehicle fueling system) as used in the Unikat filter. The first version of the filter was undersized, causing backpressure problems. After it was replaced by a larger unit, the filter performed well. The biggest problem with this system was perhaps the large geometrical size of the unit, making it difficult to install on vehicle. The manufacturer has since abandoned the fiber cartridge design, and so the experience has mostly historical significance.

The project demonstrated that all tested DPFs were able to provide over 90% reduction in the PM mass emissions, as well as reductions in other emissions and in ambient PM exposures.

It was emphasized that the DPF selection process is the most critical factor in successful implementation. Current DPF technology is not yet ready to offer off-the-shelf solutions. Careful application engineering is needed to ensure that every individual vehicle and its duty cycle are properly matched with the after-treatment technology.

The final report contains a wealth of conclusions and recommendations on underground application of DPF systems. Ultimately, the success in implementing DPF technology in an underground mine may have less to do with which system is chosen and more to do with the process and team that a mine puts together in selecting, installing, measuring, maintaining, and verifying the systems.

The significance and main benefits of this project include the following:

- Since 2002 Brunswick Mine has been steadily increasing the use of DPF systems on its LHD fleet which now has 14 out 18 units equipped with the ECS Cattrap passive DPF system. These systems are engineered and installed by the vehicle manufacturer at the time of complete remanufacturingat their facility
- Two of the four prototype DPFs used in the project have since become successful commercial systems
- The success of the Isolated Zone Study was used as a template by NIOSH for several subsequent Isozone studies done throughout the U.S.

The most significant challenges in conducting the project were:

- To maintain the collaboration of the many organizations and parties involved over the duration of the project
- Sustaining the early momentum of the project through 20 months of field testing

2.8 Evaluation of Diesel Particulate Filter Systems at Stobie Mine

This study was the final DEEP project. It was conducted at Inco's Stobie Mine in Sudbury, ON from April 2000 to December 2004. The final report was submitted to DEEP in March 2006.

The study was conducted by a team of Stobie Mine personnel with the participation of VERT, NIOSH, and CANMET.

The objective of the Stobie Mine Diesel Particulate Filter Study was to investigate the long-term effectiveness of DPF systems on a variety of underground vehicles operated in harsh physical environments.

Five heavy duty load-haul-dump (LHD) vehicles were selected as representing the primary heavy-duty workhorse in underground mining. One of these units had a dual exhaust Deutz engine, and four had Detroit Diesel DDEC 60 engines. Four Kubota tractors were selected, which were representative of light-duty vehicles used for transporting mine personnel. DPF systems on light-duty underground vehicles had not been studied anywhere at the time the Stobie project was started.

The duty cycles of the candidate vehicles were monitored for six months prior to selecting the DPFs for testing. Temperature sensors were installed in the exhaust manifolds, and signals were recorded by dataloggers mounted on the vehicles. The data obtained for each vehicle were analyzed to judge whether the engine exhaust temperature was sufficiently high to oxidize the soot captured in the filter and sustain passive DPF regeneration, or else if active DPF systems were needed, where the captured soot would be burned by supplying additional heat.

Surprisingly, the results showed that heavy-duty vehicles did not routinely achieve high enough exhaust temperatures to fully regenerate passive filters. Hence, both passive and active DPF systems were required for the LHDs. Data on light-duty vehicles clearly showed the need for active regeneration. The final choice of DPFs included a mix of active and passive systems from Engelhard, ECS, Johnson Matthey, ArvinMeritor, Oberland, and DCL.

The filters were evaluated through periodic tests which were conducted every 250 hours of vehicle operation for heavy-duty machines and monthly for light-duty vehicles. During these tests, a portable ECOM emission analyzer was used to determine exhaust concentrations of NO,

NO_2, CO, CO_2 and O_2, and to measure Bacharach smoke numbers upstream and downstream of the DPF.

Three more extensive testing periods were conducted during the summers of 2001, 2002, and 2004. These tests—performed under three reproducible steady-state engine operating conditions—involved the measurement of gas concentrations and smoke numbers upstream and downstream of the filters, particulate concentrations using a photoelectric aerosol analyzer, particle size distribution using a Scanning Mobility Particle Sizer, and exhaust opacity.

In addition to exhaust gas measurements, industrial hygiene (ambient air) measurements were performed in the vicinity of selected test vehicles before and after DPF installation. Samples were collected for RCD analysis, and elemental carbon analysis at three different location relative to the vehicle. The results showed a reduction in elemental carbon exposures when filters were used, but the test parameters were not designed to support statistically sound conclusions.

The following is a summary of the DPF specific results:

