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RELATIONSHIP OF UNDERGROUND DIESEL ENGINE MAINTENANCE TO EMISSIONS

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Gaseous and particulate exhaust emissions from 20 diesel engines in service at five underground mines were measured with high accuracy instrumentation. The engines that were tested were checked for faults or maladjustments. The vehicle and engine maintenance organization was studied at each mine and an idealized maintenance program was devised. Faults were induced in a new diesel engine to determine their effect on the characteristics of the exhaust emissions. The results, conclusions and recommendations from this investigation are presented in this final report.

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FOREWORD

This report was prepared by Southwest Research Institute, Energy Systems Research Division, San Antonio, Texas, under USBM Contract number H0292009. The contract was initiated under the Minerals Health and Safety Technology Program. It was administered under the technical direction of the Twin Cities Research Center with Robert W. Waytulonis acting as Technical Project Officer. Darlene Wilson was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as part of this contract during the period December 4, 1978 to November 1, 1983. This report was submitted by the authors on August 5, 1983.

This report embodies information which was obtained through dedicated effort by many individuals from several areas of the underground mining industry. Mr. Al Smith and Mr. Henry Luecke of Deutz and Mr. Jack Sallee and Mr. Tom Lane of Caterpillar Tractor Company provided engine emission information and support throughout the five-year duration of this program. Personnel from several mines were very helpful in characterizing mine maintenance and supporting laboratory and field engine tests. Unfortunately these people cannot be identified because of confidentiality agreements with the mines. Instead, the authors acknowledge the progressive support of this work by the underground mining industry.

Mr. Robert Waytulonis of the U.S. Bureau of Mines' Twin Cities Research Center has rendered technical direction throughout the program. During the early phases of the project, Mr. Robert Hambright and Mr. Norbert Paas set the direction of the project through their management of the program.

The authors gratefully acknowledge the technical expertise provided in the area of diesel engine emissions measurement by Robert Fanick, Robert Howard, and Danny Terrazas. The authors express their appreciation for the engine and vehicle technical expertise provided by Howard Woller, Charlie Bean, and Kenny Ash. The assistance in data reduction provided by Richard Branecky, Dr. Robert Mason and Karen Hudson was also a great help. For typing this report the authors thank Jackie Harbour, Nita Broussard, Diana Granados, and Terry Edwards.

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1. EXECUTIVE SUMMARY

1.1 INTRODUCTION

1.1.1 Background

This report summarizes the activities and results of the U.S. Bureau of Mines Contract No. H0292009. This was a research project concerning the "Relationship of Underground Diesel Engine Maintenance to Emissions."

The U.S. Bureau of Mines estimates that there are 7500 diesel units operating in coal and non-coal underground mines. Of these, 1000 are employed in coal mines (1). This includes a varied distribution of applications, engine sizes, and engine types. The introduction of diesel power to coal mines, though being a recent development in the United States, has been underway in several foreign countries for many years.

The acceptance of diesel-powered equipment is due to several advantages. For example, diesel equipment used in haulage and transportation has greater mobility and safety than electric equipment with trailing cables. In comparison to battery-operated equipment, it has greater range between service stops and can maintain a much higher power level. With respect to other internal combustion engines that could provide the same level of mobility and performance, the overall low emissions and the relative safety of diesel fuel makes the diesel the only engine presently available that is suitable for underground use with reasonable safety and health risks.

Despite the advantages, the fact remains that the diesel engine will introduce emissions into the mine ventilation system. The question in the minds of the user and regulatory agencies is "What impact does the use of diesel-powered equipment have on the health and safety of the miner?" In response to resolving the controlling of emissions, regulations have been established that limit levels of carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), and particulate in the ambient air. High tail pipe emissions levels can be reduced to established THRESHOLD LIMIT VALUES (TLV) by dilution, i.e., increasing the amount of ventilation air, or by controlling the composition of the exhaust from diesel engines. Since there is an incomplete understanding of how maintenance factors affect diesel engine emissions, the predominant method of ambient air control is by means of ventilation. Obviously, there is a practical limit to the amount of dilution that can be achieved from both a physical and economic standpoint. Therefore, control of emissions from a diesel engine is an attractive alternative to increasing ventilation air quantity. This potential has been recognized by the U.S. Bureau of Mines, which in turn has embarked on an intensive effort to establish the relationship of diesel engine operation and maintenance to its exhaust emissions.

When a mine takes delivery of a new diesel-powered unit, certification assures that certain criteria for emissions are met at the time of delivery. Once put into operation at the mine it is the responsibility of the mine operator to keep the equipment in good condition through proper maintenance. Because practically no enforceable regulations exist in regard to maintenance procedures, the condition of a diesel unit after it is in operation in the mine may vary considerably. Thus, the approach to appraising maintenance practices and their influence on emissions must include accurate measurement of emissions and a realistic assessment of the engine condition as it affects emissions.

Efforts on this project were divided into four phases:

- PHASE I - Develop Test Approach
- PHASE II - Used Mining Diesel Engine Testing
- PHASE III - Field Testing of In-Service Diesel Engines
- PHASE IV - Diesel Engine Induced Faults Testing

Results of these four phases are discussed in this final report.

1.1.2 Program Objectives

1.1.2.1 Goals and Overview

The methodology used to determine the effect of maintenance on diesel engine exhaust emissions was to individually investigate three factors:

- **Maintenance Organization** - The program used to service diesel engines was subjectively assessed at several underground mines

- **Engine Duration of Service** - Engines that had accumulated varying numbers of service hours were tested at the mines or in the SwRI laboratories.

- **Maladjustments or Defects** - Typical faults which were commonly observed in mining engines were induced in a laboratory test engine.

The changes in exhaust emission characteristics resulting from these three factors are synthesized into a maintenance/emission relationship, Figure 1.1.2.1-1.

The Phase I objectives were to develop a program plan that would establish:

- which emission components are pertinent;
- testing methodology required to quantify these emissions;
- logistics and coordination required to implement the methodology;
- data reduction required to interpret results.

To accomplish these objectives, activities focused on field visits to characterize mine maintenance and literature surveys. Field visits included mines, engine manufacturers and rebuilders, equipment manufacturers and state and federal agencies. Literature surveys included a study of SAE papers, related research projects, foreign data, and state and federal regulations.

During the initial effort six areas of maintenance activities were identified that can affect emissions directly or indirectly. These areas are as follows:

1) Air intake system,
2) Cooling system,
3) Fuel handling and quality,
4) Fuel injection system,
5) Lubrication system, and
6) Exhaust treatment.

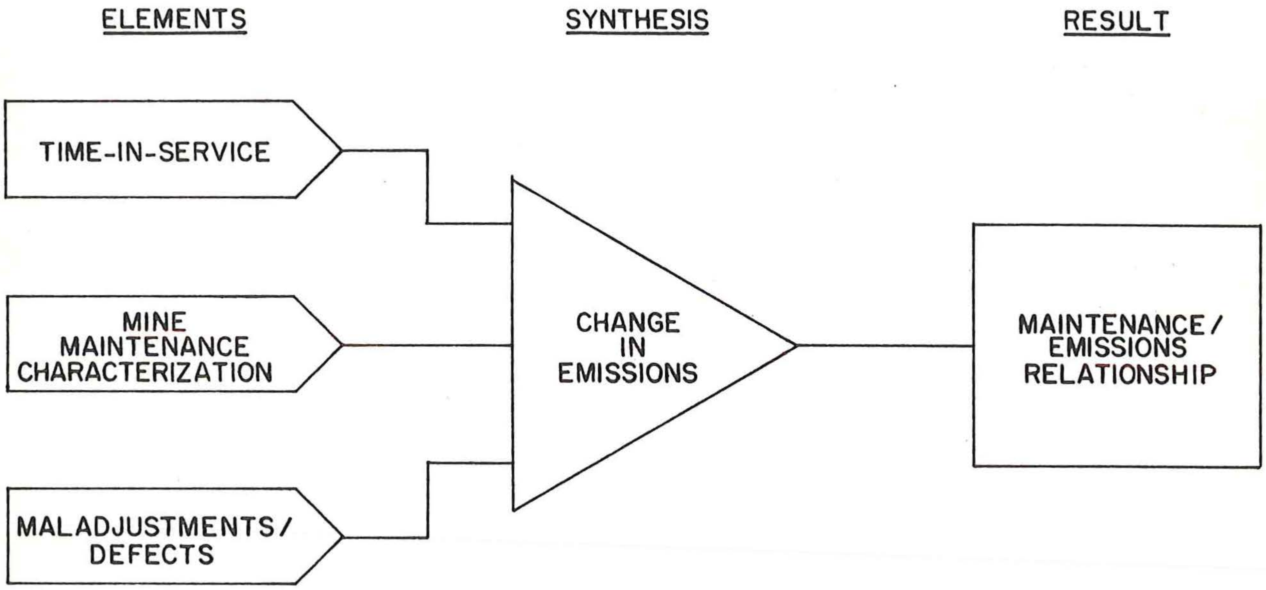

FIGURE 1.1.2.1-1 MAINTENANCE/EMISSIONS RELATIONSHIP SYNTHESIS

It was determined that two engine manufacturers supply a large percentage of all diesel engines used underground. These two manufacturers are Deutz, which produces an air-cooled engine, and Caterpillar, which produces a water-cooled engine. As a result of this finding, it was decided that efforts would be concentrated toward investigation and testing of these two engines.

One of the more significant early developments was the selection of the emission components which would be monitored and the creation of a test procedure to accurately and repeatably measure those emissions. It was found that the emissions of greatest interest from a health and safety standpoint, as well as for diesel engine performance and diagnostics, are: unburned hydrocarbons, carbon monoxide, carbon dioxide, nitric oxides, oxygen, and particulates.

From the Phase I investigation, it was determined that efforts would be directed toward three areas. The first area addressed would be the laboratory testing of used diesel engines which had been in service in underground mines. Work in this area would yield a data base to which future engine analyses could be compared. It would also provide experience in testing the particular engines involved in this program. The second area addressed would be the field testing of in-service diesel engines at mine sites. To accomplish this task, it was necessary to develop gaseous and particulate emission measurement instrumentation which would be transportable in underground mines. Furthermore while testing was being conducted at the mine, the maintenance structure and organization in force at the mine would be studied. The final area addressed would be the investigation of the effects of artifically induced faults on the production of diesel engine emission components.

1.1.2.2 Program Approach

An approach was established to perform:

- laboratory measurement of emissions from used engines from underground mines,
- measurement of diesel engine emissions at field test sites, and
- analyses of effects of induced faults on diesel engine emissions.

The used diesel engine test program, which was conducted early in the project, surveyed cooperating mines for available used engines to be sent to SwRI for testing. Due to the absence of spare diesel engines at most mines, it was necessary to divert engines being sent to rebuilders to SwRI for testing before the engines were reconditioned. Unfortunately the engines obtained in this manner were those which were considered by the mine to be unfit for service or having a sufficient number of hours of service that a breakdown was likely. Therefore the data collected from the used engines do not necessarily represent that which would be obtained from healthy engines.

As received, some used engines required minor repairs before testing could be completed. The engines were placed on a dynamometer and 13-Mode emission tests were performed. Gaseous emissions were measured at all modes using standard laboratory grade instrumentation. Particulates were measured at three modes using an 8-inch dilution tunnel. The engine was diagnosed using compression tests, injector tests, and inspections that required partial disassembly of the engine. The engine was then shipped to the rebuilder designated by the mine. Teardown and parts inspections were obtained, when available, from the rebuilder by telephone interview. A total of seven sets of tests were conducted on five diesel engines obtained from four underground mines. In addition to the typical tests performed on each engine, one engine was tested on DF-1 and DF-2 fuels, and one engine was tested with and without an altitude compensating turbocharger.

Diesel engine field testing was performed to investigate the condition of in-service diesel engines and to determine the type and degree of maintenance received by the engines tested. A complete set of portable instrumentation in three carts was developed to test diesel engines at remote sites either above ground or underground. These ruggedized carts housed all required gaseous and particulate emission measurement instrumentation. Two carts housed all instruments required for gaseous emission measurement. The third cart contained equipment required to operate a "miniature dilution tunnel" developed for this particular project. This small dilution tunnel was developed because the large dilution tunnels used in the SwRI laboratory were much too bulky to be taken underground. A portable dynamometer was purchased which could absorb up to 900 Hp. The dyno was physically modified to adapt to this specialized testing. Various diagnostic and performance instruments were used to obtain an insight into the state of health of the engines tested at the field test sites. At each field test site mine managers, foremen, and maintenance personnel were interviewed concerning the type and degree of maintenance received by diesel engines in their mines.

A total of 15 in-service diesel engines were tested at three field test sites. The three mines included one coal mine and two non-coal mines. At each mine one engine was tested with and without existing exhaust treatment. The coal mine used water bath scrubbers while the non-coal mines used catalytic converters.

At the SwRI engine testing laboratory exhaust emissions were measured from a new Deutz air-cooled engine while faults were induced in the engine. This testing was performed to investigate the effects of particular faults and combination of faults on the production of the exhaust emission components of interest. The faults investigated were intake combustion air restriction, exhaust gas restriction, diesel fuel injection timing maladjustment, and engine overfueling. The effects on exhaust emissions of these faults were investigated singly and in multiples. A total of 23 induced faults tests plus three baseline tests were conducted.

During the life of this program a total of 21 diesel engines were tested. Additionally, Caterpillar tested two new engines to provide baseline data for the project. The engines tested by Caterpillar were a 3306-PCNA six-cylinder, precombustion chamber, water-cooled, naturally-aspirated engine and an equivalent engine which was turbocharged.

1.2. SUMMARY OF RESULTS

1.2.1 Development of Test Equipment

1.2.1.1 Gaseous Emission Measurement

The scope of this research program required the measurement of gaseous emissions in underground mines. Measuring raw exhaust from diesel engines operating in an underground mining environment presents several unique problems. Some of the typical concerns include high ambient dust level, ruggedness of the instrumentation and portability of the equipment. Visits to several mines allowed the development of design criteria for portable emission measurement carts. The design criteria and instrument specifications were submitted to Beckman Instruments for recommendations and a formal bid.

Beckman fabricated two portable carts which housed all components necessary to measure diesel engine gaseous exhaust emissions. After completing a few minor structural and plumbing changes, these carts were used throughout the field testing program. The rough handling and transportation received by the carts appeared to have no effect on the accuracy of the instruments. During all diesel engine tests the instruments calibrated properly and much useful data were collected.

1.2.1.2 Particulate Emission Measurements

The measurement of particulate emissions from engines being operated in vehicles in underground mines required the development of a "mini-tunnel". A review of the space and weight requirements of a full size particulate diultion tunnel prohibited its use in an underground mine. Using the basic concept of the secondary dilution tunnel of a double dilution tunnel from the EPA heavy duty transient procedure, SwRI developed a mobile particulate cart for measuring particulate emission rates. Several experiments were required to define the operating parameters for the mini-tunnel. Its dimensions were 1-1/4 inch outside diameter by 12 inches long. The size reduction of the mini-tunnel is considerable when compared to the double dilution tunnel for the EPA transient procedure which is 8.3 inches in diameter by approximately 7 feet long.

Correlation experiments were run between the mini-tunnel and the full size dilution tunnel. As a result of the experiments, operating parameters for the mini-tunnel were determined to ensure ± 10 percent total accuracy and repeatability when compared to the full size tunnel.

Related equipment required for the use of the mini-tunnel was housed in a portable cart similar in design to the gaseous emissions carts. Also included in the cart were calibration gas bottles for all emissions measurements. The mini dilution system performed properly throughout the field testing program with the exception of tests conducted at the second field test site. At this site, particulate measurement calibrations were not performed properly and the data were lost.

1.2.1.3 Performance and Diagnostic Equipment

Proper emission characterization of diesel engines depends on careful control of engine load and speed and close monitoring of related engine parameters. Loading and controlling the test engine was accomplished through the use of a portable dynamometer. Ruggedized laboratory instruments were used to monitor parameters affecting diesel engine performance such as relative humidity, diesel fuel flow and injection timing, engine intake combustion air flow and critical engine temperatures.

To acquire accurate, repeatable engine emission data, the engine was controlled at a specific load and speed until temperatures and emissions became stable. When stabilized, all pertinent engine performance parameters and emission levels were recorded. After recording all required information at a particular engine mode, the engine was adjusted to collect data at the next mode. A total of five load/speed modes were investigated during field testing. Gaseous emissions were recorded at all five modes while particulate emissions were sampled at three modes. At one of the three particulate sampling modes, sufficient particulate was accumulated to perform a soluble organic fraction (SOF) analysis. Post test diagnostics were obtained from cylinder compression tests and diesel injector crack pressure measurements.

1.2.2 Used Engine and Field Test Engine Results

The emissions from five used engines from four underground mines were investigated at the engine laboratory of SwRI. The maintenance organizations of the mines supplying the used engines were studied and found to be widely varied. The emissions from 20 in-service diesel engines at three field test sites were investigated. The three mines which served as field test sites supported maintenance organizations which would be classified as very good to excellent. The 25 engines tested had each accumulated from a few hundred up to 9000 hours of service in various applications. The emission measurements from the various engine operating modes for each engine were averaged and weighted to yield a typical mass production of a particular exhaust component from each engine being operated under several duty cycles. Each weighted emission point was plotted versus number of hours of service delivered by the engine. A second order curve was fitted to the points representing each gaseous exhaust component for turbocharged and naturally-aspirated engines individually. The results are shown in Figures 1.2.2-1 through 1.2.2-4.

There are many parameters which affect the exhaust emissions of a diesel engine. However, if only engine age and type of intake air induction are considered, the following trends are noted. From the naturally-aspirated engines, Figure 1.2.2-1, unburned hydrocarbons and nitric oxides increased somewhat for the first 4000 hours of operation and then leveled. The production of carbon monoxide from these engines demonstrated a very gradual increase over engine life. From the turbocharged engines, Figure 1.2.2-2, unburned hydrocarbons and carbon monoxide were stable for the first 4000 hours of operation, then began to increase. Nitric oxide production gradually increased for the initial 4000 hours, then leveled.

Particulate production for the naturally-aspirated engines, Figure 1.2.2-3, demonstrated relatively slow increases or decreases for the initial 4000 hours of service, depending upon the operational mode. After this interval, particulates produced while at rated speed and full load increased. Similarly, the production of particulates from the turbocharged engines, Figure 1.2.2-4, changed little during the first 4000 hours of operation regardless of operational mode. However, after this initial period, particulates produced at rated speed and no load increased considerably. A discussion of these trends as well as detailed descriptions of the condition and performance of each engine are presented in Section 6.

1.2.3 Effects of Faults on Diesel Engine Emissions

A new Deutz F6L 912W six-cylinder, air-cooled, precombustion chamber, naturally-aspirated engine was used as a test bed to determine the effects of faults and maladjustments on the production of the exhaust gas components of interest. The effects of four faults were examined. These were intake combustion air restriction, exhaust gas restriction, fuel injection timing maladjustment, and engine overfueling. The effects of these faults singly and in combinations were tested. The production of hydrocarbons, carbon monoxide, nitric oxides and particulates were investigated under a total of 23 fault conditions.

A summary of the results is presented in Table 1.2.3-1. The production of hydrocarbons is most affected by fuel injection timing maladjustments; retardation of the injection timing having the worst effect of any singularly induced fault. The combination of timing retardation and combustion air intake restriction showed the greatest production of hydrocarbons.