- **Engelhard Catalyzed Filter (LHD Vehicle):** This passively regenerated filter was operated with no apparent problems over a period of 2221 hours, with soot filtration efficiency in excess of 98%. The system was removed when the engine's turbocharger failed and caused an oil fire. It was not clear if the filter played a role in the turbocharger failure. Increased NO_2 emissions were noted downstream of the filter, but the average tailpipe NO_2 remained at about 6% of the total NOx (43 ppm).
- **ECS/Unikat Combifilter (LHD):** The Combifilter system utilized two silicon carbide (SiC) filters connected in parallel, sized to hold soot collected over two working shifts. Each filter included an electric heater. Once the target soot load had been reached, the filter had to be regenerated by connecting to an off-board regeneration station, which supplied electricity and regeneration air to the filter. Two of the Combifilter systems were tested. The first system developed cracks in the SiC honeycomb after 940 hours, which were attributed to the active regeneration not being routinely conducted. After more intensive education of the workers on regeneration, a replacement filter worked well, yielding 93-99.8% reductions in DPM emissions over the ISO 8178 8-mode test.
- **Johnson Matthey (LHD):** Two identical filters were fitted on both sides of the dual exhaust from the Deutz engine. The filters were regenerated by a combination of passive and active regeneration. The passive regeneration was facilitated by the use of the cerium-based EOLYS fuel additive. An active regeneration backup was provided through electric heaters which had to be connected to a shore regeneration station providing the electric power and air. Filtration efficiencies remained high, ranging from 84 to 99%, however, the pressure drop levels were high, indicating that active regeneration was often not properly conducted by the operators. After 2057 hours, one of the SiC honeycombs separated from its shell, causing a leak of unfiltered exhaust.
- **ArvinMeritor (LHD):** This automated, fuel burner regenerated system encountered problems with the control software, as well as soot breakthrough. The testing was terminated after 116 hours.
- **Oberland-Mangold (LHD):** This fuel additive regenerated system showed low soot filtration efficiency from the very beginning of the test, and was deemed to have failed.
- ECS/Unikat Combifilter (Tractor Vehicle):
- This filter system achieved 577 hours of operation over nearly three years, with excellent soot filtration efficiencies of over 99%.
- **DCL Titan (Tractor):** Two filters were used: one in service on vehicle, while the other was being regenerated using an off-board heater. The filter system was successfully operated for nearly three years, achieving 864 hours of operation and soot filtration efficiencies of about 99%.

- **ECS/3M (Tractor):** The system was operated for 453 hours, with filtration efficiencies from 77 to 94%.

The project concluded that both heavy- and light-duty mining vehicles could be retrofitted with DPFs. However, most of the filter systems required a significant amount of maintenance and attention from the vehicle operators to function properly.

Matching the vehicle and its duty cycle with the appropriate DPF system was essential for the successful operation of DPFs.

The project also established that communication with the vehicle operators and proper dashboard signals were very important. Operators need to be attentive to DPF alerts and high backpressure alarms. If not, serious harm could be inflicted on the DPF or to the engine.

3 DEEP Legacy

3.1 Contribution to Science and Technology

An important part of the legacy of the DEEP program is its contribution to science and technology. The contributions of the DEEP research occurred in the following areas:

- Contributions to knowledge resulting from DEEP research data and analyses (a number of examples are given when discussing the individual DEEP projects)
- Contributions to research methodology (e.g., sampling methods developed for the light-duty vehicle project and the isolated zone sampling procedures)
- Exchange of knowledge and experience through a multi-stakeholder collaboration (national and international)
- Capacity building among Canadian researchers and research organizations (such as CANMET-MMSL)
- Adoption of new DPM control practices and equipment in some Canadian mines.

3.2 DPM Control Recommendations

Three groups of strategies can be identified that are most effective in reducing exposure to diesel particulate matter in underground mines:

- Upgrading to newer technology, cleaner diesel engines
- Engine maintenance
- Retrofitting old engines with diesel particulate filters

Replacing older models of diesel engines with more advanced and cleaner engine technology can be an efficient and cost effective method of DPM emission control. The emission benefit associated with new engine technologies was first noticed in the 1990s, when the first electronically controlled engines were introduced to underground mines. Expressed in terms of the US EPA PM emission certification levels, upgrading from the Tier 1 (1996 for engines above 175 hp) engine technology to a Tier 2/3 (2003/6) engine can bring a DPM emission reduction of 62.5% (from 0.4 to 0.15 g/bhp-hr).

In view of the very stringent emission standards for surface nonroad engines legislated by the US EPA, new engine technology will become an even more important DPM control strategy in the future. The exact Tier 4 emission requirements and implementation dates depend on the engine power. As an example, for engines of above 175 hp the current DPM emission standard of 0.15 g/bhp-hr will be lowered by a further 90%, to 0.015 g/hp-hr, effective in 2011. Thus, if mining authorities wish to ensure further significant DPM exposure reductions, they simply need to legislate that mining engines meet emission requirements equivalent to those for their non-mining, EPA-certified counterparts. One of the differences between surface and underground mine application which will have to be investigated is related to NO_2 emissions, which are grouped together with NO emissions in EPA legislation, but have separate exposure limits in mines. Tier 4 engines are expected to be fitted with catalytic diesel particulate filters, which may increase the proportion of NO_2 in the total NOx emissions. However, the Tier 4 legislation also introduces very stringent NOx reduction requirements (on the order of 90% for engines above 75 hp), which become effective three years after the respective Tier 4 DPM standards. Thus, fully Tier 4 compliant, ultra-low NOx engines are not likely to present an NO_2 emission problem, even at a high NO_2:NOx ratio.

Proper engine maintenance has been identified as a very important method of reducing DPM and other engine emissions in underground mines. While the DPM emission reduction potential of this method is difficult to quantify, based on the case studies conducted by DEEP, it can be significant. Therefore, it is recommended that emission-based maintenance programs be implemented in mines. Proper engine maintenance is also very important in engines retrofitted with particulate filters.

For in-use mining engines, retrofitting with diesel particulate filters remains the most effective method of PM emission control, providing over 90% DPM reduction potential. However, retrofit DPF technology is not ready to offer off-the-shelf solutions. Many of the DPF systems evaluated under DEEP projects were troubled by technical problems, required significant amount of maintenance, and were costly. Some of the conclusions and recommendations formulated by DEEP in regards to retrofit DPF technology were:

- The DPF selection process is the most critical factor in successful implementation. Careful application engineering is needed for every individual vehicle and its duty cycle.
- Proper DPF system and engine maintenance, as well as training and communication with vehicle operators, are essential for successful DPF operation.
- Passive DPF systems, when properly selected, can offer a robust DPM control solution for heavy-duty vehicles. However, many catalyst-based passive DPFs increase the concentrations of NO_2, which can present an air quality problem in many mines.
- A number of active DPF systems exist that can be applied to both heavy- and light-duty mining vehicles. Some of the systems are relatively simple and reliable, but are maintenance intensive (e.g., systems that require daily operators' intervention to perform regeneration). Automated systems which are being developed to perform the regeneration without operator's action are very complex and still prone to technical problems.

3.3 Technology Transfer

In order to make its experience available to possibly wide audience, DEEP undertook a technology transfer initiative. It involved a number of actions:

- DEEP projects and their results were reported through annual MDEC technical conferences
- "Plain language" 2-page summary sheets were prepared for each of the completed DEEP projects (available in the attached CD-ROM)
- Maintenance training materials and training program have been developed for underground mines
- Four regional workshops were held which conveyed the results of DEEP research and experience to the mining community.
- A significant number of technical presentations were made at international conferences by personnel associated with DEEP research.

The regional workshops were conducted between the Fall of 2003 and Spring of 2004. Their exact dates and locations are listed in Table 2.

Table 2. DEEP Regional Workshops

Location	Date	Number of Attendees
Marathon (Hemlo), Ontario	September 16th, 2003	24
Val-d'Or, Québec	October 6th, 2003	37
Saskatoon, Saskatchewan	October 19th, 2003 (*in Conjunction with 16th CIM Operators' Conference)*	32
Bathurst, New Brunswick	May 4^{th} and 5^{th}, 2004	35

A fifth workshop that had been scheduled for Smithers, BC had to be cancelled due to a lack of interest and registrants.

The aim of these workshops was to transfer the know-how, technology, and understanding of the issues, gained from the past six years of DEEP project work in defining, measuring and controlling diesel emissions in mining. The intent was to make this transfer available to those in the Canadian mining industry especially mine operations that had not participated or shared in the knowledge gained up to this point. The workshop agendas followed almost identical formats with presentations of:

- DEEP research projects, both completed and ongoing
- Expertise and experience from research institutions from Canada and the U.S.
- Regional (Canadian) projects from mining companies looking at engine maintenance and emissions control
- Regional updates from provincial regulators on existing and proposed regulations.

Attendees of the workshops were provided with a CD workshop manual which contained copies of the presentations, DEEP final project reports and two page summaries, and resource materials such as certified engine lists from both CANMET and MSHA. In addition attendees were provided with portfolio binders and notepads for taking notes and a complimentary lunch.

The individual workshop fee was $100.00 which covered attendance along with the above mentioned items. The primary funding and sponsorship of the workshops was provided by DEEP. Additional funding was provided by corporate sponsorship fees of $1000.00 each from Lubrizol/Engine Control Systems, Clean Air Systems, Catalytic Exhaust Products, Deutz Corporation and Ecom America. For this fee the sponsors were provided with an area to present product brochures and display of their corporate logo on the workshop banner.

From the inception of DEEP, its website http://www.deep.org has been and will continue to be an effective technology transfer medium. The structure and objectives of DEEP are outlined there along with the final reports of all of the research projects.

3.4 Remarks on DEEP Organization

- For the benefit of future research programs of this type, it is appropriate to mention the difficulties of mounting and maintaining the DEEP research work, and challenges encountered during the program.
- The initial schedule of three years to conduct the desired research was overly optimistic. Several factors influenced the need for extending the time necessary to complete the work:
  - There was considerable variation among the sponsors of DEEP regarding their detailed knowledge about diesel issues. This meant that time had to be spent in learning about those issues. Some frustration was evident among those most knowledgeable in being patient with those learning. Given the constitution of the DEEP members, it is not clear that this could have been avoided
  - All project proposals were sent to peer reviewers prior to having detailed discussion at the Technical Committee. The amount of effort spent in getting these peer reviews done, and the amount of time spent reviewing them and discussing changes to the proposal, were far greater than had been anticipated.
  - Conducting field testing is difficult in the best of conditions. While some DEEP projects were run relatively independent of mine operations, other projects were intimately tied into production. These latter projects were often adversely influenced by changes in mine planning and diesel usage, both of which meant

delays in accumulating the required total hours of testing. Often decisions made by DEEP teams to take a vehicle out of production so that specific tests could be run on it were met with frustration by operating personnel.

- Keeping keen interest in DEEP was a challenge because of the length of the program.

- Trying to obtain decisions by consensus often adversely influenced efficiency.

- Efforts on technology transfer were particularly rewarding. The regional workshops held across Canada received positive feedback. Excellent presentations made at international conferences meant that DEEP and Canadian work was being followed in Europe and Australia as well as in the United States. Open dialogue among DEEP researchers helped coordinate projects within and outside of DEEP.

- Extensive in-kind contributions by stakeholders and interested parties was a critical component for the success of DEEP. It is estimated that in-kind contributions were at least double the cash contributions. It is a testimony to the importance of diesel usage and worker health that stakeholders committed these resources.

- Even though sometimes contributing to the frustration with inefficiency, having stakeholders covering multi-disciplinary interests resulted in an overall comprehensiveness of DEEP research program. Canada lends a special environment in which government, labour and industry can discuss issues and opinions frankly; without this environment DEEP could not have existed or thrived.

Appendices

Appendix A: Memorandum Of Understanding On The Diesel Emissions Evaluation Program

This memorandum is intended to provide the basis upon which parties will join together cooperatively to fund and manage research aimed at reducing non-coal miners' exposure to diesel emissions in underground environments.