Overfueling the engine was the single fault which had the greatest effect on carbon monoxide. Any other fault in conjunction with overfueling, with the exception of timing advance, increased the production of carbon monoxide above the level created by overfueling alone.

The production of nitric oxides was most affected by injection timing. Retarding the timing decreased NO_x production while advancing the timing by more than 4^o crank angle substantially increased production of NO_x. Other faults influenced the production of nitric oxides by only to a limited extent.

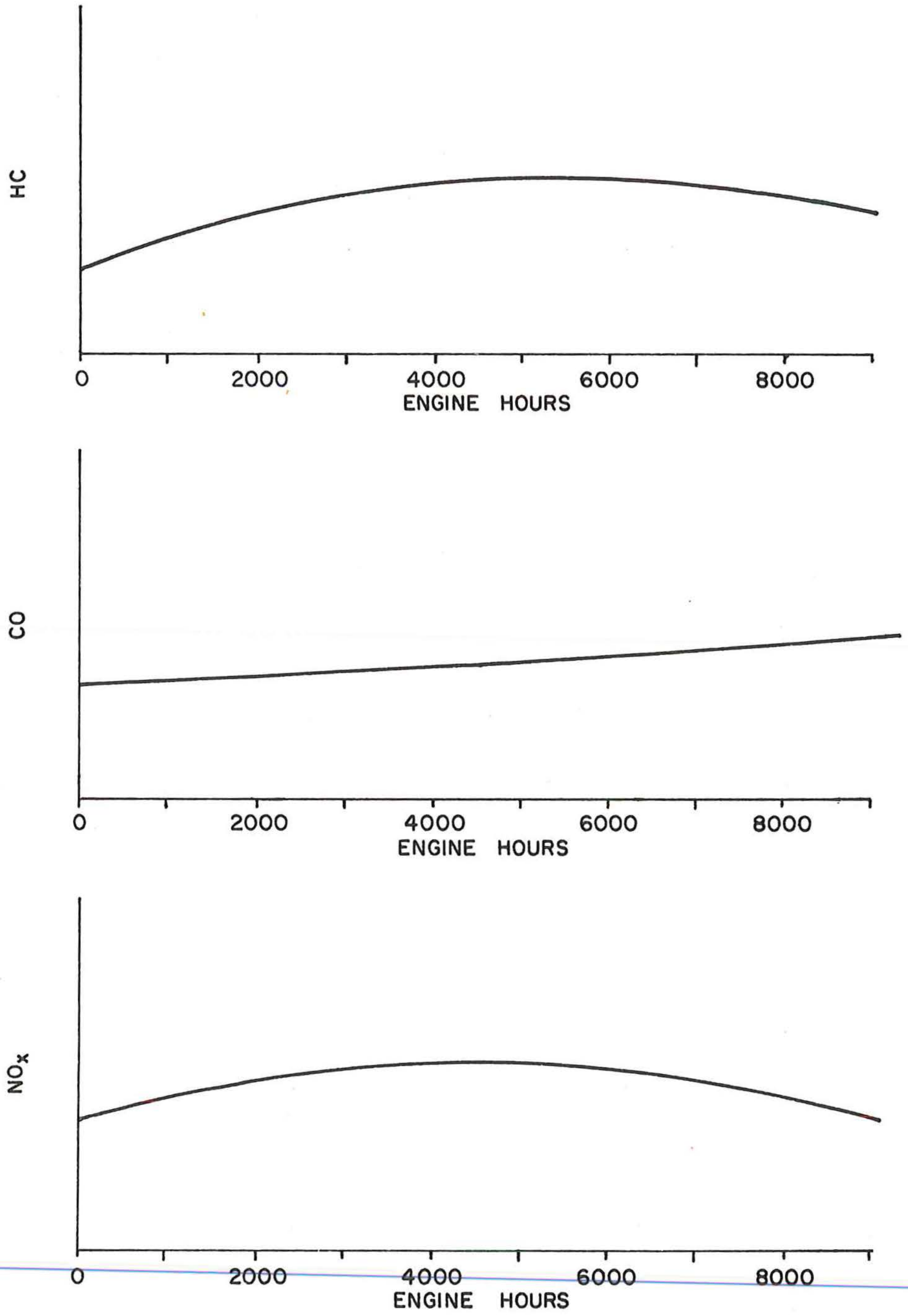

FIGURE 1.2.2-1 GASEOUS EXHAUST EMISSION TRENDS WITH TIME FOR NATURALLY-ASPIRATED ENGINES OPERATING UNDER MEDIUM DUTY CYCLE

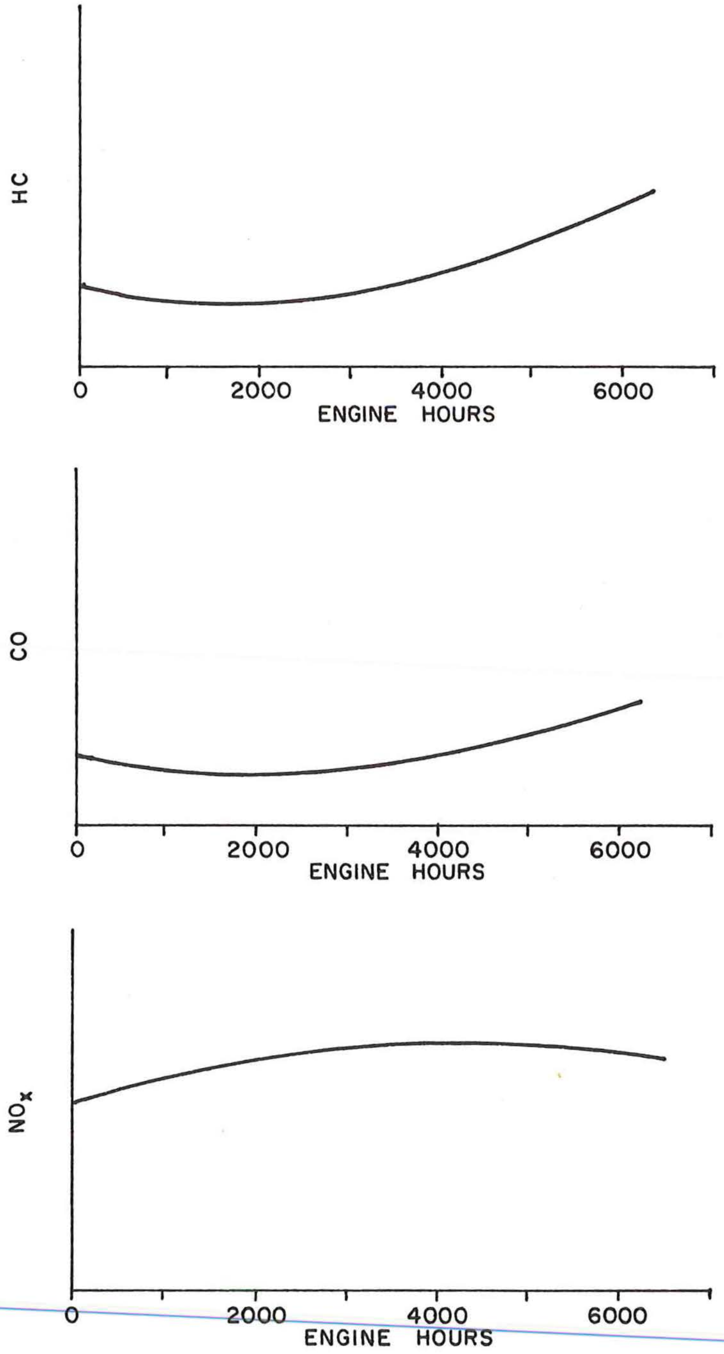

FIGURE 1.2.2-2 GASEOUS EXHAUST EMISSION TRENDS WITH TIME FOR TURBOCHARGED ENGINES OPERATING UNDER MEDIUM DUTY CYCLE

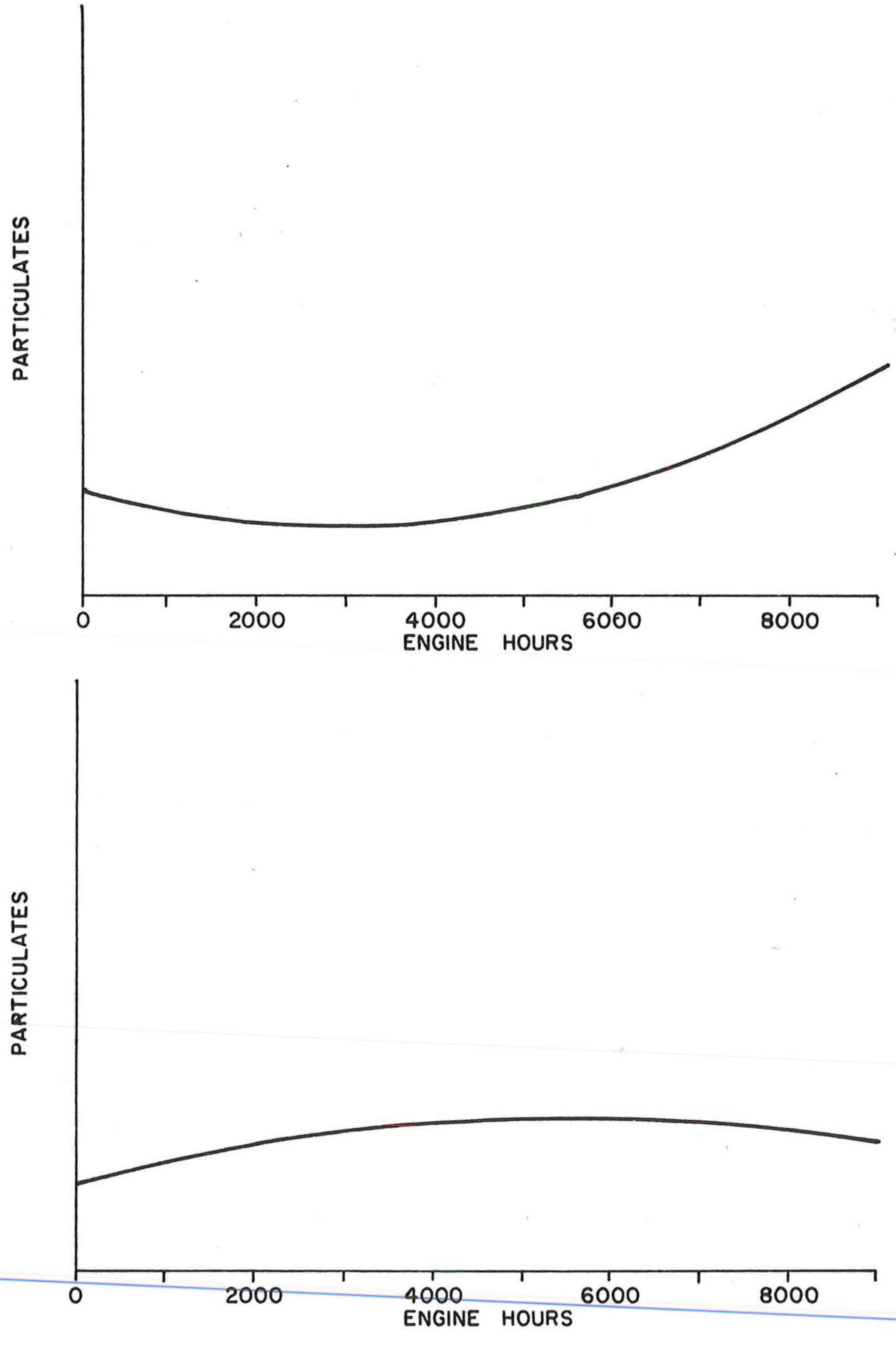

FIGURE 1.2.2-3 PARTICULATE EMISSION TRENDS WITH TIME FOR NATURALLY-ASPIRATED ENGINES OPERATING AT RATED SPEED/FULL LOAD (TOP) AND RATED SPEED/NO LOAD (BOTTOM)

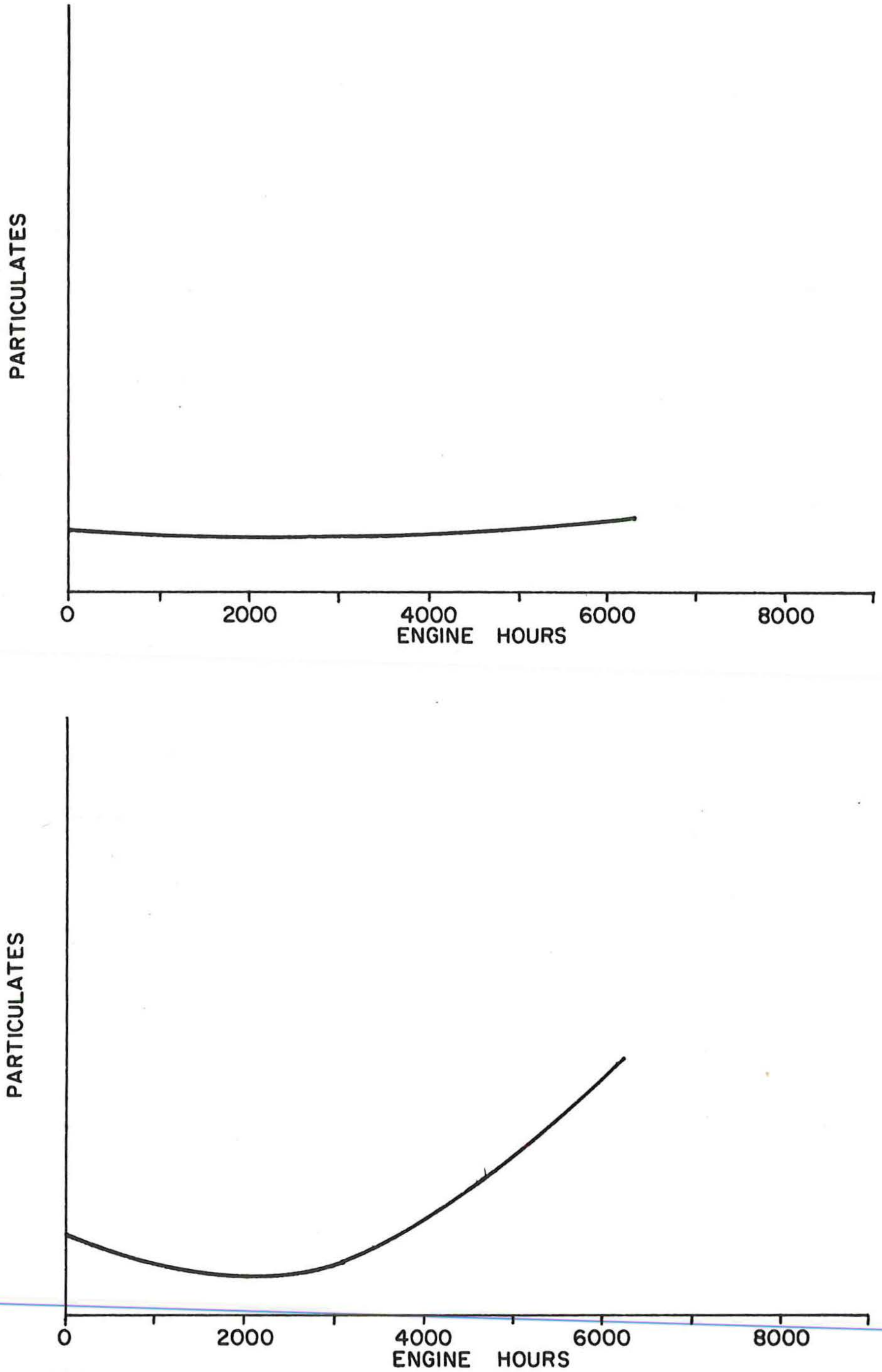

FIGURE 1.2.2-4 PARTICULATE EMISSION TRENDS WITH TIME FOR TURBOCHARGED ENGINES OPERATING AT RATED SPEED/FULL LOAD (TOP) AND RATED SPEED/NO LOAD (BOTTOM)

Table 1.2.3-1 Effect of Faults and Maladjustments on Diesel Engine Exhaust Composition: Arrows Indicate Change from Baseline

NO.	FAULT DESCRIPTION		HC	CO	NO_x	PART.*
1-1	Intake Restriction (in - H_2O)	25	→	→	→	→
1-2		50	→	→	→	↗
2-1	Exhaust Restriction (in - Hg)	3.0	→	→	→	→
2-2		6.0	→	→	→	→
3-1	Timing Advance (from Mfg. Spec.)	-4°	↑	↗	→	↑
3-2		+4°	↗	→	→	→
3-3		+8°	↗	→	↗	→
4-1	Overfueling (% rated)	10%	→	↗	→	↗
4-2		20%	→	↑	→	↗
5-1	Intake Restriction Timing Advance	25 -4°	↗	→	→	↗
5-2		50 -4°	↑	↗	→	↑
6-1	Exhaust Restriction Timing Advance	3.0 +4°	↗	→	→	→
6-2		6.0 +8°	→	→	↗	↗
7-1	Intake Restriction Overfueling	25 10%	→	↗	→	↗
7-2		50 20%	→	↑	→	↑
8-1	Overfueling Timing Advance	10% +4°	→	↗	→	↗
8-2		20% +8°	→	↗	→	↑
9-1	Intake Restriction Exhaust Restriction	25 3.0	→	→	→	→
9-2		50 6.0	→	↗	→	↗
10-1	Exhaust Restriction Overfueling	3.0 10%	→	↗	→	↑
10-2		6.0 20%	→	↑	→	↑
11-1	Int., Exh. Restric. Overfuel, Timing Adv.	25,3.0 10%,+4°	→	↗	→	↑
11-2		50,6.0 20%,+8°	→	↑	→	↑

*This represents particulate production at the most severe engine operating mode.

↑ indicates > 200% increase above baseline

↗ indicates 50% to 200% increase

→ indicates < 50% increase

The quantity of particulate produced by the engine while operating under full load was most affected by combining intake restriction with overfueling. With the engine operating at rated speed and no load, the combination of fuel injection retardation and intake restriction had the greatest effect on particulate production, increasing particulate quantity above baseline level by a factor of 50.

2. CONCLUSIONS

2.1 DIESEL ENGINE EXHAUST TRENDS OVER ENGINE LIFE

During the "mine visitation" portion of the program, several mines were investigated which had poor diesel engine maintenance organization and procedures. At these mines engines were reported to have relatively low service lives and often failed unexpectedly. During the "in-mine engine testing" portion of the program it was difficult to obtain permission from mines to perform the in-depth testing necessary. Only mines having good engine maintenance programs were willing to allow such testing to take place. Therefore it must be asumed that with a few exceptions most of the engines tested had received proper maintenance throughout their lives. With this qualification in mind, the following conclusions can be deduced.

In the absence of severe faults or maladjustments, exhaust emission quality does not demonstrate significant degradation during the initial 4000 hours of service. After 4000 to 5000 hours of service the engines tested during this program typically developed the following trends in production of specific exhaust emission components:

- Unburned hydrocarbons increased
- Carbon monoxide increased
- Nitric oxides decreased
- Particulates increased

There are two plausible explanations for the trends which were observed.

1) After many hours of service engine component wear becomes significant and affects the composition of the exhaust gas stream.

2) Older engines are not as carefully maintained and minor faults and maladjustments become more prevalent.

While interviewing vehicle and engine maintenance personnel at one underground mine, it was found that new vehicles and engines received "manufacturers' recommended service"; however, older vehicles were serviced only when a fault occurred. The situation in this one mine was an exception to consistent maintenance observed at nearly all other mines. Furthermore, since only one engine was tested from this mine, inconsistent maintenance does not explain the observed trend in exhaust emission production. Therefore, gradual engine component wear is believed to be the principal cause of the observed changes in exhaust gas constituent concentrations over time.

2.2 EFFECTS OF DIESEL ENGINE FAULTS ON THE COMPOSITION OF EXHAUST GAS

Diesel engine faults or maladjustments can drastically affect the concentrations of particular components in the exhaust gas stream. Induced individually in a naturally-aspirated, air-cooled engine, faults were observed to have the following effects:

- **Combustion air intake restriction** - increased particulates
- **Fuel injection timing maladjustment** - increased unburned hydrocarbons, increased nitric oxides, increased particulates
- **Engine overfueling** - increased carbon monoxide, increased particulates

Certain combinations of faults display synergism. For example, when the test engine was operating at rated speed and full load, neither intake restriction nor overfueling induced singularly had a significant effect on the production of particulates. However, when these two faults were induced simultaneously, particulate production increased by 1000 percent.

2.3 PERFORMANCE OF DIESEL ENGINES

As a result of testing performed during this program it is concluded that properly maintained diesel engines in service in underground mines can be expected to perform several thousand hours with minimal degradation of exhaust gas characteristics.

3. RECOMMENDATIONS

3.1 FUTURE USBM PROGRAMS

3.1.1 Develop an Underground Diesel Engine Maintenance Guide

The application of diesel engines in underground mines requires significantly different service and maintenance than that employed in surface operations. Many mine managers realize this and have developed special maintenance procedures. The development of a maintenance program for diesel engines in underground service would ensure mine operators knowing the particular requirements and critical items of service indigenous to the underground environment.

3.1.2 Develop Diesel Engine Powered Equipment Operation Guidelines

While diesel engines effectively perform most underground tasks while producing low levels of emissions, special procedures could be developed which would further minimize the production of pollutants. For example, an idling engine which could be shut down produces emissions unnecessarily. Also, a heavily loaded diesel engine operating at low speed can produce much more particulate than the same engine producing more horsepower at rated speed. Furthermore, this operational guide could assist the operator in detecting potential problems as he operates the vehicle.

3.1.3 Encourage Development of Diesel Engine Performance and Exhaust Measurement Instrumentation

Mine maintenance crews attempting to maintain engines at optimum performance are hampered by the absence of specialized instrumentation which can be used underground to easily determine engine condition. Technology is available for the development of an instrument package which would significantly aid maintenance crews. The U.S. Bureau of Mines should directly or indirectly stimulate the development of such instrumentation.

3.2 MAINTENANCE FOR DIESEL ENGINES IN UNDERGROUND MINES

3.2.1 Engine Intake Air Filters

It has been demonstrated that a substantially plugged intake air filter will increase the production of carbon monoxide by as much as 30 percent and the production of particulates by as much as 160 percent. It is therefore quite important to maintain the air filter in a good operating condition. If at all possible, it is recommended that intake air restriction sensors and indicators be provided on all diesel powered equipment. Such a sensor will be most useful if the indicator is located in the operator compartment.

Not all air intake system failures can be detected by a pressure drop indicator. A broken air line or punctured filter cannot be detected by this method. The best method presently available for detection of these failures is a visual inspection of the air intake system. A failure of this type does not cause an immediate alteration in emission characteristics. However, it allows ambient dust to be ingested by the engine. If this condition is not quickly repaired, it will cause rapid engine wear, resulting in increased emissions and reduced performance. Filter cleaning programs, other than complete filter cartridge rebuilds, are not recommended due to the possibility of filter damage.

3.2.2 Engine Cooling System

The loss of engine cooling will lead to scuffed cylinder walls and pistons, cracked heads, and burned valves. These conditions directly affect emission production and output horsepower. Air-cooled engines reject heat via cooling fins which are designed into the engine. During normal operation these fins become coated with oil and dust which bakes on to form a carbonaceous coating over the fins. This coating has a high thermal impedance, resisting heat flow to the ambient air. If this layer is allowed to build on the engine, overheating is inevitable. To prevent this situation, the engine should be steam cleaned periodically.

A liquid-cooled engine relies on transfer of heat from the coolant to the radiator and from the radiator cooling fins to the ambient air. As with an air-cooled engine, the surface of the cooling fins must be kept clean. Internal coolant passages of the radiator and engine must be kept free of mineral and rust deposits. Mine water is generally high in minerals and salts, rendering it unfit for use in engine cooling systems. It is recommended that a premix of a 50 percent mixture of distilled water and antifreeze be made available in the mine for addition to the cooling system when necessary.

3.2.3 Diesel Fuel Handling and Quality

There is considerably confusion in the mining industry concerning whether No. 1 or No. 2 diesel fuel should be used underground. It has been found that No. 2 diesel fuel:

- possesses better lubrication properties, extending fuel injection component life
- produces lower levels of the regulated exhaust gas components
- has higher energy content per gallon.

For these reasons it is recommended that No. 2 diesel fuel be used when the ambient temperature is above the cloud point of the fuel. This recommendation is made with the assumption that the slight increase in particulate production caused by No. 2 fuel is not an overriding factor.

The sulfur present in all diesel fuels directly affects the emissions of SO_2 and particulate sulfates. Additionally, sulfur in the fuel accelerates engine wear. It is therefore important to obtain the lowest sulfur fuel available.

The method by which diesel fuel is transported from the surface to the vehicle directly affects the cleanliness of the fuel. In general it is important to minimize the

3.2.7 Synergism of Diesel Engine Faults

During the testing conducted for this program it was found that the level of emissions caused by a pair of faults occurring individually is not nearly as severe as those two faults occurring simultaneously. This synergistic effect is exemplified in the data obtained from induced faults analyses. If an otherwise properly adjusted engine has an air intake restriction of 50 inches of water, particulates produced may increase by 75 percent. If an engine is overfueled by 20 percent and otherwise adjusted properly, the exhaust particulates may increase by 44 percent. However, if the engine has 50 inches of water intake restriction and is overfueled by 20 percent, the exhaust particulates may increase 1000 percent over a properly adjusted engine. This emphasizes the need of a maintenance program that considers all aspects of diesel engine maintenance.

4. FACTORS AFFECTING DIESEL ENGINE EXHAUST EMISSIONS

4.1 POSTULATED FACTORS DRIVING EMISSION CREATION

4.1.1 General Considerations

To study emissions from diesel engines and effects of maintenance on their composition and concentration, other factors need to be considered that have additional, separate, or combined influence. Figure 4.1.1-1 shows these factors and how they affect emissions. These can be separated into three groups. Group I has direct or indirect influence on the operation or performance of the engine and its exhaust emissions. Group II involves treatment of the exhaust after it has left the exhaust pipe. Group III consists of engine design factors, determining how well the engine performs while producing low emissions. Table 4.1.1-1 summarizes the three groups of measures applicable to modification or control of these factors.

4.1.2 Effect of Diesel Emissions After Release

4.1.2.1 Ambient Air Quality

The present method of controlling emissions in the mine ambient air is by dilution of the exhaust to levels below established Threshold Limit Values (TLV). Inspections by MSHA and State Inspectors include sampling ambient air near the mine face or the operator. If the TLV limits are not exceeded, no problem exists. Table 4.1.2.1-1 shows the present TLV limits that can be enforced.

Table 4.1.2.1-1. TLV Limits Enforceable in Mines (Ambient Air)

	TLV-TWA (ppm)	TLV-STEL (ppm)	TLV-C (ppm)
Carbon monoxide, CO	50	400	--
Carbon dioxide, CO_2	5000	15,000	--
Nitrogen dioxide, NO_2	5	5	5
Sulfur dioxide, SO_2	5	5	5
Formaldehyde	2	2	2
*Oxides of Nitrogen, NO_x	25	(CFR 30 - equivalent nitrogen dioxide)	
*Aldehydes	10	(CFR 30 - equivalent formaldehydes)	

---

* From CFR 30

Dust in coal mines is controlled to less than 2 mg/m^3 and in non-coal mines to less than 10 mg/m^3 unless it contains quartz. Depending on the quartz concentration, the maximum dust concentration will be less than 10 mg/m^3. Neither diesel

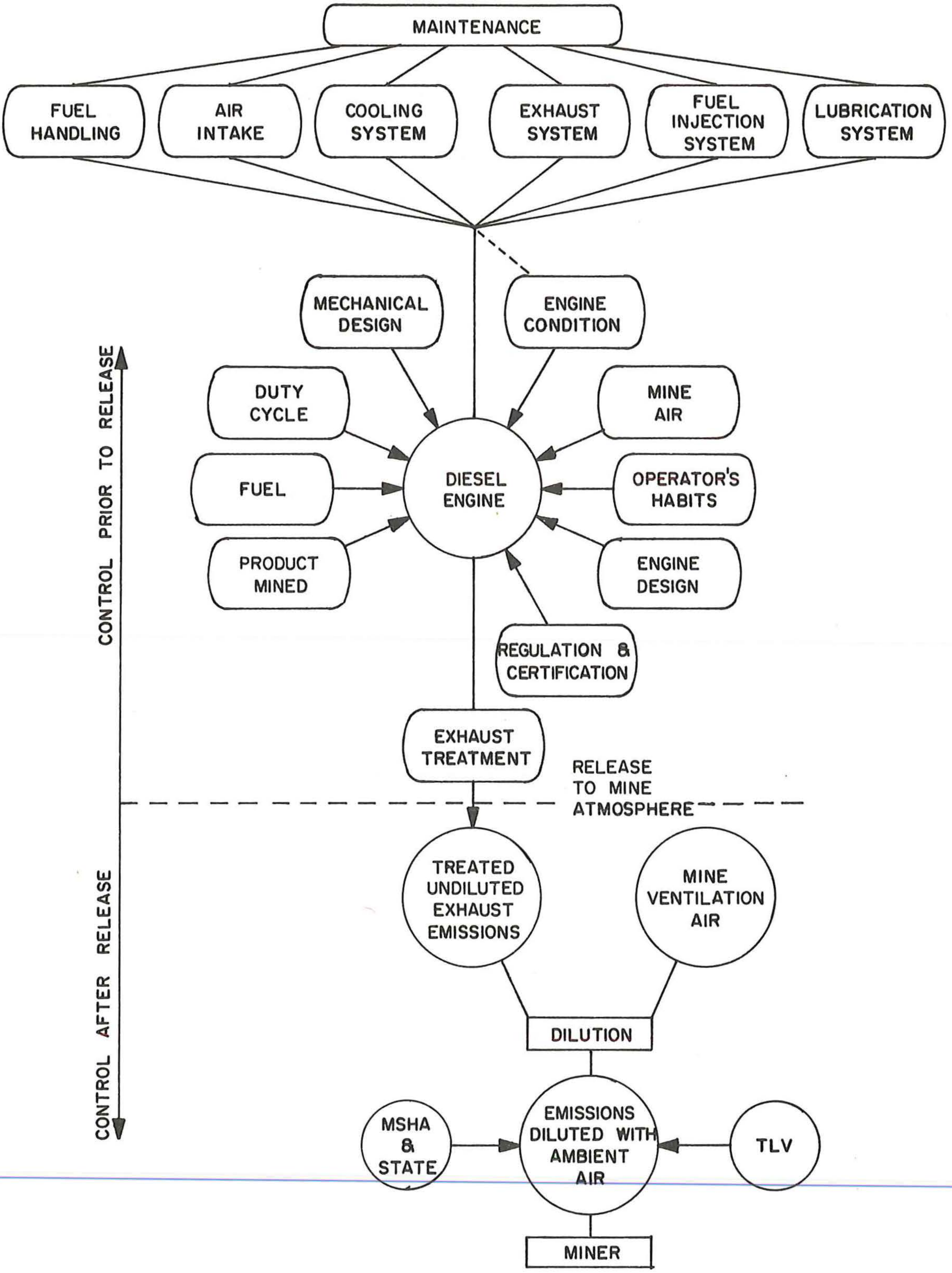

FIGURE 4.1.1-1 CONTROL OF DIESEL ENGINE EXHAUST EMISSIONS

Table 4.1.1-1 Factors Affecting Diesel Engine Exhaust Quality in the Mine

Group I - Controlling Factors Before Discharge

1.	Operator Habits	Training Experience Personal Attitude Incentives/Bonus
2.	Duty Cycle	Mine Condition Extraction Plan Equipment Selection Tramming Distance
3.	Mechanical Design	Auxiliary Engine Components Drive Train Arrangement
4.	Engine Condition	Maintenance Normal Wear Damage
5.	Fuel	Fuel Quality Control Sulfur Content Contamination Handling and Storage
6.	Mine Environment	Grade Drift Size Humidity Water Dust
7.	Maintenance	(Discussed in detail in this report)
8.	Exhaust Treatment	Water Scrubber Water Spray Catalytic Converter Fume Diluters Mixing Exhaust Pipe Location

Group II - Control After Discharge

1.	Ventilation	Amount of Ventilation Air Direction of Air Air Curtains Ventilation Plan

Group III - Control Through Engine Design

		Combustion Method Injection System Design Intake Air Method Exhaust Gas Recirculation Mixing Process Water Injection

particulates nor unburned hydrocarbons are controlled at this time. The three categories of TLV limits itemized in Table 4.1.2.1-1 are defined as follows by The American Conference of Industrial Hygienists:

> **Threshold Limit Value-Time Weighted Average (TLV-TWA)** - This is the time-weighted average concentration for a normal 8-hour workday or 40-hour workweek, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect.
>
> **Threshold Limit Value-Short Term Exposure Limit (TLV-STEL)** - This is the maximum concentration to which workers can be exposed for a period up to 15 minutes continuously without suffering from (1) intolerable irritation; (2) chronic or irreversible tissue change; or (3) narcosis of sufficient degree to increase accident proneness, impair self-rescue, or materially reduce work efficiency. This is provided that no more than four excursions per day are permitted, with at least 60 minutes between exposure periods, and provided that the daily TLV-TWA also is not exceeded. The STEL should be considered a maximal allowable concentration or absolute ceiling, not to be exceeded at any time during the 15-minute excursion period.
>
> **Threshold Limit Value-Ceiling (TLV-C)** - This is defined as the concentration that should not be exceeded even instantaneously. For some substances, e.g., irritant gases, only this category may be relevant. For other substances either two or three categories may be relevant, depending upon their physiologic action. It is important to observe that if any one of these three TLVs is exceeded, a potential hazard from that substance is presumed to exist.

4.1.2.2 Health Effects

The health effects of exhaust emissions (CO, CO_2, NO_2, SO_2) that are presently regulated in the ambient mine atmosphere have been studied extensively. The following briefly discusses each.

- CO_2 is a product of complete combustion and has only a slight health effect in higher concentrations. Being an asphyxiant, it will cause an increase in breathing rate at concentrations above one percent.
- CO (carbon monoxide) is toxic in relatively low concentrations, reducing the ability of the blood to transport oxygen to the cells.
- NO_x Oxides of Nitrogen includes all compounds of nitrogen with oxygen. NO (nitric oxide) is produced during the combustion process but oxidizes into NO_2 in the oxygen rich exhaust of the diesel engine. NO_2 (nitrogen dioxide) is considered highly toxic and a ceiling limit of 5 ppm in the ambient mine atmosphere is enforced. Pulmonary edema has resulted after exposure to 80 ppm NO_2 for 30 minutes. Irritation of the eyes is normally experienced at levels of 10-20 ppm.
- SO_2 (sulfur dioxide) has a ceiling limit of 5 ppm. Production of sulfur dioxide is directly related to the sulfur content of the fuel, and can be controlled by merely limiting the sulfur in the fuel. The upper

respiratory tracts are affected by SO_2 while SO_3 (sulfur trioxide) affects the lower respiratory tracts.

- Unburned hydrocarbons are presently not regulated as exhaust constituents. Characteristically, they can range from CH_4 (methane) to the C_{30} type heavy hydrocarbons found in lubricants. Measurements of hydrocarbons may include only the lighter ones, depending on the sampling technique. Presently, little is known concerning their health effects.

- Aldehydes are partially oxidized hydrocarbons which include formaldehyde and acrolein and are considered irritants. Formaldehyde has a TLV-C limit of 2 ppm and acrolein of 0.2 ppm TLV-C.

- Diesel exhaust particulate matter are presently regulated only by the total dust concentration of the mine ambient air. Particulates can be divided into the soluble organic fraction and insolubles. Insolubles are primarily carbon and sulfates while the soluble organic fraction (SOF) consists of a large number of different compounds, see Figure 4.1.2.2-1. The soluble organic fraction of the total particulate mass is of interest from the health standpoint, since it contains compounds that may be carcinogenic. Their impact on health is still undetermined. Table 4.1.2.2-1 contains some of the diesel particulate compounds.

4.1.3 Factors Affecting Emissions Before Release

4.1.3.1 Operators' Habits

Assuming the same mine, equipment, and conditions exist for a particular situation, two different operators will seldom handle the equipment the same way. Abuse, lack of training, personal attitudes, and incentive programs are only a few considerations. Basically, the human factor is a variable that cannot be controlled by engineering methods yet will affect exhaust emissions. It should be considered a management problem rather than an engineering problem.

4.1.3.2 Duty Cycles

Duty cycles for different mining equipment vary considerably from mine to mine and from equipment to equipment. Although no typical duty cycle has been established at this time, most equipment operates under either light- or heavy-duty cycles. Light-duty includes support equipment, personnel carriers, lubrication vehicles and other equipment with relative light use. Engines are small (up to 50 Hp), and the daily operating time is usually less than two hours. Because these engines are small and operating time is short, their impact on mine ventilation is minimal. Heavy-duty includes all production equipment and heavily utilized equipment. Engines range up to 400 Hp. Their impact on mine ventilation is significant. Table 4.1.3.2-1 shows the basic categories of both heavy- and light-duty cycles as they were observed in the mines.