1. Objectives

The Diesel Emissions Evaluation Program (DEEP) has the following objectives:

- To identify the most reliable and appropriate sampling/analytical methods for determining exposures to diesel particulate matter (DPM) and oil mist in a variety of underground non-coal environments;
- To evaluate the field performances (i.e. efficiency and control) and costs of a variety of currently available diesel emission control technologies;
- To study new untested diesel emission control strategies that may have better performances and/or costs than the currently available technologies.

DEEP deliverables are a series of final reports by researchers conducting specific projects within the overall DEEP framework. These reports will be made available to the DEEP participants and to the public. Verbal technical reviews may be made periodically to the DEEP participants to ensure high quality information transfer.

2. Organization

The DEEP organizational structure includes a Management Board, a Secretariat, a Technical Committee and individual Project Teams.

2.1 Management Board

The Management Board will have responsibility to oversee all aspects of DEEP including financial matters, legal matters, and approving all technical projects.

The Management Board will consist of at least one senior representative of each stakeholder (a stakeholder may decline to be represented). A stakeholder is defined as an organization having made a direct financial contribution to DEEP, labour and governmental organizations in the mining sector, and such other parties as the Management Board may decide. The organizations signing this Memorandum prior to April 1, 1997 are the founding stakeholders of DEEP.

The financial constitution of the Management Board will be decided upon by the founding stakeholders.

The Chairman and Vice-Chairman of the Board will be elected from the Board members. The Treasurer of DEEP will be the Mining Division of the Canadian Mining Industry Research Organization (CAMIRO), which will have one individual as a member of the Board. The Secretariat of DEEP will be the Natural Resources Canada, and will be a member of the Board. The Chair of the Technical Committee will be a member of the Management Board.

2.2 Treasurer

The Mining Division of CAMIRO, as Treasurer of DEEP will:

- collect and hold in a separate account, all funds contributed to DEEP;
- pay all invoices approved by the Project Team leader and the Technical Committee Chair;

- keep the Management Board, Technical Committee, Project Teams, and sponsors informed on a monthly, quarterly and annual basis of the financial position of DEEP and all projects;
- issue a final program financial report summarizing all transactions;
- arrange for an independent annual audit of the financial dealings of DEEP;
- be a member of the Management Board

2.3 Secretariat

The Secretariat is designed to provide and assist in information distribution to ensure that participants as well as outside interested parties and agencies are kept informed on the process of DEEP. The Secretariat staff will be selected on the basis of their experience and knowledge of the underground environment and associated health issues. The Secretariat will be responsible for managing the day to day operations of DEEP and will be a member of both the Management Board and the Technical Committee. The Secretariat of DEEP will:

- ensure the preparation and distribution of material for and participate at regular meetings of the Management and Technical Committees;
- ensure preparation of professional documents, including annual reports, progress reports, proposals, and activity descriptions as required;
- keep all pertinent DEEP records and maintain a database of DEEP participants and an expanded mailing list of interested parties;
- circulate and solicit comments on proposals as directed by the Technical Committee and Management Board;
- be the point of contact for DEEP;
- prepare items and press releases for publication as requested by the Management Board;
- co-ordinate the activities of the Management and Technical Committees;
- plan, organize and manage technology transfer activities associated with DEEP in accordance with the Management Board;
- on behalf of DEEP, manage the Intellectual Property as required.

2.4 Technical Committee

The Technical Committee will be appointed by the Management Board and will be based on expertise, geographical location and affiliation. Scientific authorities and researchers will be invited to become members of the Technical Committee.

The Chair and Vice-Chair of the Technical Committee will be appointed by the Management Board.

2.5 Project Teams

Each Project Team, carrying out a specific part of DEEP, will be appointed by the Technical Committee and approved by the Management Board. Project Team members will be selected from the organizations funding the project, from the organization providing the research site, from organizations deemed to have an in-kind contribution, and the researchers whose proposal for doing the research has been approved. Other scientific experts may be appointed to a Project Team.

Each Project Team Leader will be appointed by the Technical Committee and approved by the Management Board. Each Project Team leader will report to the Technical Committee as required and in accordance with the project contract. A Technical Committee member may be a project leader.

2.6 Responsibilities

The Management Board's responsibilities include the following

- develop strategies to promote DEEP within the mining industry, governments and the public;
- expand DEEP participation as needed;
- provide strategic direction and establish administrative policies for DEEP;
- appoint and maintain the Technical Committee;
- approve and arrange funding for specific projects (including revisions) within DEEP and approve Project Team leaders;
- establish guidelines for project acceptance, technical quality, peer reviews and for ethical and confidentiality requirements for all projects;
- review and comment on Progress Reports issued by the Technical Committee.

The Technical Committee will:

- develop and implement a research program that is consistent with the strategy provided by the Management Board and report to the Management Board;
- formulate research priorities and solicit research proposals;
- evaluate specific proposals by peer review and, with the active involvement of all potential participants, submit recommendations to the Management Board for establishing a project. Research costs including in-kind costs and schedule are to be provided to the Management Board. Each proposal will be developed in compliance with the guidelines set forth by the Management Board;
- nominate the Project Leader and the Project Team;
- review and track the progress of each approved project and report to the Management Board as requested;
- ensure quality of work;
- ensure contract deliverables have been achieved and that the draft final report of each project is peer-reviewed;
- accept each final report and specify each project's completion;
- ensure the timely distribution of research results;
- assume other responsibilities as may be assigned.

Each Project Leader will:

- organize the project team and assign tasks to accomplish project deliverables;
- plan and execute the specific project within the cost and schedule approved and in compliance with established by the Management Board;
- report periodically to or at the request of the Technical Committee on progress being made;
- analyze and interpret results obtained;
- conclude the project with a Technical Report and, as may be requested by the Technical Committee, give presentations to stakeholders.