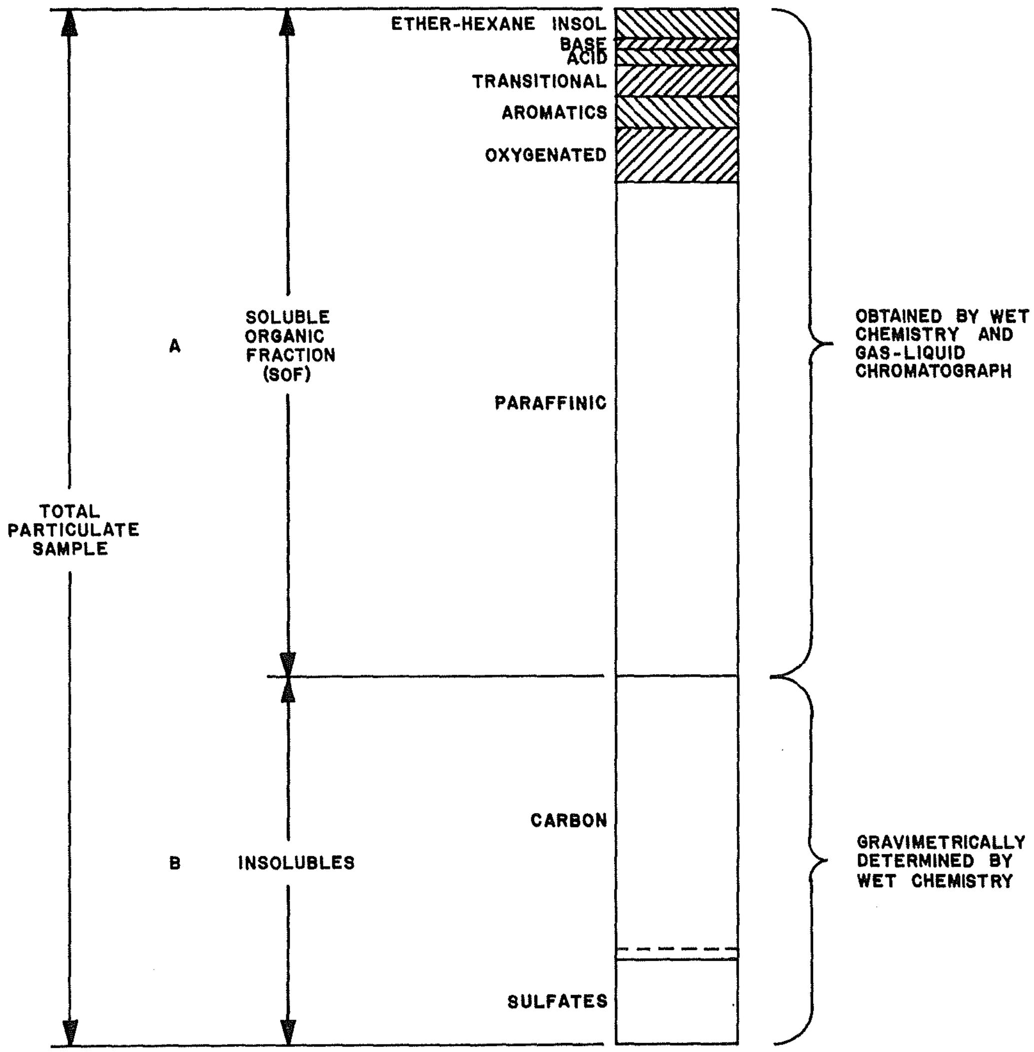

FIGURE 4.1.2.2-1 ANALYSIS OF TOTAL PARTICULATE FROM DIESEL EXHAUST

Table 4.1.2.2-1. Compounds Extracted from Diesel Particulate

ACIDIC COMPOUNDS

Phenol
Cresol
Dinitro-o-cresol
Benzoic acid
o,m,p-Phenylphenols

BASIC COMPOUNDS
Pyridine
Aniline
Benzacridene
o-Boluidine

PARAFFINIC COMPOUNDS

Pentane
Hexane
Octane
n-Tetradecane
n-Pentadecane
n-Hexadecane
n-Octadecane
n-Nonadecane

n-Eicosane
n-Heneicosane
Cyclohexane
Methylcyclohexane

AROMATIC COMPOUNDS

Benzene
Toluene
Diphenyl
Anthracene
Styrene
Xylene
Pyrene
Chrysene

Benzo(a)pyrene
Benzo(j)fluoranthene
Benzo(b)fluoranthene
Trimethylnaphthalene
Ethylfluorene
Dimethylphenanthrene

TRANSITIONAL COMPOUNDS
Dioxane
Methoxyphenanthrene

OXYGENATED COMPOUNDS
Hydroquinone
9,10-Anthraquinone
Furfural
Furfuryl alcohol
Cyclohexanol
2-Hexanone
Methylacetate
Crotonaldehyde
2-Pentanone

Table 4.1.3.2-1. Basic Groups of Duty Cycles

Heavy-Duty	Light-Duty
Front end loaders	Personnel carriers
Load haul dump units	Mechanics' vehicles
Telescoping haul trucks	Lube trucks
Rear dump trucks	Fuel trucks
Scooptrams (mucking)	Mantrips
Roof Bolters	Powder platforms
Scaling rigs	Roof drills (air-diesel)
Locomotives (mucking)	Scaling rigs (air-diesel)
Clean up loaders	Scoop trams (supply)
Graders	Locomotives (supply-man trip)
Dozers	Supply vehicles

Since many conditions can alter a duty cycle, it is clear that it would be difficult to show a typical duty cycle for even a certain type of equipment. There is no "standard" duty cycle for mining applications at this time. Some hypothetical duty cycles are presented later in this report to ease data reduction and analysis. The duty cycle is affected by several factors shown in Table 4.1.3.2-2. To emphasize the impact which mine layout and design has on engine duty cycle, vehicle motions in several mines are illustrated in Figures 4.1.3.2-1 through 4.1.3.2-6.

Table 4.1.3.2-2. Factors Affecting Duty Cycle

1. Equipment design and size
2. Engine design and size
3. Mine atmosphere: temperature
   altitude
   humidity
   dust
4. Mine condition: level - inclined
   wet - dry
5. Length of tramming
6. Payload
7. Specific gravity of muck
8. Speed
9. Operator's habit

4.1.3.3 Mechanical Design

Design, arrangement, and component selection affect ultimate exhaust emissions. A unit with hydrostatic drive performs differently from one with a torque converter power shift transmission under the same conditions. Intake air restrictions, air recirculation, removal of radiated heat, and sizing of components are among the mechanical design considerations. Exhaust treatment is considered part of the mechanical design. The efficiency of the exhaust treatment system (scrubber, converter spray or diluter) will affect emissions. Basically, this factor includes all methods of controlling emissions by design.

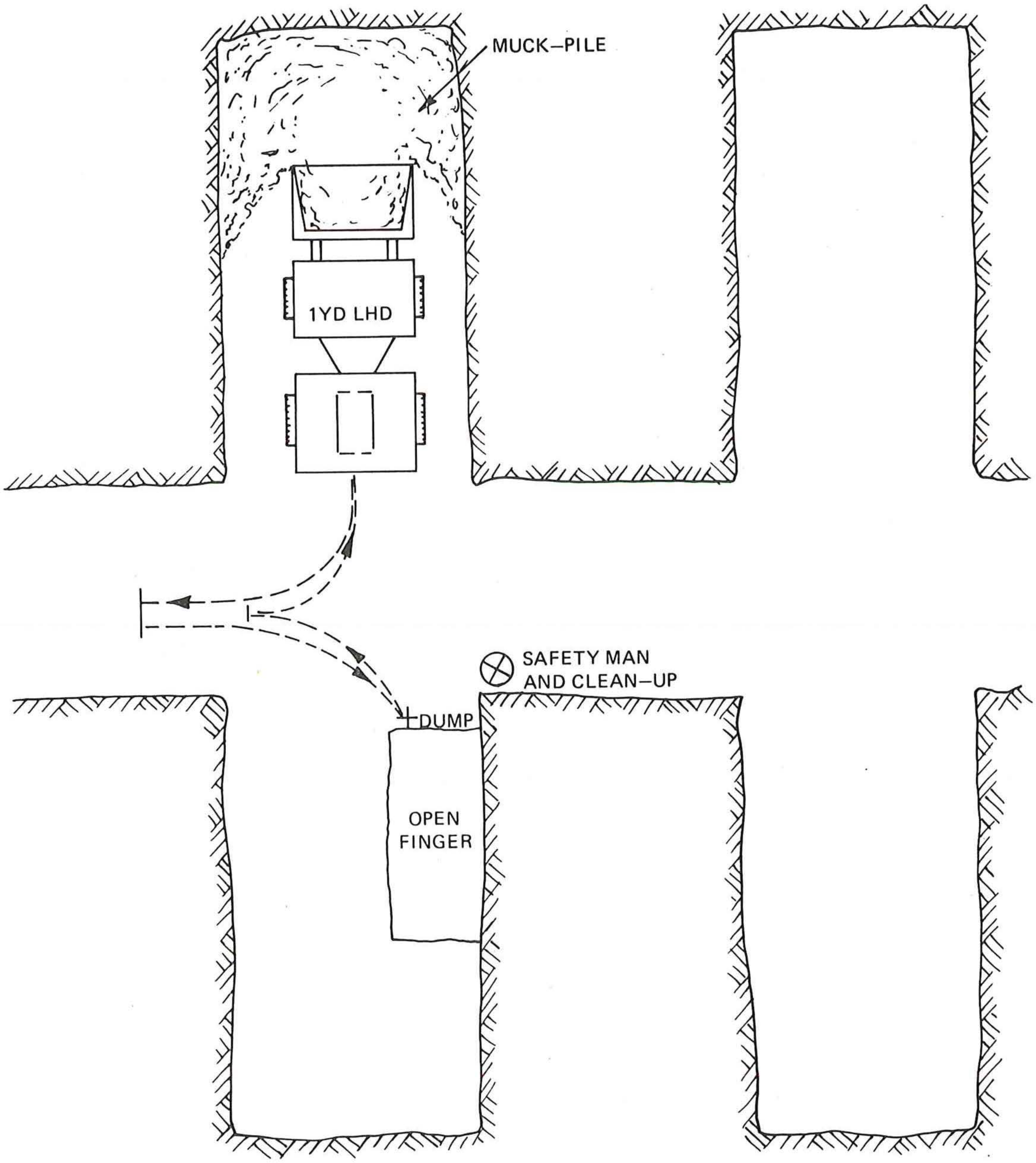

FIGURE 4.1.3.2-1 MUCKING IN A HARD-ROCK MINE

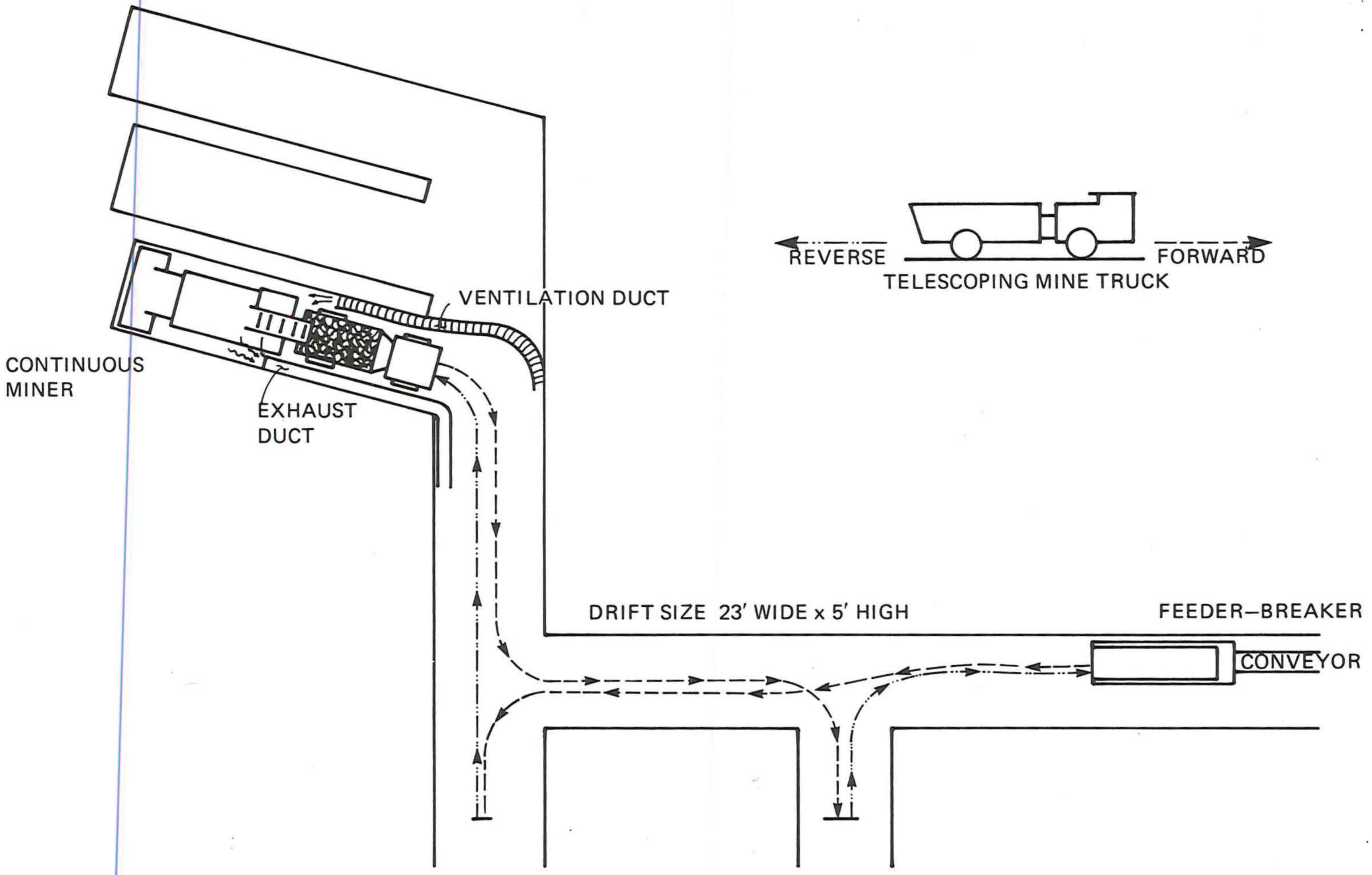

FIGURE 4.1.3.2-2 HAULAGE IN A POTASH MINE

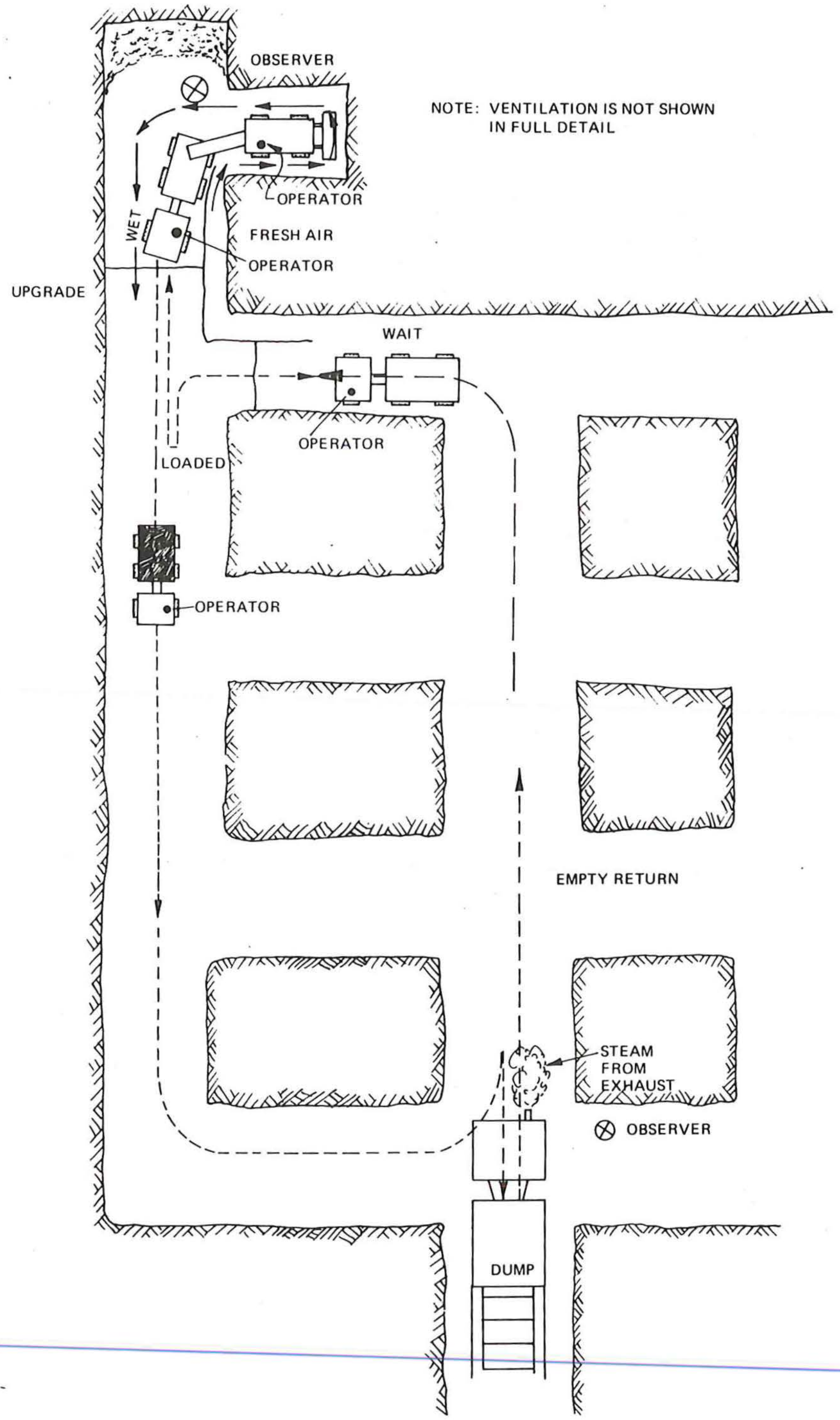

FIGURE 4.1.3.2-3 HAULAGE IN A COAL MINE

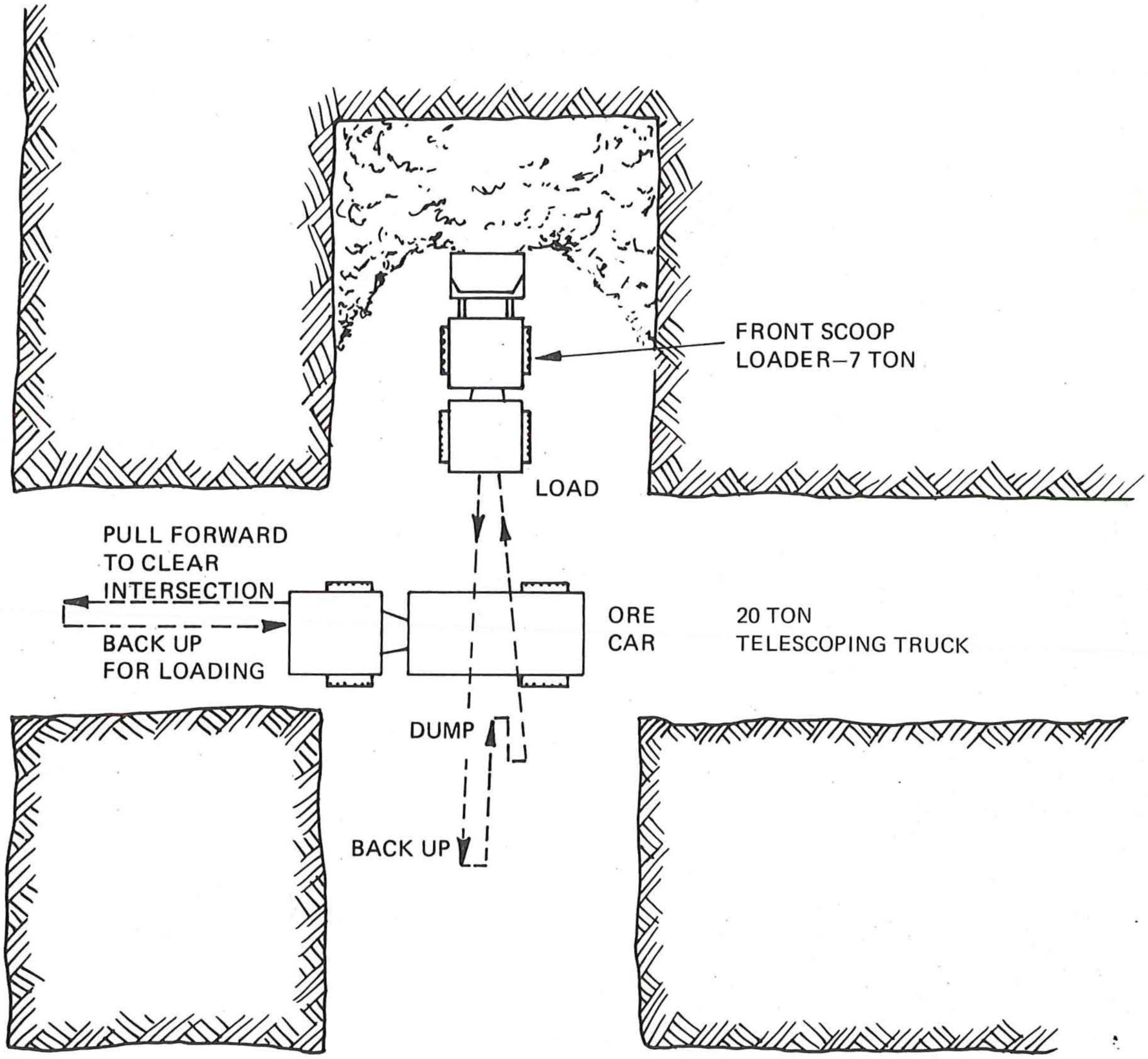

FIGURE 4.1.3.2-4 LOADING IN A HARD-ROCK MINE

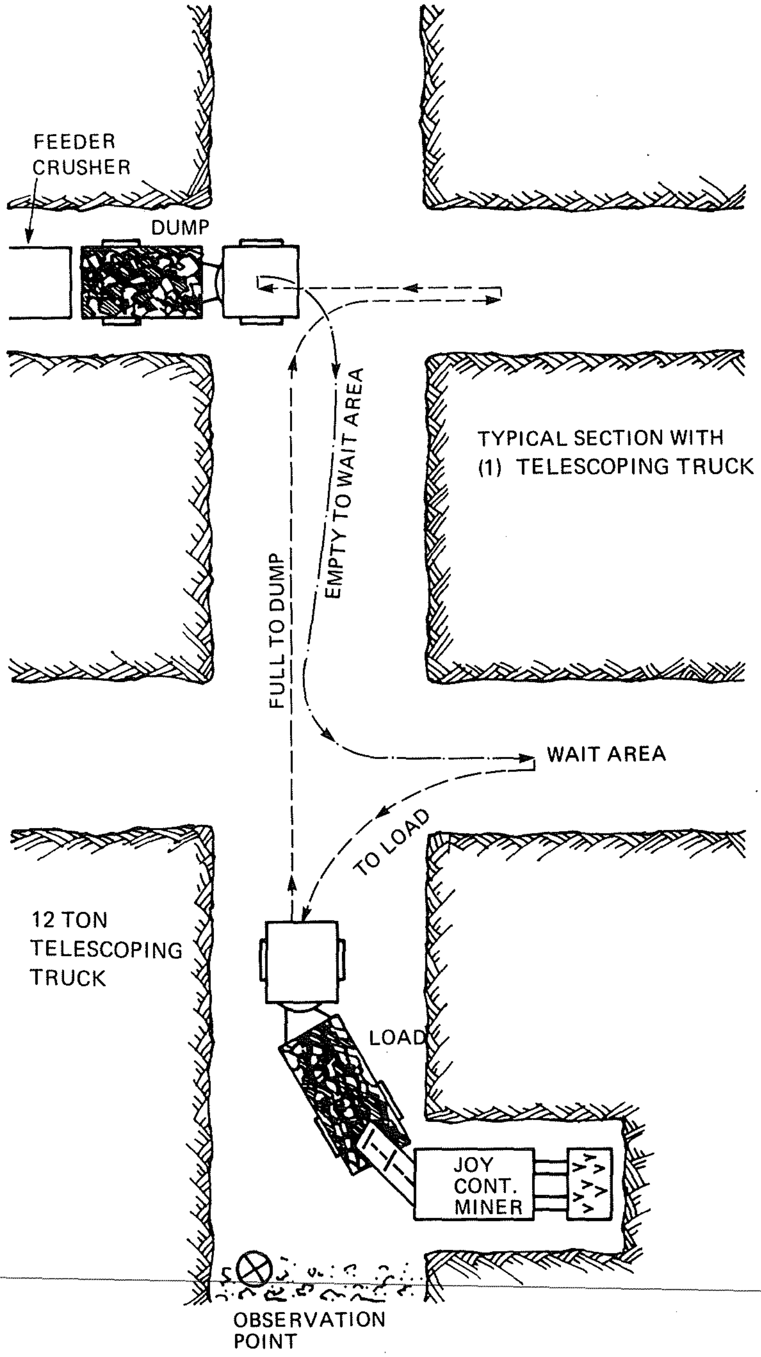

FIGURE 4.1.3.2-5 HAULAGE IN A COAL MINE

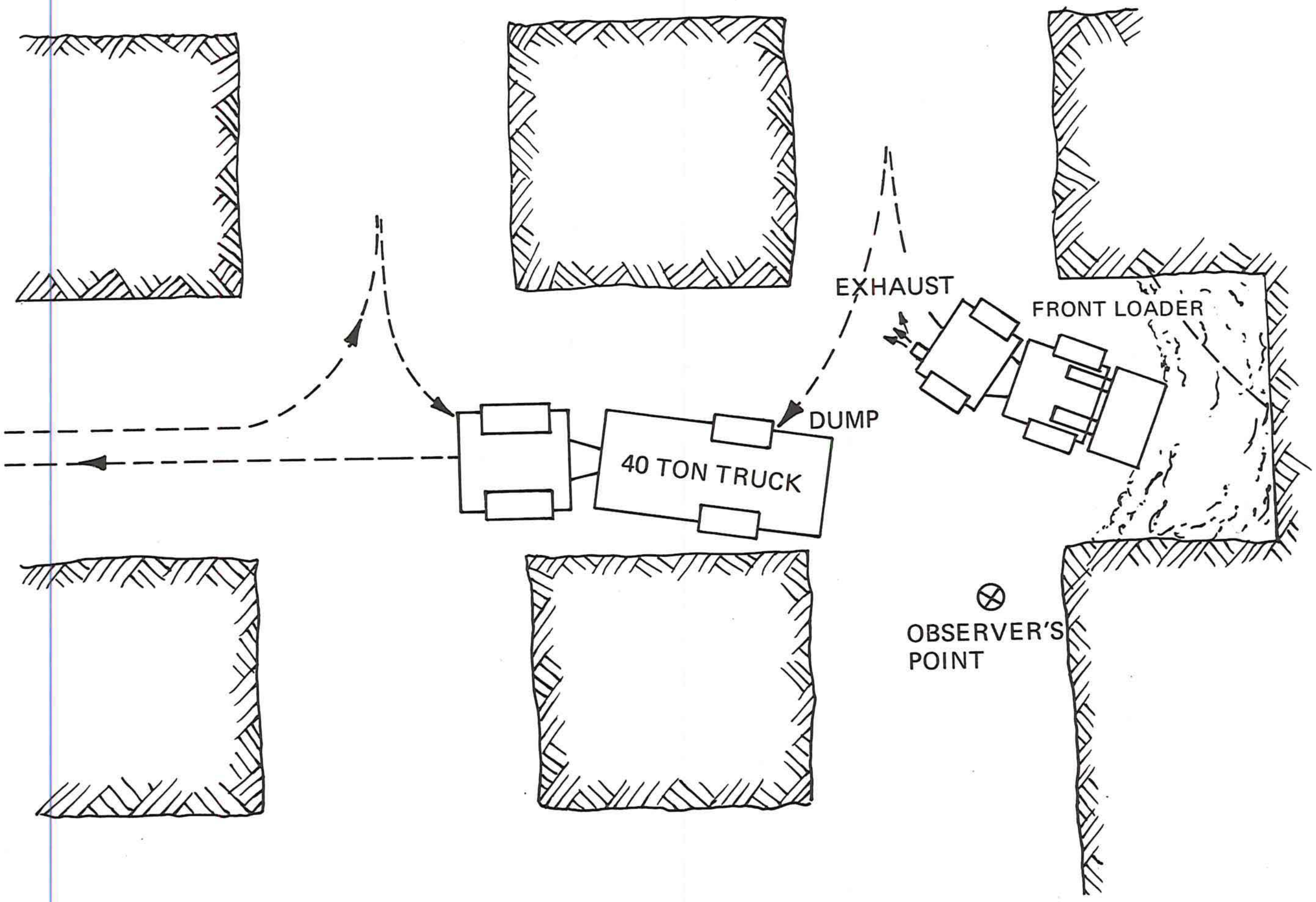

FIGURE 4.1.3.2-6 LOADING IN A HARD-ROCK MINE

4.1.3.4 Fuel

Fuel has a direct effect on emissions. Regardless of any other condition, fuel sulfur will produce SO_2 and sulfates in the emissions in proportion to its percentage in the fuel. The percentage of sulfur in the fuel is limited to less than 0.5 percent but may vary considerably. Fuel preference voiced by mine managers is about equally divided between No 2. Diesel and No. 1 Diesel, but a mine will in may cases buy what it can get. Possible mixing with other liquids and contamination with solids and water are additional factors requiring large-scale sampling to determine what is actually burned in a diesel engine operating underground.

4.1.3.5 Mine Environment

Mine environments vary with each mine and even within one mine. The following list shows a number of factors of the mine environment that can affect emissions directly or indirectly.

- Mine size
- Grade
- Altitude of mine
- Ambient air temperature
- Dust, concentration, and composition
- Humidity
- Water
- Ventilation
- Methane concentration

In addition, diesel engine emissions will alter the mine atmosphere and temperature, sometimes creating a "mini-environment" in the immediate vicinity of the engine different from the rest of the mine.

4.1.3.6 Engine Condition

Perhaps the factor most affecting emissions is that of engine condition. The engine may have two types of faults:

- Reversible (temporary),
- Irreversible (permanent).

Reversible conditions include plugged air cleaners, improper timing, etc. Irreversible conditions are those that require repair or overhaul such as broken rings, burned valves, etc. Engine condition change, however, usually results from one or more of the six maintenance criteria in Figure 4.1.1-1. If everything operated perfectly, the engine would normally be expected to operate approximately 10,000 hours depending upon the severity of the duty cycle and proper care for the engine. However, problems with any of the above areas, or a combination of them, may result in a prematurely deteriorated engine.

4.1.3.7 Maintenance

Improper maintenance is one of the major factors in premature engine deterioration and emission changes. It is also the one factor a mine operator has more control over than any other. Maintenance can be effective with a properly organized maintenance plan. Elsewhere in this report the subject of maintenance will be discussed in detail.

4.2 DIESEL ENGINE MAINTENANCE PROBLEMS OBSERVED IN THE MINING INDUSTRY

4.2.1 General Observations

Maintenance of any equipment, including diesel engines, consists of an effort to keep it in operating condition for production and ultimately profit. Maintenance in itself does not yield a profit in a direct sense; in fact, equipment is an expense while idled for maintenance. Maintenance procedures such as a preventive maintenance program and periodic repairs and replacements or adjustments, if properly designed and performed, will extend the useful life of equipment. These procedures will also increase its availability for production by reducing unscheduled repairs. It further permits scheduled maintenance rather than unscheduled breakdowns. Such a maintenance program is not free. Careful planning of the entire organization is necessary. Full cooperation between production and maintenance and a certain number of spare units are generally part of a successful program.

Good maintenance is a necessity from an economic point of view. Excellent production rates and lower operating costs have been achieved by some companies. Other operations are troubled with frequent breakdowns and low availability to a point where the operation becomes unprofitable. Lack of maintenance also increases the risk of equipment failure, possibly resulting in accidents. Improper maintenance or lack of it can increase exhaust emissions, particularly with diesel engines.

Why maintenance is often neglected is difficult to determine. Operations have been observed where maintenance effort is minimal and equipment is run to destruction. Engine life as low as 200 hours was reported during the field interviews. Many operations showed little knowledge of the economics of a good maintenance program, but stated that the operation makes a profit despite equipment problems. Education of such operations in the economics of maintenance may add a completely new perspective. The understanding of failure mechanisms and reasons for premature deterioration of performance and emissions is discussed in detail later in this report.

4.2.2 Maintenance in Underground Mines

The type of maintenance in underground mines varies from poor to excellent. However, there are unique problems all mines have in common that are not experienced in other industries. Underground environment is hard on the equipment. Wet conditions, abrasive materials, and dust can reduce the life of equipment. The severity varies with mines: some have level, wide, haulage drifts while others are narrow and steep, containing sharp rocks.

Working areas in underground mines are usually small. The problem of supplying the maintenance shop with the necessary parts exists at all mines. In some, about a week lead time is required to deliver an item to the shop. Maintenance shops in underground mines vary as much as maintenance organizations themselves. Some mines have well lighted and large, ventilated shop areas where the more complicated repairs can be undertaken. Some mines purchase specialized engine diagnostic equipment for the preventive maintenance program. On the other end, small poorly lighted cutouts may serve as shops. Equipment may consist of a few wrenches, a torch, and a large hammer.

The skills and qualifications of the mechanics also range from expert to totally unskilled. Mines in remote and undesirable locations may have difficulties in finding good skilled people. On-the-job training is often the only good solution. High turnover only adds to these problems. A large variation in maintenance organizations was observed during field visits. One mine had one "good" mechanic that was moved from job to job when other mechanics couldn't handle the work. Another mine had a four year traning program and very stable employment, but a very ineffective preventive maintenance program. A small mine which was contacted had considerable maintenance problems until all preventive maintenance work was subcontracted to several engine and equipment dealers in the area. This dramatically reduced downtime and increased equipment availabiity. Oil analysis programs of varying effectiveness and success were employed by many mines.

4.2.3 Training of Maintenance Personnel

Aside from the lack of a good preventive maintenance program, lack of skills and experience by the mechanics can be considered the greatest obstacle to a successful maintenance organization. To overcome mechanic inexperience, training programs are necessary. Such programs can be conducted in several ways.

- **Previous Training** - If a trained and qualified mechanic can be hired, only short training or orientation may be required. However, there is a shortage of good mechanics.

- **Mechanic Schools and On-the-Job Training** - Graduates from trade schools with some basic skills can be hired and assigned to work with skilled mechanics. Sometimes they can be given some additional in-mine formal training. This can be a good method, but will take several years before the mechanic is highly skilled.

- **Transfer of Employees and On-the-Job Training** - Operators of equipment or other employees often have a good knowledge of equipment from their experience. With proper training, such employees sometimes make good mechanics after several years of mechanic's work.

- **Hire New People and Train** - This is probably the most costly approach since all training has to be provided. It takes years before such a new employee has learned all needed skills to be a good mechanic.

- **Subcontract Maintenance** - This approach eliminates any training by the mines, but may not be feasible at many places. If a lack of skilled people in the general areas exists, the problem is not solved. The responsiblity for the training is simply transferred to the subcontractor. However, for small mines this could be a good approach.

- **Utilize Experience** - If a shortage of skilled mechanics exists in an area, employment of lower skilled people for less difficult responsibilities will free the highly skilled people for more difficult tasks. This method may require the more highly skilled people to be moved around within the mine where they are needed.

Regardless of the type of organization and the previous training of the mechanics, changing technology and new equipment require continued training. This may be done through special seminars or presentations by manufacturers of engines and equipment. The better the training, the more successful the maintenance organization will be. Ultimately, the availability of equipment for production will improve. This will eventually increase productivity and overall success of the operation.

4.3 MAINTENANCE ORIENTED FAILURE MECHANISMS AFFECTING EMISSIONS

During field visits, six areas of maintenance activities were identified which can affect emissions either directly or indirectly through engine deterioration. These areas are as follows in their order of frequency and significance:

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

The following section of this report will show for each of the above areas, the mechanisms of their effects on emissions. Various design criteria, maintenance requirements, and other considerations will be discussed for each.

4.3.1 Air Intake System

4.3.1.1 Effects of Air Cleaners on Emissions

The air intake system can affect emissions in two ways:

- **Directly - intake restriction due to plugged filter.** This condition is temporary and can be corrected by cleaning or changing the intake system or filter element. Emissions are affected due to reduced air/fuel ratio causing changes in the CO (gaseous) and smoke (particulate) emissions. Other effects are loss of power and possible overheating.

- **Indirectly - failure of any part of the engine resulting from dust ingestion.** Faulty filter elements, broken intake air hoses, or loose connections are the main causes of dust ingestion. If this condition persists and equipment is operated in dusty conditions, engine wear will lead to increased oil consumption, increased particulate emissions, and changes in gaseous emissions. This will also cause loss of power and overheating. This is irreversible damage requiring engine rebuild for restoration.

4.3.1.2 Discussion of Air Intake System Problems

Based on mine visits and literature surveys, the air intake system of a diesel engine can be considered the most vulnerable and often most neglected part of a diesel engine. A dusty working condition encountered near operating faces of underground mines requires more effective air intake systems and considerably more attention than is needed for surface or stationary equipment. Filters with precleaners **and** daily service are necessary under extreme conditions. Some engine rebuilders routinely replace all pistons from returned engines, since most of them are not reusable due to damage by dust. One Caterpillar rebuilder stated that at his facility only one out of five pistons from underground engines can be reused, while for surface equipment, at least one out of two are reusable. All the rebuilders interviewed considered dust intake the main reason for engine failures. Exhaust emission changes due to intake air system failures are shown in Figure 4.3.1.2-1.

The total dust concentration in the metal mine atmosphere is limited by CFR-30 to 10 mg/m^3 or less, depending on the silica concentration. For coal mines, the maximum concentration allowable is 2 mg/m^3. However, localized short-term dust levels considerably higher have been reported. Information from a filter manufacturer indicated a peak level of 150 mg/m^3 had been measured at the engine air intake of a vehicle operating in a coal mine.

Rebreathing of engine exhaust can create additional problems. Evidence of particulates attached to air intake cleaners has been found by some mines. The approximate mass of dust collected by an air intake filter on a given engine for a specified operating time can be calculated as follows: given the engine speed and average dust concentration in the combustion air.