3. Terms Of Reference

3.1 Timing

The DEEP program starts February 27, 1997 and ends December 31, 2000. The three funding calendar years will be 1997, 1998, and 1999. The final year will be used to finalize on-going research and report-writing and may use committed funds not spent in the first three years.

3.2 Research Program

The overall scope of DEEP is defined in a document entitled *Program Description for DEEP (January 15, 1997)*. This document will serve as a starting framework for DEEP. Revisions that may be necessary from time to time will be made by the Management Board.

3.3 Funding

Each stakeholder on the Management Committee will submit a written confirmation either

- Setting forth an amount of money the stakeholder will commit towards funding DEEP projects for each calendar year 1997, 1998, and 1999 (before Dec. 31 of the preceding year); or
- Describing the in-kind contributions the stakeholder is committed to making; or
- Both of the above.

Each stakeholder making a cash commitment to DEEP has the opportunity to select the specific projects it wants to fund. If, at the beginning of each calendar year, a stakeholder wishes to waive the opportunity to fund specific projects, then the Management Board will decide how such funds are to be spent. In the case that a stakeholder has specified a project-specific funding, but is unable to select projects for the full amount of its committed funding, then such committed funds will, at the end of each calendar year, either be directed by the stakeholder to a specific planned project for the next calendar year, or revert to the jurisdiction of the Management Board.

3.4 Attendance at meetings

An individual may be designated by a member or the Management Board or the Technical Committee to attend meetings in the member's place and will fully represent the member not in attendance.

3.5 Contracting Policy

a. All projects will be negotiated between the Management Board and the contracting agencies.
b. A standard non-disclosure agreement, provided by the Management Board, will be signed between all participants of a project.
c. Program results will be shared with all DEEP participants through progress reports and written final reports.
d. Program results will be made available to the public within a reasonably short time frame after project completion.

4. Intellectual Property

The disposition of all intellectual property, produced or generated during the performance of a DEEP project and which can be protected by patents, trademarks, copyrights, industrial designs, or other proprietary know-how, will be decided by the DEEP Management Board or dictated by each project's signed contract. Notwithstanding a Board decision regarding the ownership of such intellectual property, a cash funding sponsor of a project will have a non-exclusive, unconditional, irrevocable, royalty-free right and license to use in its own operations and those of its subsidiary throughout the world in perpetuity such intellectual property as may have arisen during the performance of said project.

5. Means For Decision Making

The Management Board and Technical Committee will strive to reach consensus on all matters. In the event of an impasse, decisions shall be made by a simple majority of the members present.

Acknowledgement and Acceptance of this Memorandum of Understanding.

____________________ for ______________________

(Print Name) (Name of Organization)

____________________ ______________________

(Signature) (Date)

Appendix B: Program Description For Diesel Emissions Evaluation Program (DEEP)

January 15, 1997, updated February 9, 1998

Summary

In view of the recent review of health effects of diesel particulate matter (DPM) by the American Conference of Governmental Industrial Hygienists (ACGIH) and their notification that the Threshold Limit Value for DPM will be set at 0.15 mg/m3, the Diesel Emissions Evaluation Program (DEEP) is being formed by the collaboration of industry, labour, government and researchers in Canada and the United States with the goal of reducing underground miners' exposure to diesel emissions. This goal will be achieved by focusing on two primary research objectives: 1) evaluating aerosol sampling and analytical methods for DPM, as well as developing means to distinguish between DPM and oil mist; and 2) evaluating the in-mine performances and costs of various diesel exhaust control strategies.

This document provides an overall framework for DEEP, out of which individual projects at specific mine sites will be defined and sponsored. Each shareholder of DEEP will make annual financial commitments to DEEP, but will decide which specific projects it wishes to sponsor.

It is imperative that all affected and interested parties participate fully in individual project planning and execution. The DEEP organizational structure consists of a Program Management Committee, a Technical Committee, a secretariat and treasurer. CAMIRO Mining Division acts as treasurer while the secretariat duties are performed by Natural Resources Canada.

1. Purpose

This document provides a description of the Diesel Emissions Evaluation Program (DEEP). Rather than being a proposal for conducting work, this description provides the framework from which specific research proposals will be solicited. The overall purpose of DEEP is to evaluate: (1) aerosol sampling methods for diesel particulate matter (DPM) and (2) strategies to reduce miners' exposure to diesel exhaust pollutants.

2. Background

The Canadian ad hoc Diesel Committee met in Markham, Ontario, on March 26-27, 1996 to discuss issues pertaining to diesel exhaust exposure and control in mining. A major topic of discussion at this meeting, and three Diesel Workshops sponsored by the U.S. Mine Safety and Health Administration (MSHA) in the Fall of 1995, was the addition by the American Conference of Governmental Industrial Hygienists (ACGIH) of DPM and oil mist to the Notice of Intended Changes for 1995-96. For the first time the ACGIH proposed, after reviewing available animal and human health studies, a threshold limit value (TLV) of 0.15 mg/m^3 for DPM and a reduction to 0.2 mg/m^3 for some oil mists. If these values are adopted as permissible exposure limits, many mines in Canada and the U.S. would have difficulty meeting this limit at all times.

The ad hoc Diesel Committee agreed that the goal of reducing exposure to diesel emissions was best accomplished by collaboration of the several sectors having a stake in reducing exposure. These sectors include: mine operators, labour, regulators, fuels and additive producers, equipment (machine, engine and exhaust emission controls) manufacturers, and Canadian and U.S. research agencies. The Committee further endorsed the concept of a North American consortium to conduct diesel research and appointed a Steering Committee to guide the formation of the consortium and to specify objectives of DEEP.