Air consumption for a four-stroke, naturally-aspirated, diesel engine is calculated as:

$$A = \frac{V \cdot n \cdot e}{2000}$$

where

A = Air consumption (std m^3/min)
n = Engine Speed (rpm)
V = Displacement of Engine (liters)
e = Volumetric efficiency = 0.9 (assumed for this engine)

The total amount of dust collected by the filter is as follows:

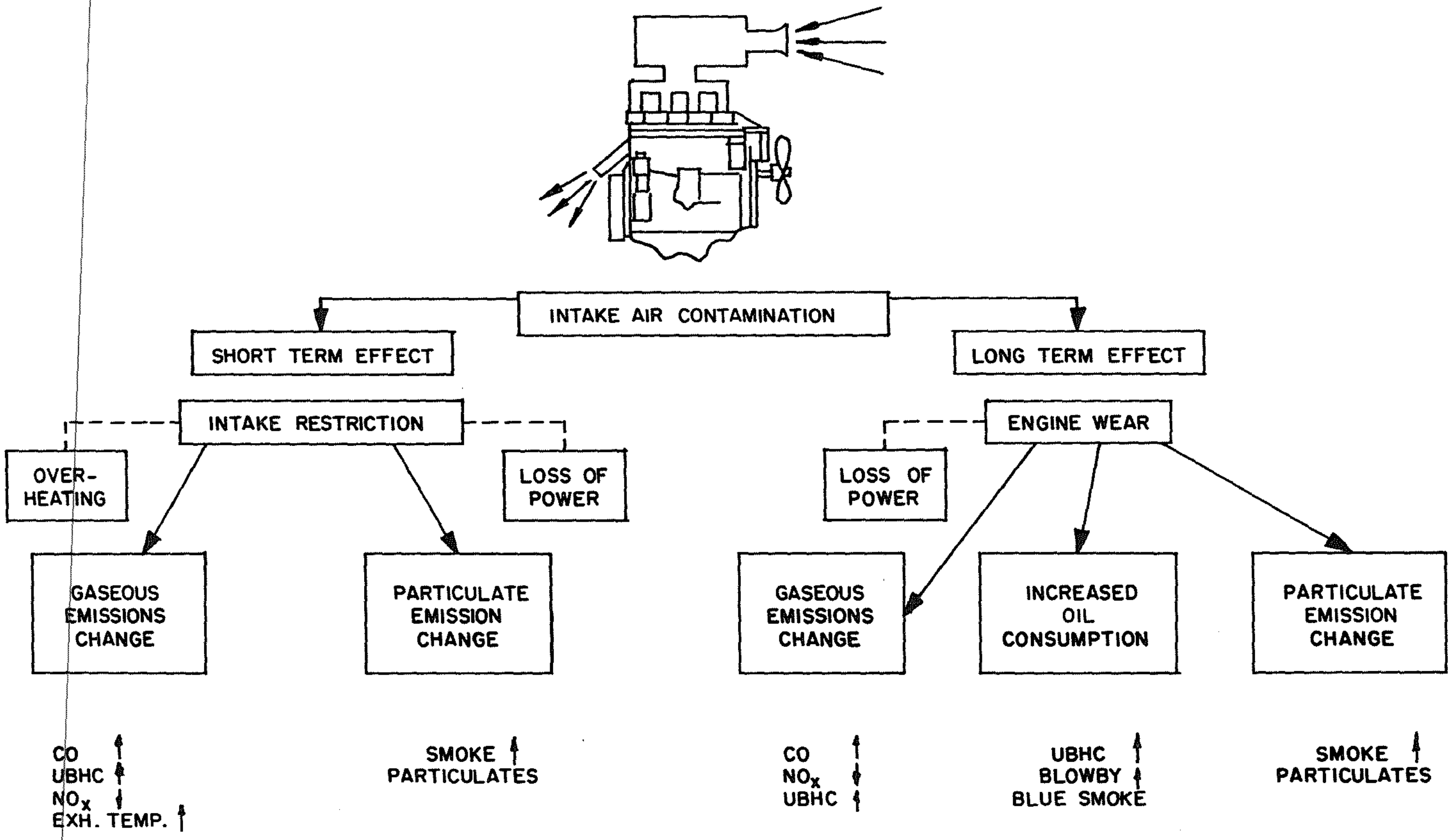

FIGURE 4.3.1.2-1 RELATIONSHIP OF AIR CONTAMINATION TO EMISSIONS

$$D = \frac{A \cdot d \cdot T}{1000}$$

where

D = Total collected dust (gram)
A = Air consumption (std m^3/min)
d = Average dust concentration (mg/m^3)
T = Time (min)

For a typical 10-liter engine, the hourly air consumption at 2200 RPM is 600 std m^3/hr. At a maximum allowable dust concentration of 10 mg/m^3 of air, and for a typical six-hour shift, total dust suspended is 36 grams. This dust must be collected by the filter, which must be removed after it has reached its design filtration capacity to avoid excessive intake air restriction. Without the filter, this amount of dust will be ingested by the engine.

A unique condition can be observed in many haulage drifts, reference Figure 4.3.1.2-2. In traveling with the ventilation air, a condition may be encountered where air and vehicle travel at the same speed, in the same direction. This will cause exhaust recirculation through the engine and sometimes operation in a "cloud of dust". The same condition has also been observed in railroad tunnels and rail haulage drifts. One mine had such a problem in which a loaded haulage truck had to negotiate an incline under full load. The vehicle speed matched the velocity of the ventilation air. This condition resulted in an operation surrounded by dust and exhaust gases. The mine solved the problem by reversing the ventilation air flow.

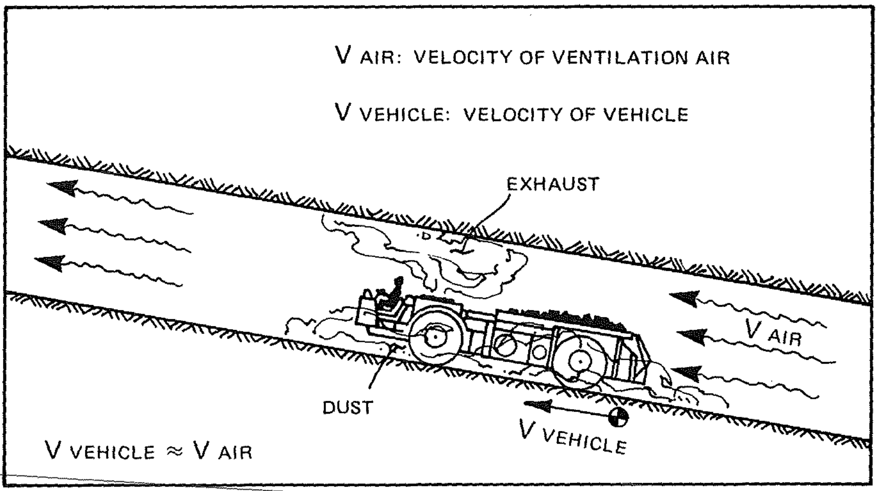

FIGURE 4.3.1.2-2 VELOCITY COINCIDENCE OF VEHICLE AND AIR

4.3.1.3 Types of Air Intake Systems in the Mining Industry

Types of air intake systems found on mobile underground mining equipment include:

- Oil bath air cleaner
- Dry cartridge air cleaner
- Air cleaner with precleaner
- Air cleaner with pressure drop indicator

Oil Bath Air Cleaners

Oil bath air cleaners are still commonly found on mobile equipment in underground mines. Until recently, one engine manufacturer furnished this type of filter with its basic engine. Unless otherwise requested by the customer, the original equipment manufacturer used it as the "standard air cleaner". Shortcomings of oil bath air filters are well-known to engine manufacturers. They do not endorse the use of oil bath filters underground.

The effectiveness of an oil bath filter in removing dust is less than that of a dry paper element filter, but the initial intake restriction for a paper element is higher. If properly serviced, the intake restriction rise will be slower than for a paper element. One of the main disadvantages of an oil bath air cleaner is its loss of filtering capability if tilted, a condition common for mobile equipment.

Dry Element Air Cleaners

Dry element air cleaners illustrated in Figure 4.3.1.3-1 are the most common type found on underground mobile equipment. If properly sized and frequently serviced, adequate protection of the air intake system can be expected. Large, oversized filters are required to achieve an acceptable service frequency in the high dust concentrations found in a mine atmosphere. Data from mine visits indicate a filter service frequency of from two times per shift to once per two working weeks is common. Almost all mines visited had some equipment with oil bath air cleaners. Most newer vehicles are now equipped with dry cartridge air cleaners, mostly with precleaners and pressure drop indicators.

Air Intake Filters with Precleaners

Air intake filters with precleaners are often used under severe dust conditions. Most precleaners will effectively remove dust particles above 10 micron in size before they reach the main filter element. Most arrangements use a cyclonic precleaner in combination with a dry filter element. Some filters use two dry elements in line (two-stage) and a cyclonic prefilter, Figure 4.3.1.3-2. The purpose of all these arrangements is to prevent a portion of the dust from reaching the main element and in this way to extend the time between filter changes.

Air Intake Cleaners with Pressure Drop Indicators

Air intake cleaners with pressure drop indicators offer the advantage of warning the operator when a predetermined intake restriction has been reached. The filter element can then safely be replaced. At present, no indicator is offered that measures the total pressure drop across both the filter and the flame arrester for Schedule 31 equipment, see Figures 4.3.1.3-3 and 4.3.1.3-4.

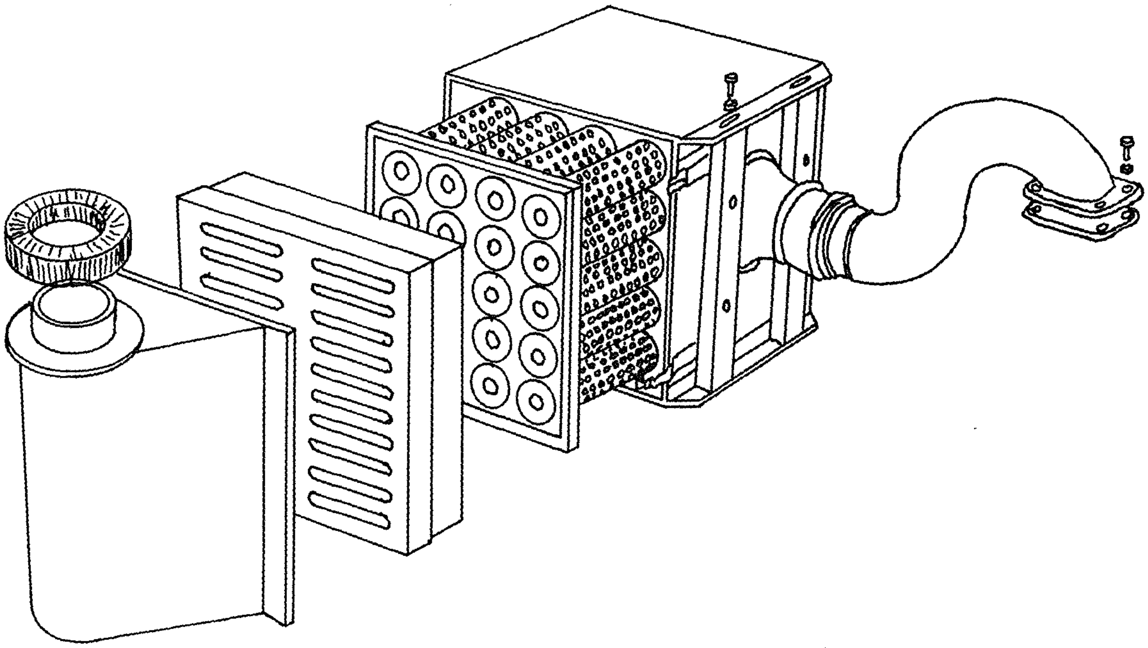

FIGURE 4.3.1.3-1 DRY ELEMENT AIR CLEANER

The pressure drop indicator as presently offered for Schedule 31 equipment does not detect a plugged flame arrester. No approved pressure drop indicator for that purpose is being marketed at present. One mining operator suggested a remote indicator in the operator's cab to enable the operator to monitor air intake pressure continuously. What is actually needed is a device which would measure and display intake air dust concentration as well as pressure drop. Such a system could detect a loaded filter or an air leak. A device to perform this task which is sufficiently inexpensive, rugged, and reliable is not yet available.

4.3.1.4 Filter Cleaning Programs

Not all manufacturers of filters and engines are in agreement on the subject of filter cleaning for reuse. Some manufacturers discourage any type of filter cleaning program while others have published certain cleaning procedures. Damage caused to the elements while cleaning, possible loss of sealing surfaces and altered filter characteristics may allow dust to enter the engine or change the intake restriction. Past studies at SwRI show that the pores of a cleaned filter will plug faster than a new

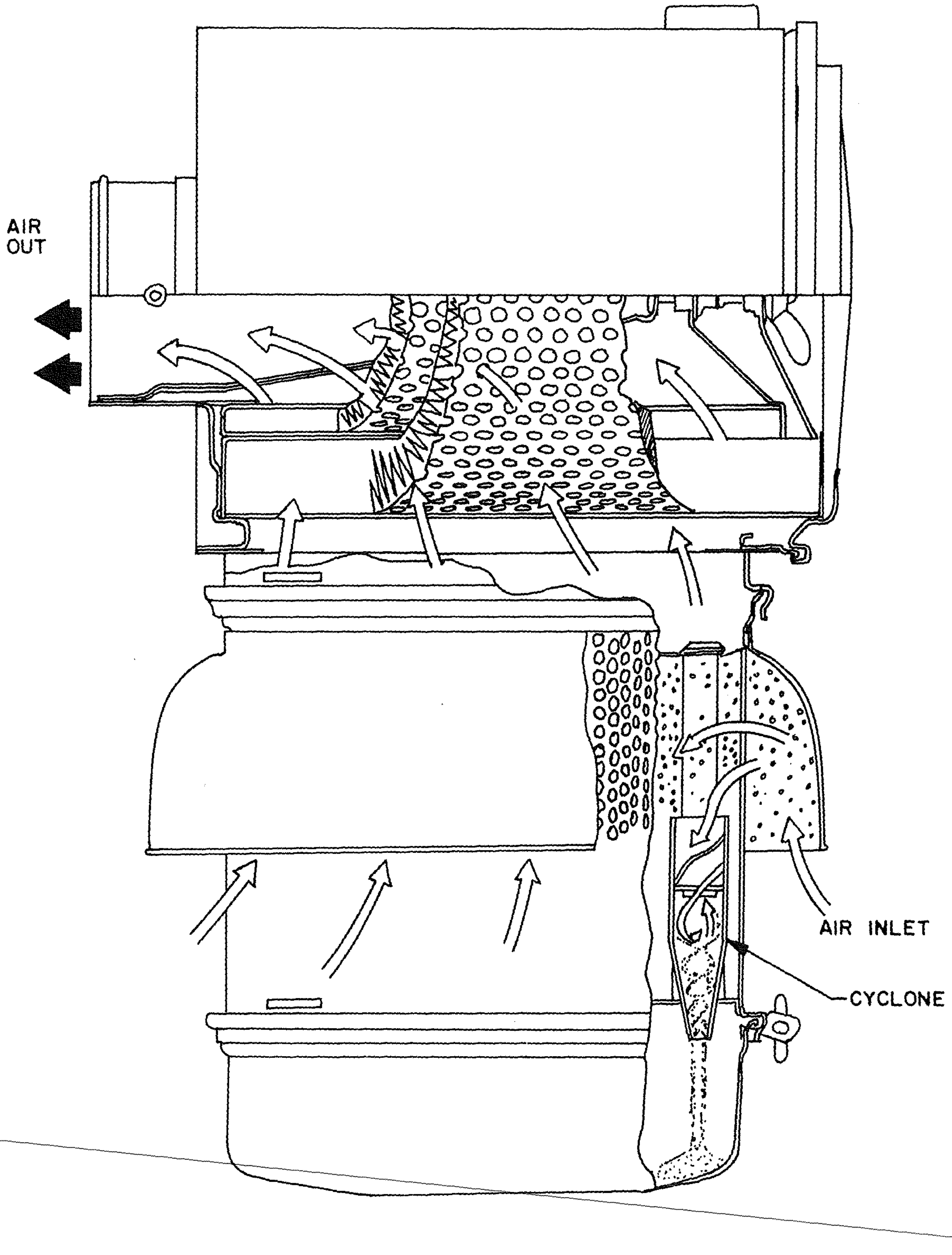

FIGURE 4.3.1.3-2 TWO-STAGE FILTER WITH CYCLONIC PRECLEANER

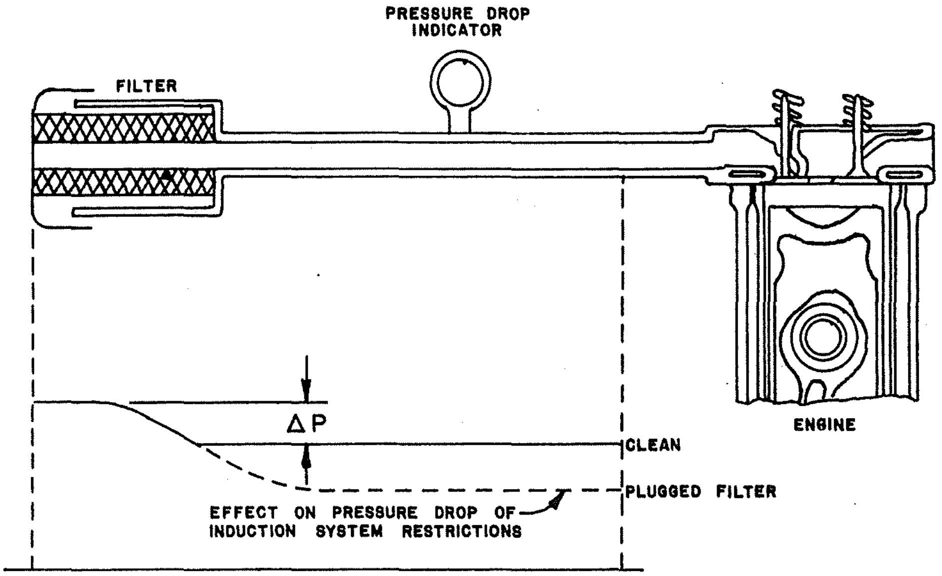

FIGURE 4.3.1.3-3 FILTER PRESSURE DROP INDICATOR

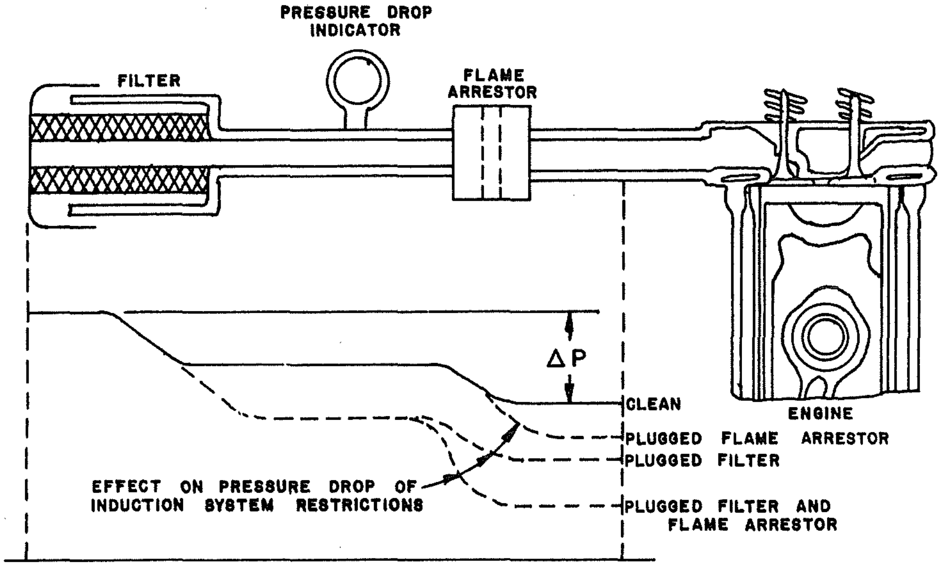

FIGURE 4.3.1.3-4 SCHEDULE 31 PRESSURE DROP INDICATOR

filter element. Many particles are embedded in the element and cannot be removed through cleaning.

If a cleaning program is used, a strict inspection program is necessary to assure quality. Blowing or knocking dust from the element is discouraged. It is considered risky and a poor maintenance practice. A filter rebuild program that is offered at some Caterpillar distributors consists basically of a complete rebuild of filters, including a new paper element. Only the structural metal parts are reused. After the old filters are disassembled, the rebuild follows basically all steps necessary to build a new filter. The final product is a filter that can be considered the same quality as a new filter. It will meet all specifications of a new filter, but at only about two-thirds of the cost.

4.3.1.5 Air Filtration Design Considerations

When designing an air intake system for a diesel powered mining vehicle, the largest possible filter unit that can be fitted should be selected and mounted in a well protected area. The filter should be a dry cartridge type, preferably with a precleaner and a pressure drop indicator with remote indicator at the operator's cab. Mounting of the filter should be such that the elements can be changed without the possibility of admitting dirt into the intake system. A poor design is shown in Figure 4.3.1.5-1. Upside down and horizontal mountings, Figures 4.3.1.5-2 and 4.3.1.5-3, respectively, are generally good arrangements.

Summary of Intake System Design Considerations

Hoses:	A flexible section is generally required because of vibrations and relative movement between engine and air cleaner. Clamps should be wide and secure.
Protection:	Rock fall or collisions with the ribs can damage an unprotected filter system. Provisions should be made for adequate protection.
Rebreathing:	Special deflector plates and ducting, as well as strategic location of intake and exhaust openings will limit engine exhaust rebreathing.
Precleaner:	Use of a precleaner reduces the load on filter elements and the frequency of filter servicing.
Indicator:	Various devices are available to indicate the condition of the filter and signal a need for filter servicing. Relayed to the operator's cab, indications are more likely to attract his attention.
Installation:	The engine air induction system should be designed with due consideration of filter maintenance and servicing. A properly installed air cleaner should prevent accumulated dust, dirt, and other foreign matter from falling into the engine or induction air passages when the filter is removed for servicing or replacement.

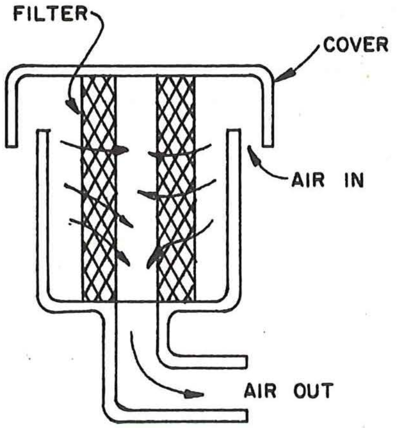

FIGURE 4.3.1.5-1 POOR FILTER MOUNTING

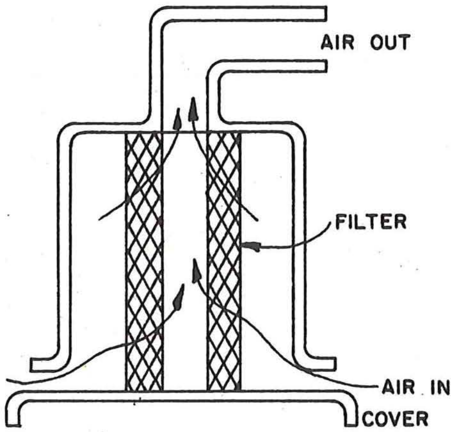

FIGURE 4.3.1.5-2 BETTER FILTER MOUNTING

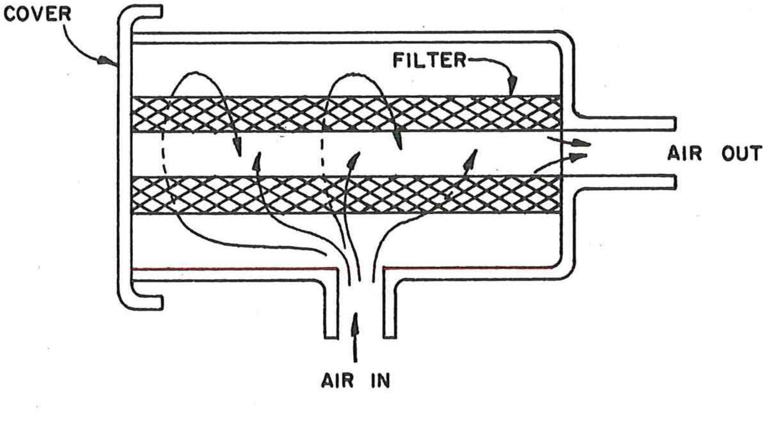

FIGURE 4.3.1.5-3 BEST FILTER MOUNTING

4.3.1.6 Maintenance of an Air Intake System

Filters are normally changed and serviced by maintenance personnel. The job can also be performed by a properly trained operator under proper conditions. It is most important that the engine be shut down and precautions taken to prevent dirt from falling into the engine intake system during filter servicing. Unless a pressure drop indicator is provided, a fixed filter change interval which is based on past history is recommended. This will not, however, offset the advantage of an indicator. Filters with pressure drop indicators are becoming more and more popular in underground mines. However, damage to the intake system or hoses or defective (leaking) filter cartridges are at present detected only by visual inspection. A leak test of the entire intake system would ensure its proper function and should be part of a preventive maintenance schedule.

Many mines do not reuse filters; however, various "filter cleaning programs" are used at some mines. Programs range from extensive cleaning with solvents and testing to simple knocking off of dirt before filter reuse. Any of these methods is discouraged since there is no way to detect a defective air cleaner. Running an engine for even a single shift without proper filtering can cause permanent damage. Mines that have admittedly had operators run with air intake cleaners removed also have a history of "sudden" engine failures.

4.3.2 Fuel Quality and Handling

4.3.2.1 Fuel Quality

Fuel quality affects exhaust emissions directly and indirectly. Selection and handling of the diesel fuel for use in the mine should be carefully performed. Sulfur content, accidental mixing with other fluids, and contamination are factors contributing to higher emissions and engine degradation. Emission mechanisms influenced by fuel contamination are diagrammed in Figure 4.3.2.1-1.

The sulfur content of diesel fuel directly affects the emissions of both SO_2 and particulate sulfates. Engine design does not alter these emissions. Reduction of fuel sulfur to less than the maximum allowable 0.5 percent will proportionally reduce SO_2 and sulfate emissions. Higher sulfur fuel contributes toward accelerated engine wear and affects emissions indirectly through engine degradation. Catalytic converters are also degraded by fuel sulfur and become ineffective through "sulfur poisoning". Selection of lower sulfur fuel is presently practiced by some mines.

4.3.2.2 Fuel Selection

Preference of mines for either No. 1 or No. 2 diesel fuel is divided. Generally, No. 2 diesel fuel is more readily available and typically has a 3.3 percent higher energy content per gallon than No. 1 diesel fuel. Lubrication properties of DF-2 reportedly result in slightly lower injection system wear. However, many mines have reported engine life using No. 2 fuel being far less than would be expected under ideal conditions. Most likely, these engines failed prematurely for other reasons.

The principal reason for use of No. 1 diesel advanced by mines using it is generally lower emissions. Some mines conducted experiments with a mixture of No. 1

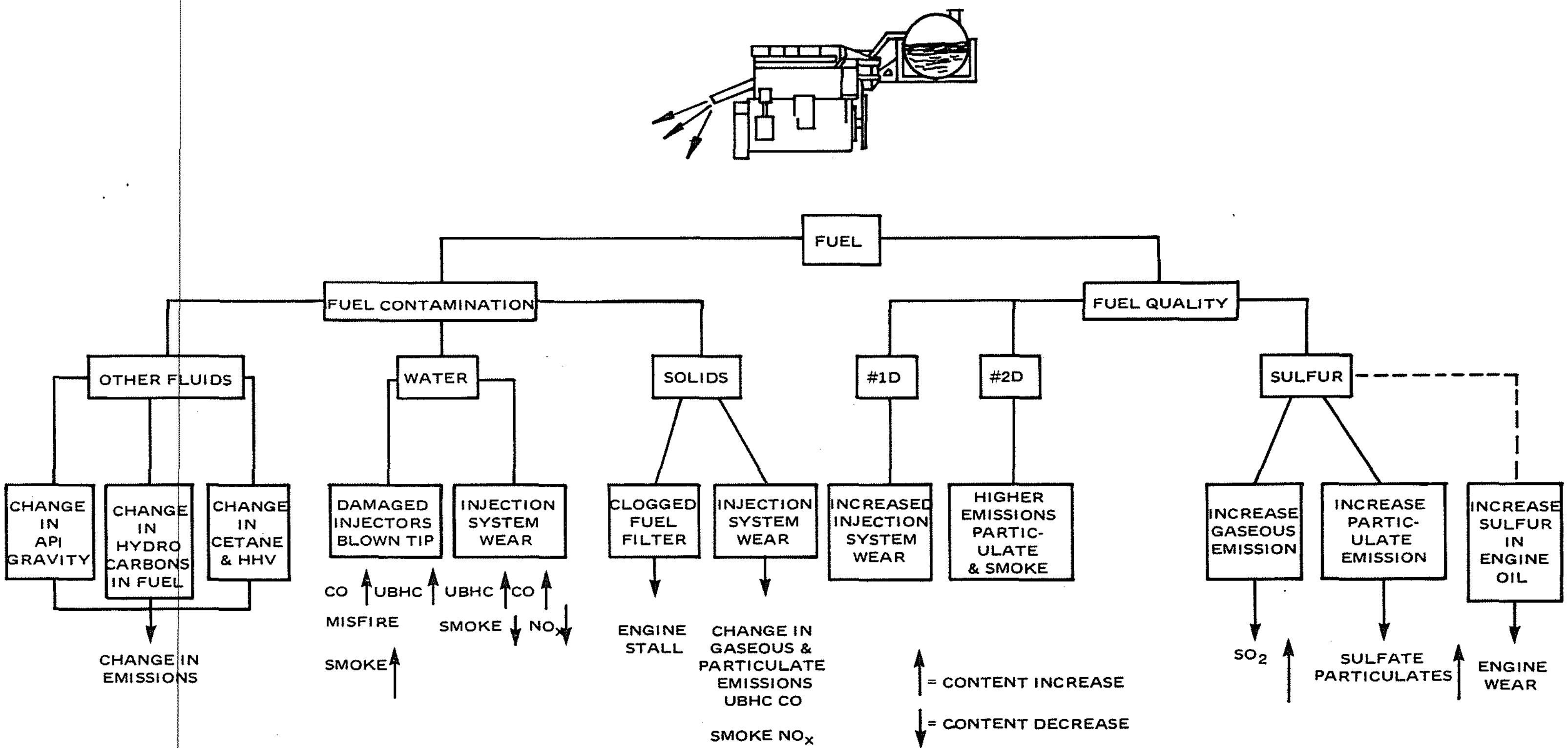

FIGURE 4.3.2.1-1 RELATIONSHIP OF FUEL CONTAMINATION TO EMISSIONS

and No. 2 diesel fuel. The availability of No. 1 diesel fuel is not always assured, and mines have often changed to No. 2 diesel if No. 1 is not available. Almost all mines have reported that miners can notice a change in fuel from the odor of engine exhaust. Several mines believe the oil industry will eliminate No. 1 diesel completely.

From SwRI studies, there is evidence that fuel quality does affect emissions. One of the used engines analyzed for this project was tested with both DF-1 and DF-2. These results can be compared with data collected from a new engine of similar design(1). Figures 4.3.2.2-1 through 4.3.2.2-3 illustrate the comparison. These tests indicate that gaseous emissions are generally lower while particulate emissions are higher when the used engine is fueled with DF-2. However, the particulate levels reported in Figure 4.3.2.2-3 are all quite low and should not be of concern.

4.3.2.3 Fuel Additives

Little information was found concerning use of fuel additives other than unsupported claims of reduced emissions. Consequently, several laboratories that have made studies or evaluated fuel additives were contacted. None have produced any evidence of positive long-term benefits of fuel additives regarding engine emissions. During a field trip, past experience of one mine with a fuel additive was discussed. The only benefit was reduction of visible smoke, with no measured reduction of particulate matter. Furthermore, components of the fuel additive may be harmful when respired with exhaust gases.

4.3.2.4 Equipment Manufacturers' Fuel Recommendation

Before looking at manufacturers' specifications, it is helpful to understand the meaning of some of the more common specs and how they are obtained.

- **D-86 Distillation** - This analysis results in a curve relating temperature to volume percent of sample evaporated. The end point of this curve can be used to determine whether the fuel is DF-1, DF-2 or a blend of the two. Reference ASTM D-86. The maximum DF-1 end point temperature is 626°F. The maximum DF-2 end point temperature is 700°F. The 50 percent point of the D-86 distillation is used in the calculations of Cetane Index.

- **API Gravity** - This analysis yields fuel density. The measurement is performed according to ASTM D-287. This value is also used in the calculation of Cetane Index.

- **Sulfur Content** - Sulfur content of the fuel is generally measured by x-ray fluorescence.

- **Cetane Number** - This is a measure of the ignition delay of the fuel. Reference ASTM D-613.

- **Cetane Index** - This is a value which is an approximation of the Cetane Number. It is much less expensive to obtain. Reference ASTM D-976.