3. Goals And Objectives

The goal of DEEP is to reduce miners' exposure to diesel exhaust pollutants by systematically testing and evaluating control strategies to reduce diesel emissions at specific mine sites. Specific objectives include:

- Evaluation of diesel exhaust and oil mist aerosol measurement methodologies to determine benefits/limitations of each;
- Implementation and evaluation of comprehensive emission control strategies to reduce diesel emissions with particular attention to DPM concentrations to determine efficiency, technical feasibility and costs.
- Measurement of DPM and diesel gaseous pollutants.

It will also be necessary to carry out laboratory evaluations of promising, but untested, emission control methods to determine their safety, feasibility, and effectiveness.

Specific research priorities were identified by the ad hoc Committee in Markham. These included evaluation of: DPM aerosol measurement methods, modern engine technology, alternative fuels and fuel additives, exhaust emission control technologies, and engine maintenance.

4. Program Organization And Scope

The Steering Committee recognizes that the formation of DEEP will be done according to the requirements of its sponsors. However, in order to give potential sponsors some understanding of how DEEP is currently being viewed by interested stakeholders, the following potential organizational structure is presented.

1. A Scope of Work (Appendix 1) was drafted to convey the reasons why DEEP should be conducted and the essential elements of the proposed research. This document was widely circulated to gain support from potential sponsors and collaborators. Formal announcements of DEEP as a collaborative undertaking by parties in industry, labour, and government have been made to trade magazines and the media.
2. Stakeholders are being solicited to provide support in the form of funding or in kind contributions and to determine details of individual projects within DEEP. The Canadian Mining Research Organization (CAMIRO) Mining Division has agreed to facilitate financial arrangements. DEEP will consist of individual and specific projects and each project will be financed independently of the other projects. There will likely be a modest administration fee to join DEEP and to enable parties to sit at the table where project development will occur. It will also be necessary that DEEP shareholders have budgetary planning within their own organizations. Each DEEP shareholder organization will be able to help plan and to elect which specific projects it will sponsor.
3. It is envisioned that DEEP will have a Program Management Committee (PMC), consisting of representatives of each shareholder. The PMC will have responsibility for overall DEEP management including financial and legal matters and will be chaired by CAMIRO. Reporting to the PMC will be a Technical Committee (TC), appointed by the PMC and consisting of shareholder representatives, other stakeholders with an interest in DEEP, and other technical consultants. The TC will provide project planning, project execution and technical advice to the PMC. The proposed structure is shown on the next page.
4. It is imperative that all affected parties participate in individual project planning and development. It is therefore essential that labour and governmental bodies be adequately represented on the Technical Committee.

5. Not every part of the scope of DEEP will be performed at every field site. One of the tasks of the TC is to identify mines willing to participate as host sites for specific parts of the research program. Detailed questionnaires for both mine management and miners will be distributed. Information will be collected on diesel operations and other characteristics that will influence the decision on whether to consider the mine as a site for a particular project. The TC will also conduct mine site visits to obtain firsthand information and to brief mine management and labour on each proposed project. The TC will select mines with varying characteristics, which represent a broad cross-section of operational conditions. Ordering the individual project priorities will be done by the TC and each project will be carried out under the same standards as other projects within DEEP. In this way it is hoped that the TC will be able to integrate results at different mine sites into a cohesive whole at the end of DEEP's work.
6. Each project will have site-specific Project Work Plans developed in close cooperation with all affected parties. Each plan will include the schedule, specific requirements, personnel needs and measurements to be made.
7. An Agreement with each selected mine for each proposed project will be formally executed by the PMC. CAMIRO will solicit funding for each project as required. DEEP shareholders need not participate in funding for all projects. However, DEEP shareholders will need to participate up to their stated funding commitment.
8. Each project will have a volunteer Project Coordinator (most likely from a member of the TC) to provide an interface between the project and the TC. Results from each project will be reported via documents (and symposia, workshops) to all stakeholders.

Organization of Research Activities: The large scale and complexity of the program require that research be coordinated to avoid duplication and that the research teams collect a minimum set of data to allow sampling and control strategies to be accurately evaluated and compared. Each site-specific, demonstration project team will collect similar types of data using questionnaires and on-site data collection techniques, as follows.

The first requirement will be to identify mines willing to participate as sites for various DEEP projects. Data on potential sites will be collected by using detailed questionnaires for both mine management and miners covering the nature of diesel operations and other mine characteristics that will influence the decision on whether to include the mine in the overall DEEP framework.

Air quality measurements will be carried out on constituents such as: CO, CO_2, NO, NO_2, SO_2, DPM, drill oil mist, hydrocarbons, sulfate fraction of DPM, respirable dust, respirable quartz and particle size distribution data. DPM measurements will be made using respirable combustible dust (RCD), size selective (SS) and elemental carbon (EC) methods.

Engine maintenance, duty cycle, fuel consumption, exhaust temperature and back pressure, and production data for vehicles used in the test section will be documented.

Ventilation data on the test section will be collected.

The metal and nonmetal mine sites selected as hosts for DEEP projects should represent a variety of mining operations from the point of view of diesel fleet, mining method, size and production parameters. The mines should produce different types of products (metal and nonmetal) to ensure the entire spectrum of diesel equipment is represented. The type of ore body will affect the selection of the aerosol methods used to evaluate DPM control. For example, one of the sites selected should have a high sulfide ore body, because this type of ore is suspected to interfere with the RCD analytical method. Other mine settings (salt, nickel/copper, zinc/lead) may reveal problems with the other sampling and analytical methods. Prospective mines will be expected to comply with all standards governing diesel usage before studies will commence. Studies will not be conducted at mines which do not meet these standards.

5. Evaluation of Aerosol Measurement Methods

Objective: The objective is to compare and evaluate three currently available methods for sampling and analyzing DPM. Past research conducted in Canada and the U.S. has raised questions concerning the accuracy and precision of the three aerosol methods (RCD, SS and EC) used to sample for DPM. The Canadian ad hoc Committee strongly recommended that these methods be compared and evaluated underground. The results of this comparison will permit proper interpretation of exposure data and evaluation of the control methods. It is unlikely that any one method will, by itself, be completely satisfactory for evaluating all control strategies, thus it is likely that more than one aerosol measurement method will be required in the control evaluation portion of the research program.

Approach: Arrays of DPM aerosol samplers (RCD, SS and EC) will be installed at selected locations in the mine test section, such as the test section intake and exhaust airways and on the diesel production equipment. The exact number of samplers deployed will depend on the number required to yield satisfactory statistical results and will be determined through preliminary tests. Additional aerosol samplers such as micro-orifice uniform deposit impactors (MOUDI's), real-time aerosol monitors (RAM) and an array of dichotomous samplers will likely be used to collect additional data necessary to interpret the results accurately. Ore samples will be analyzed for sulfur and carbon content, and accurate records will be maintained regarding mining activity, and diesel use.

Each method provides slightly different information which will assist in interpreting results. RCD provides estimates of the respirable mine aerosol concentration and the fraction of the aerosol that is combustible (assumed to be mainly diesel in origin). The RCD method provides a measurement of the entire DPM fraction of the respirable aerosol, plus other respirable aerosols which are combustible such as oil mist. The SS method separates the respirable aerosol into two size fractions. The portion of the respirable aerosol less than 0.8 µm is assumed to be mainly diesel in origin. Both the RCD and SS methods are limited by the error associated with gravimetric analysis.

The elemental carbon method measures the carbon fractions of the respirable aerosol using thermo-optical analysis. Estimates of the elemental carbon (EC), organic carbon (OC) and the total carbon (TC) are obtained, with nearly all of the EC portion of the respirable aerosol coming from diesel exhaust. This method is extremely sensitive and provides a surrogate measurement of DPM. Since the EC method is limited by filter loading, the sampling array may include the impactor used in the SS method.

None of these methods directly measures the respirable oil mist fraction apart from other respirable aerosols. Analytical methods developed by Inco at their Central Process Technology laboratory and by NIOSH will be evaluated to determine this portion of the aerosol.

6. Evaluation of Potential Control Strategies

Objective: The intent of this research program is to demonstrate and evaluate control strategies that are commercially available, or that have been demonstrated through laboratory testing to be safe and ready for field evaluation. With respect to previously proven technology, however, it is the intent of this program to duplicate past research only when necessary to obtain additional data to quantify exposure reduction effectiveness, and cost. The following strategies are possible candidates for evaluation either singly or in combination (the list is not intended to be comprehensive, nor does the order of the list indicate priority):

- Alternative fuels, such as biodiesel fuel, or low sulfur fuel in combination with exhaust emission control devices such as diesel oxidation catalysts (DOCs);
- Low emission, electronically controlled engines;
- Fuel additives;
- Ceramic engine coatings and other retrofit engine upgrades;
- Exhaust aftertreatment devices such as DOCs and particulate traps (filters);
- Impact of maintenance practices on emissions.

Experimental approach: Due to the site specific nature of the demonstration projects, the complexity, the heavy involvement of the mine and the need for thorough coordination amongst all participants, a detailed approach is not included here, but instead will be spelled out in each site specific project workplan.

Generally, it is envisioned that DPM, oil mist aerosols and selected gases (CO, CO_2, NO, NO_2, SO_2) will be measured before and after each control strategy is implemented. In the simplest scenario, measurements will be made in the section intake airway, on the production vehicle near the vehicle operators location and in the section exhaust airway. Since the concentration of DPM and gaseous pollutants generated within the selected section depends on ventilation airflow and vehicle duty cycle, data will be recorded to monitor these parameters.

Analysis of data and costs of controls: Data will be collected on the mine's diesel fleet to determine if the control option being tested could be used at other sites in the mine and to project the costs of the control. Useful information that will be collected includes: equipment type, manufacturer, model, engine type, emission controls, age, general location and use.

To ensure that the control strategies being demonstrated receive a fair evaluation the duty cycle of the production vehicles will be observed. Observers will record the production activities of these vehicles in the test section by breaking the production cycle into the various elements. The time needed to complete each element will be recorded. This information will be used to ensure that improvements in air quality observed in subsequent phases of the project are due to reductions in emissions and not due to changes in vehicular duty cycle. Fuel consumption, production and exhaust parameters will also be monitored to provide further information on duty cycles. This information will assist in data interpretation and in cost projection.

Pre- and post-engine inspection: Inadequate engine maintenance can significantly increase diesel exhaust emissions and interfere with the accurate evaluation of control strategies. Prior to the evaluation and demonstration of the control strategies, project staff, in conjunction with mine maintenance personnel and perhaps an authorized dealer representative, will determine the state of engine maintenance of the production vehicles to be used in the test section. Deficiencies will be fixed prior to the start of the study.

To ensure the control strategy had no ill effect on the test vehicle engines, a postengine inspection will be conducted.

Engine Emission Testing: Tail pipe exhaust emissions measurements, especially DPM measurements, are useful to establish an emission reference for comparison during the air quality study. Before and after the engine inspections, the test vehicles emissions may be measured either with portable equipment such as the "tail pipe sniffers" being developed by Noranda and others, laboratory grade equipment brought underground, or from engines removed from the vehicle and tested in the laboratory. If possible, this evaluation will include an evaluation of emissions before the in-mine studies begin, and at periodic intervals after the completion of the tests, to determine the impact of maintenance on emissions. Emissions will be evaluated using portable instrumentation while operating the engine on a dynamometer (if available) or during torque converter stall.

Diesel fuel and oil chemical analysis: The quality of both the diesel fuel and the lubrication oil is important in an engine maintenance program. Fuel contamination can occur during the transfer process from a mine's bulk storage to vehicle fuelling. To assure proper transfer of fuel, samples will be taken from the mine's bulk fuel storage above ground, main storage tank underground, and from the nozzle of underground fuel vehicles. All fuel samples will be analyzed for sulfur content. This is particularly important if the mine is using catalytic exhaust emission control devices which perform most effectively with low sulfur fuel. Irregularities will be noted and recommendations made to correct deficiencies.

Information on the type of drill oil will also be collected, and if necessary, samples will be collected for chemical analysis. This information will assist in differentiating drill oil mist aerosol from DPM aerosol.

Ventilation: Ventilation is the primary means of reducing contaminant concentrations. Since airflow dilutes contaminant concentrations, including diesel aerosol, knowledge of ventilation parameters are necessary for the interpretation of pollutant data. Prior to the start of the study, the mine operator will provide ventilation data for the test section to ensure that all required air volumes are met. If the ventilation data shows that the section has inadequate air quantity, the mine operator will be requested to correct this condition before further studies are conducted. In certain instances, it may be desirable to acquire additional ventilation data that could be useful in optimizing fresh air distribution without increasing the total air volume provided to the mine.

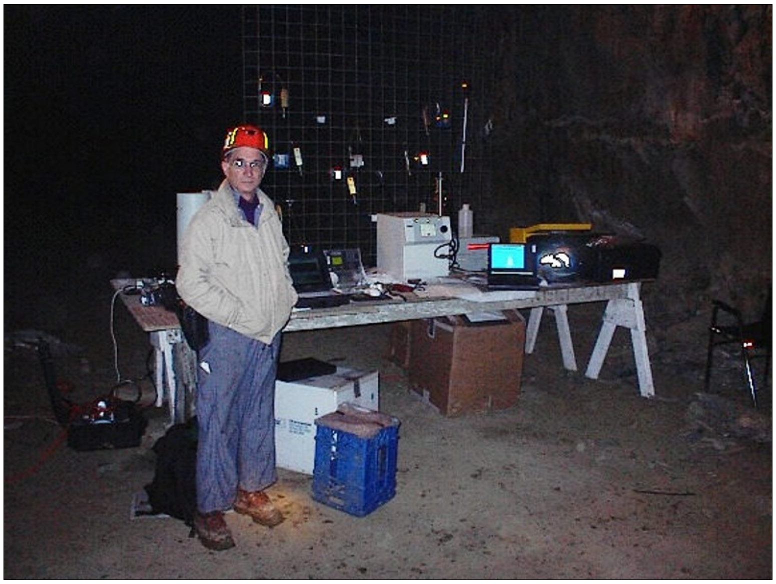
Project support by the mine: Co-operation of each host mine is critical to the success of the DEEP program. The selected mines will generally provide basic safety training and equipment for visiting personnel, required electrical power for instruments, and space for sampler pump recharging and calibration. The mines will also provide vehicles for the transportation of personnel, equipment and materials on a daily basis. Mine management will provide personnel to facilitate the study and ensure safety.

7. Technology Transfer and Training

A significant portion of the anticipated impact of this research program rests on the knowledge and technology which will be transferred to the mine sites and mine personnel involved with the project. Project technical staff will train mine personnel, including worker representatives, in the methods to be used during the air quality surveys and control evaluation portions of the research. The objective of the training is to familiarize these staff with the methods so that they can participate fully in the underground mine study, and pass along the information to other mine personnel. Subject matter would be presented to selected mine engineers, technologists and representatives of the safety and health committees prior to the start of the study. The content of the presentations would include: project overview, aerosol sampling basics, and control strategy information.

Results from this research program will be published and presented in technical papers and meetings and reported in contract reports. Emphasis will be placed on presentations before the Canadian ad hoc Diesel Committee and publication in refereed mining journals.

Appendix C: Photographs from Selected DEEP Projects



Brunswick DPF study:
Isozone: NIOSH instruments

Brunswick DPF study:
Isozone: CANMET instruments

Brunswick DPF study:
Isozone: DPM samples

Brunswick DPF study:
Nanomet instrument (1)

Brunswick DPF study:
Nanomet instrument (2)

Brunswick DPF study:
Cattrap DPF

Brunswick DPF study:
Combifilter DPF

Brunswick DPF study:
DCL DPF

Brunswick DPF study:
Oberland-Mangold DPF

Maintenance Project:
Project training (1)

Maintenance Project:
Project training (2)

Maintenance Project:
Project training (3)

Maintenance Project:
Emissions testing

Maintenance Project:
UGAS instrument

Stobie Mine DPF Study:
Emissions testing (ArvinMeritor DPF)

Stobie Mine DPF Study:
NIOSH testing (1)

Stobie Mine DPF Study:
NIOSH testing (2)

Stobie Mine DPF Study:
NIOSH testing (3)

Stobie Mine DPF Study:
Johnson Matthey DPF

Stobie Mine DPF Study:
ArvinMeritor DPF

Stobie Mine DPF Study:
DPF system on Kubota tractor