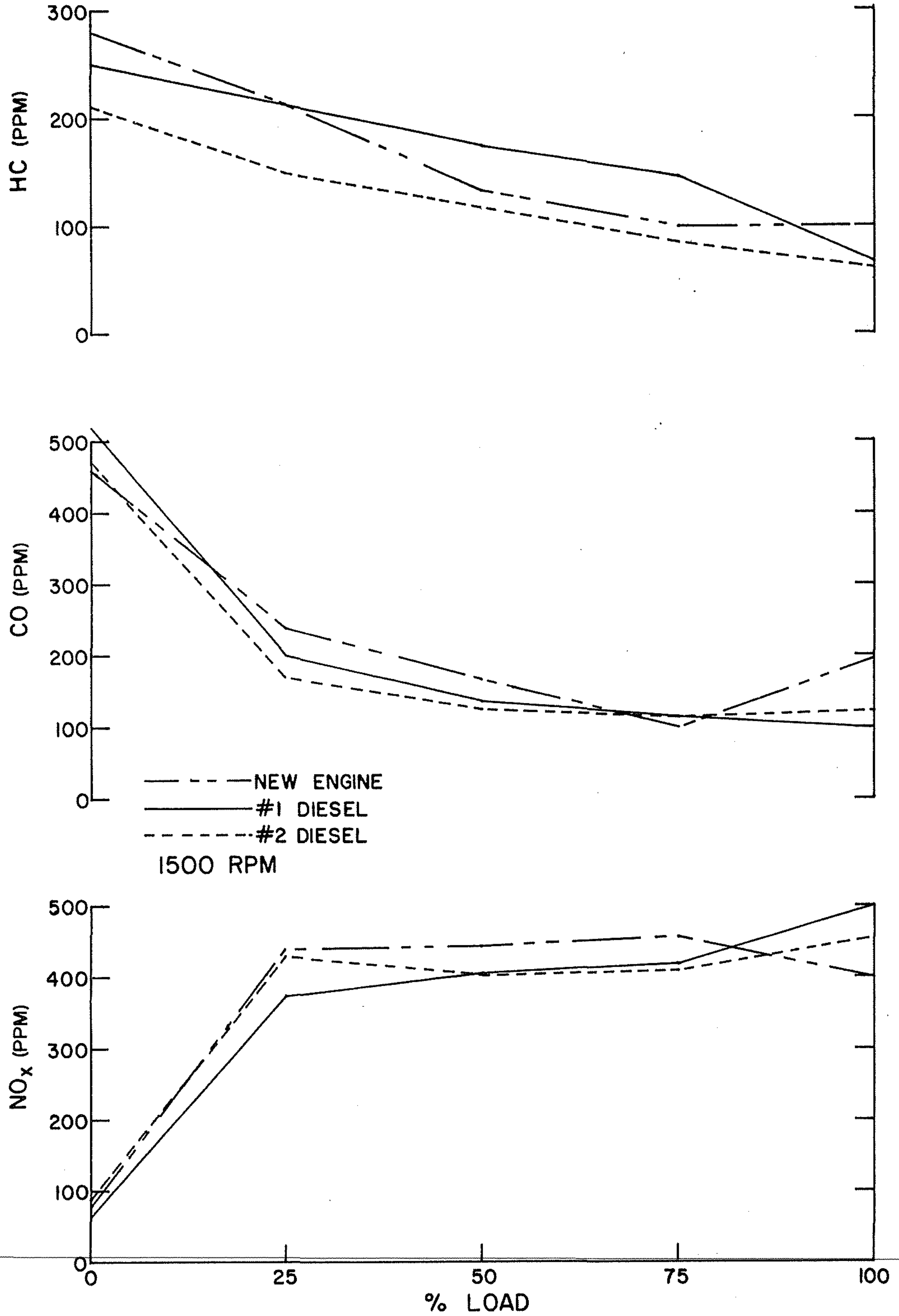

FIGURE 4.3.2.2-1 GASEOUS EMISSIONS CONCENTRATIONS AT 1500 RPM FOR A CATERPILLAR 3306 PCT DIESEL ENGINE

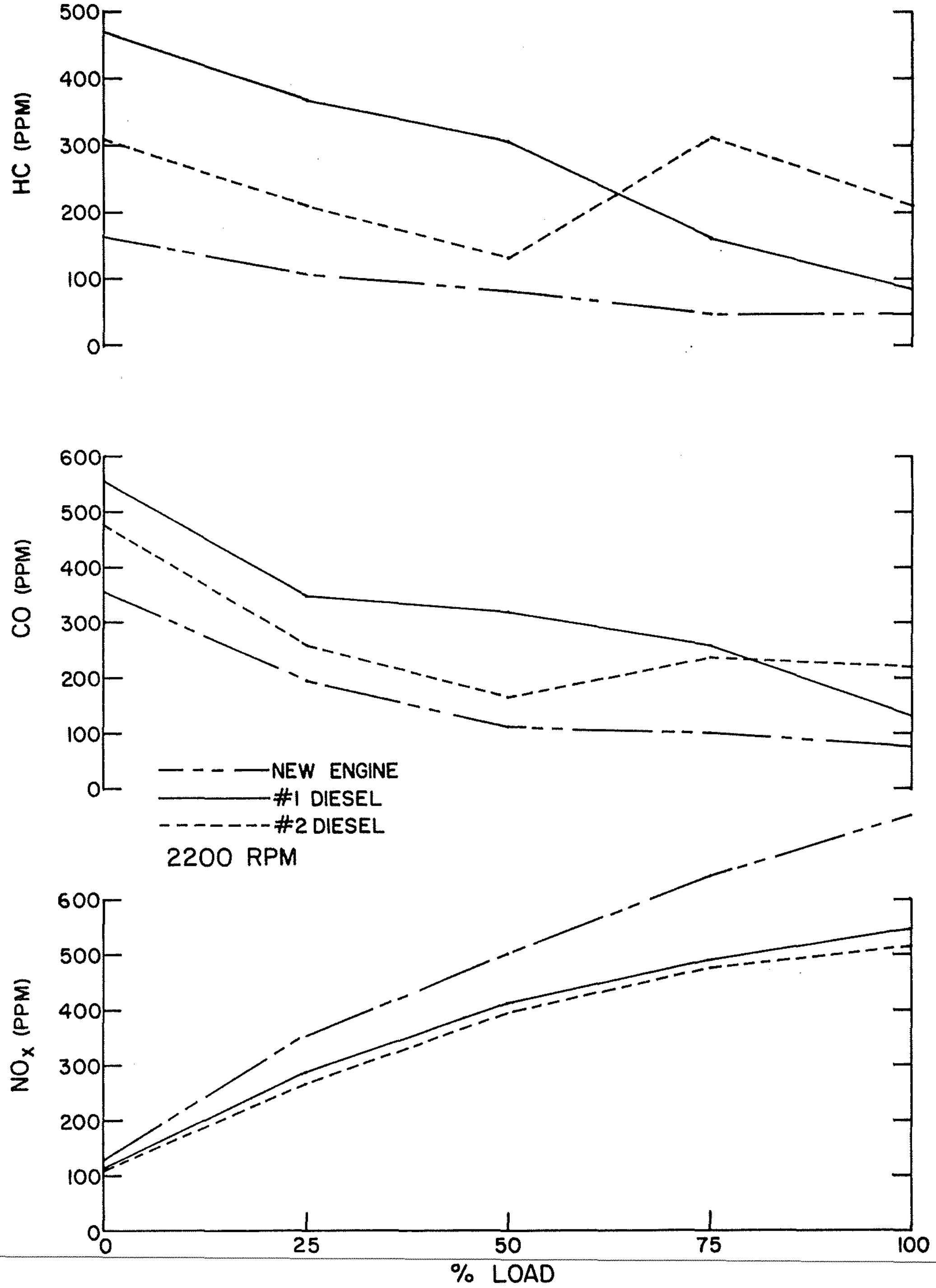

FIGURE 4.3.2.2-2 GASEOUS EMISSIONS CONCENTRATIONS AT 2200 RPM FOR A CATERPILLAR 3306 PCT DIESEL ENGINE

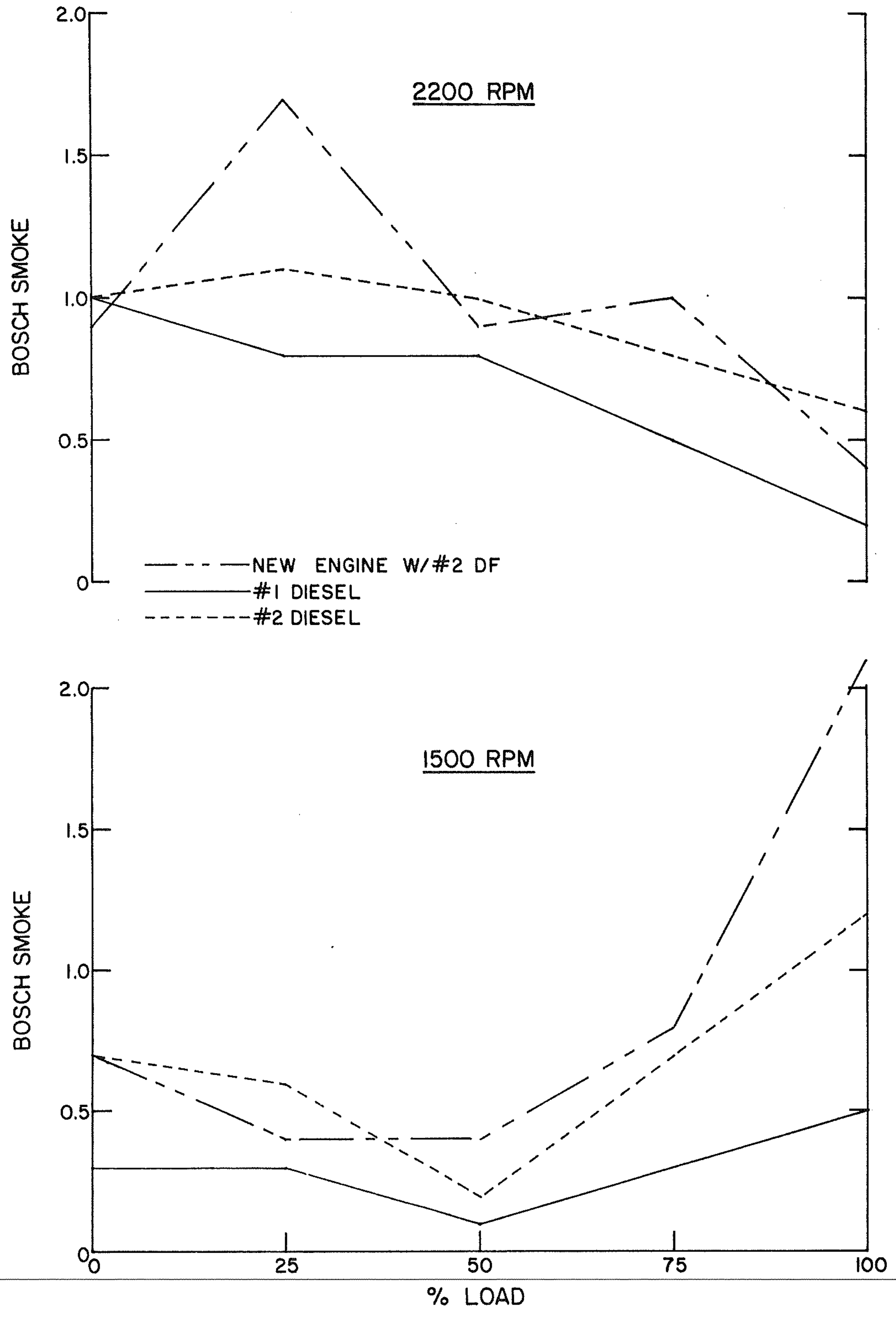

FIGURE 4.3.2.2-3 PARTICULATE EMISSIONS FROM A CATERPILLAR 3306 PCT OPERATING AT 1500 RPM AND 2200 RPM

Several manufacturers of diesel powered mining equipment were contacted for fuel recommendations. Some refer to the engine manufacturers' specifcations as their only reference. Others recommended as follows:

Company A: From its operating manual for a LHD unit:

Cetane: 35 (minimum)
Water and Sediment: 0.1% (maximum)
Pour Point: 10°F (6°C) below ambient temperature
Flash Point: 140°F (60°C) (minimum)
Cloud Point: No higher than ambient temperature
Sulfur Content: 0.3% by weight (maximum)
Gravity (API): 32-40 at 60°F (162°C)
Viscosity: 40 SUS (maximum)
Carbon Residue: 3.5% by weight (maximum)
Ash: 0.2% by weight (maximum)

Company B: From its operator's manual for a Telescoping Truck:

> "Use only diesel fuel recommended by the engine manufacturer that gives satisfactory engine operation. The flash point (open cup) must not be less than 140°F or the sulfur content greater than 0.5 percent by weight. Precautions should be taken to keep the fuel clean and free from dirt."

Company C: From its operator's manual for a LHD unit:

> "Use only No. 1 or No. 2 diesel fuel with a minimum cetane number of 35."

The manual also recommended filling the fuel tank before parking the machine to prevent moisture condensation in the tank.

Company D: Has no specific recommendations other than engine manufacturers', but stated that the fuel sulfur content is regulated to 0.5 percent maximum.

Company E: From its operator's manual:

> "Use only diesel fuel recommended by engine manufacturer that gives satisfactory engine operation. The flash point should not be less than 140°F or the sulfur content greater than 0.5 percent weight. Precautions should be taken to keep fuel clean and free from dirt and water."

4.3.2.5 Engine Manufacturers' Fuel Recommendations

The two largest manufacturers of engines for underground mining application were contacted and the following statements were received:

Engine Manufacturer A: From its Industrial Engine Manual:

> "Fuel: Use only distillate fuels (ASTM No. 1 or No. 2 Fuel Oil, or No. 1D or No. 2D diesel fuel oil are examples) with a minimum cetane number of 35. Heavier oil is generally preferable because of its energy content."

Engine Manufacturer B: From phone contact with its engineering department:

> "No specific recommendations, but mines should use at least No. 2 diesel for underground use, although MSHA likes No. 1 diesel."

From another manufacturer of diesel engines of mainly over-the-road and construction equipment, more detailed specifications were received, and are included for reference.

Engine Manufacturer C:

> "The quality of fuel oil used for high-speed diesel engine operation is a very important factor in obtaining satisfactory engine performance, long engine life, and acceptable exhaust.
>
> Fuel selection should be completely distilled material. That is, the fuel should show at least 98 percent by volume recovery when subjected to ASTM D-86 distillation. Fuels marketed to meet Federal Specification VV-F-800 (grades DF-1 and DF-2) and ASTM Designation D-975 (grades 1-D and 2-D) meet the completely distilled criteria.
>
> Residual fuels and domestic furnace oils are not considered satisfactory for "C" diesel engines; however, some may be acceptable.
>
> **Note:** "C" does not recommend the use of drained lubricating oil as a diesel fuel oil. Furthermore, "C" will not be responsible for any engine detrimental effects which it determines resulted from this practice.
>
> All diesel fuel oil contains a certain amount of sulfur. Too high a sulfur content results in excessive cylinder wear due to acid build-up in the lubricating oil. For most satisfactory engine life, fuels containing less than 0.5 percent sulfur should be used.
>
> Fuel oil should be clean and free of contamination. Storage tanks should be inspected regularly for dirt, water or water-emulsion sludge, and cleaned if contaminated. Storage instability of the fuel can lead to the formation of varnish or sludge in the tank. The presence of these

contaminants from storage instability must be resolved with the fuel supplier."

'C' designs, develops, and manufactures commercial diesel engines to operate on diesel fuels classified by the ASTM as Designation D-975 (grades 1-D and 2-D). These grades are very similar to DF-1 and DF-2 of Federal Specification VV-F-800. Residual fuels and furnace oils, generally, are not considered satisfactory for 'C' diesel engines. In some regions, however, fuel suppliers may distribute one fuel that is marked as either diesel fuel (ASTM D-975) or domestic heating fuel (ASTM D-396), sometimes identified as furnace oil. In this case, the fuel should be investigated to determine whether the properties conform with those shown in the Fuel Oil Selection Chart presented in this specification.

4.3.2.6 Fuel Specifications and Data

A national survey on diesel fuels is published annually by the Bartlesville Energy Research Center, Department of Energy. It provides information on fuel for the United States and is divided into fourteen regions. Tests of 211 samples of diesel fuel from 97 refineries throughout the country were made by 31 refining companies in one survey. Compilation is under a cooperative agreement between the Department of Energy (DOE), Bartlesville Energy Technology Center (BETC) and the American Petroleum Institute (API). Specifications for diesel fuel are summarized in the Federal Specifications and ASTM Diesel Fuel Properties, Table 4.3.2.6-1.

Table 4.3.2.6-1. Minimum Specifications for Diesel Fuel

SPECIFICATION OR CLASSIFICATION GRADE	**VV-F** 800 DF-1	**ASTM** D-975 1-D	**VV-F** 800 DF-2	**ASTM** D-975 2D
Flash Point Min.	40°C	38°C	50°C	52°C
Carbon Residue (10% residuum) % max	0.15	0.15	0.20	0.35
Water & Sediment, % by volume max.	0.01	trace	0.01	0.05
Ash, % by wt. max.	0.005	0.01	0.005	0.01
Distillation Temperature, 90% by volume recovery, min.	--	--	--	282°C
max.	300°C	288°C	330°C	338°C
End Point, max.	330°C	--	355°C	--
Viscosity, 100°F (38°C)				
Kinematic, cs., min.	1.4	1.4	2.0	2.0
Saybolt, SUS, min.	--	--	--	32.6
Kinematic, cs., max.	3.0	2.5	4.3	4.3
Saybolt, SUS, max.	--	34.4	--	40.1
Sulfur, % by wt., max.	0.50	0.50	0.50	0.50
Cetane Number	45	40	45	40

4.3.2.7 Diesel Fuel Handling

Fuel contamination is usually a result of improper handling or storage. Contamination with moisture condensing inside containers or leakage into containers, accidental mixing with other fluids by mistake, or use of dirty containers and pumps. Contamination with solids such as sand or dust may result from storage in dusty areas. Open containers, or unnecessary transfer from one container to another are the main causes of fuel contamination. Many engine fuel systems are equipped with filtering and water separation equipment adequate to handle small amounts of contamination. Continued and excessive contamination will result in engine and fuel injection system problems and, consequently, emissions changes.

Many mines with diesel equipment were not designed for diesel use. As a result, no special facility for diesel fuel storage or transfer underground was provided. Small cutouts near the shop area where fuel is stored in 55 gallon oil drums are a common occurrence at many mines converted to diesel-powered equipment, Figures 4.3.2.7-1 and 4.3.2.7-2. While some mines eventually introduce better fuel handling methods, other mines continue use of oil drums despite inventory control and contamination problems. Storage of diesel fuel with hydraulic fluid, pneumatic tool oil, and engine oil in the same common area can cause problems with accidental mix-up of such fluids.

Surface storage facilities, Figure 4.3.2.7-3, in conjunction with direct piping to underground fueling areas or transfer by special tank cars, Figure 4.3.2.7-4, are the best methods for shaft mines. At adit mines, either fueling at surface or use of special tank cars are the best methods.

Fuel Handling Systems for Adit and Drift Mines - Figure 4.3.2.7-5 shows the four basic fuel transfer systems found in adit and drift mines. The best method for fueling at a surface facility would be by bringing the vehicles out of the mines, Figure 4.3.2.7-6. In larger mines, this may be unfeasible or uneconomical. A special fuel truck, Figure 4.3.2.7-7, or a special tank trailer or container, Figure 4.3.2.7-8, would be the next best approach. A portable container, however, adds some handling and possibility for contamination. The so-called "55-Gal Drum System" in any situation is the least desirable method of fuel transfer since the risk for mix-up, contamination and intermixing is the highest with this system, Figure 4.3.2.7-9.

Fuel Handling System for Shaft Mines - Figure 4.3.2.7-10 shows six basic methods of fuel handling observed during field visits. The most desirable method of fuel transfer to underground is by piping directly from surface tanks to the underground fueling facility, Figure 4.3.2.7-11 and Figure 4.3.2.7-12. When a central fueling station is not feasible due to mine size or other considerations, transfer into special tank vehicles or tank trailers is an alternative, Figure 4.3.2.7-12. Transfer in 55-gallon drums, Figure 4.3.2.7-13, is the least desirable.

If a direct pipe is not feasible, special tank trailers designed to fit into the cage, with delivery either directly to the diesel vehicle or fueling near the shaft without additional fuel transfer, is the most desirable method, Figure 4.3.2.7-14. The use of special containers and transport by service vehicles to the diesel units, without any transfer into other containters, is an acceptable method. Fuel handling methods that involve several transfers into different containers, Figures 4.3.2.7-15 4.3.1.7-16, are the least desirable methods. If such a system is used with 55 gallon drums, as in

FIGURE 4.3.2.7-1 COMMON FUEL STORAGE CONDITIONS

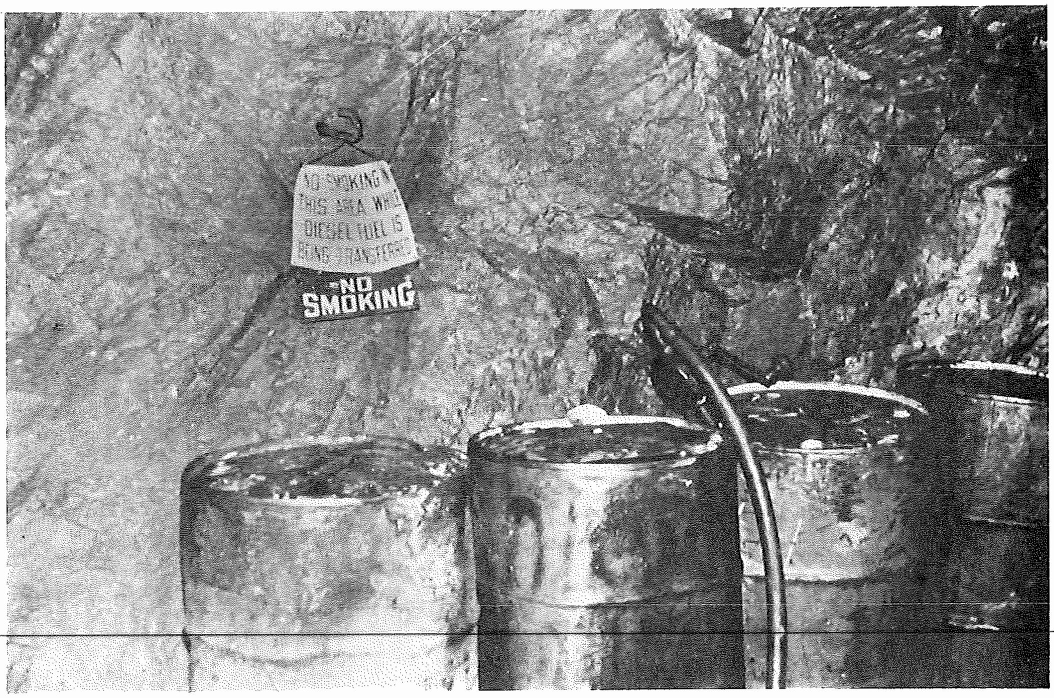

FIGURE 4.3.2.7-2 FUEL STORAGE IN HARD-ROCK MINE

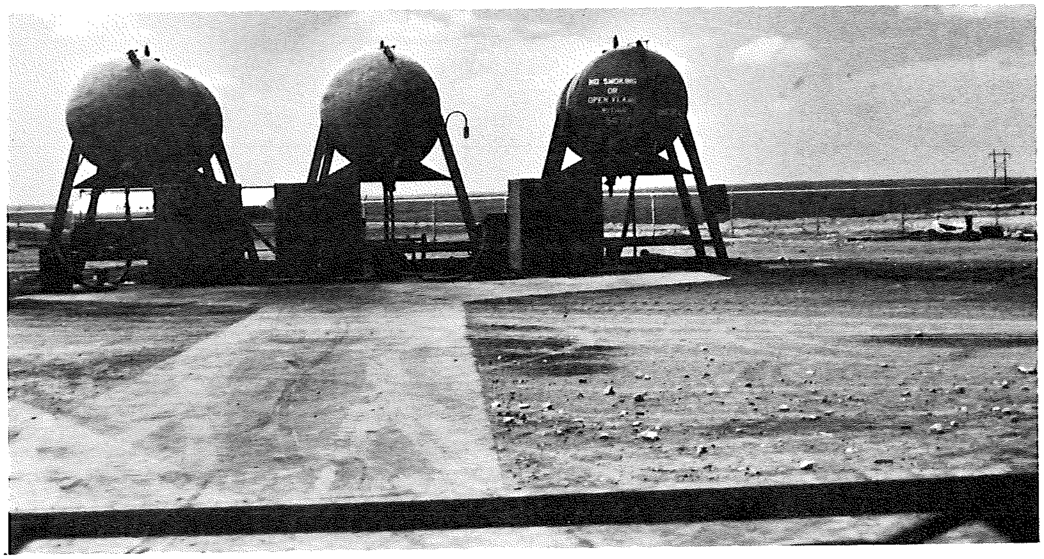

FIGURE 4.3.2.7-3 SURFACE STORAGE OF FUEL FOR UNDERGROUND MINE

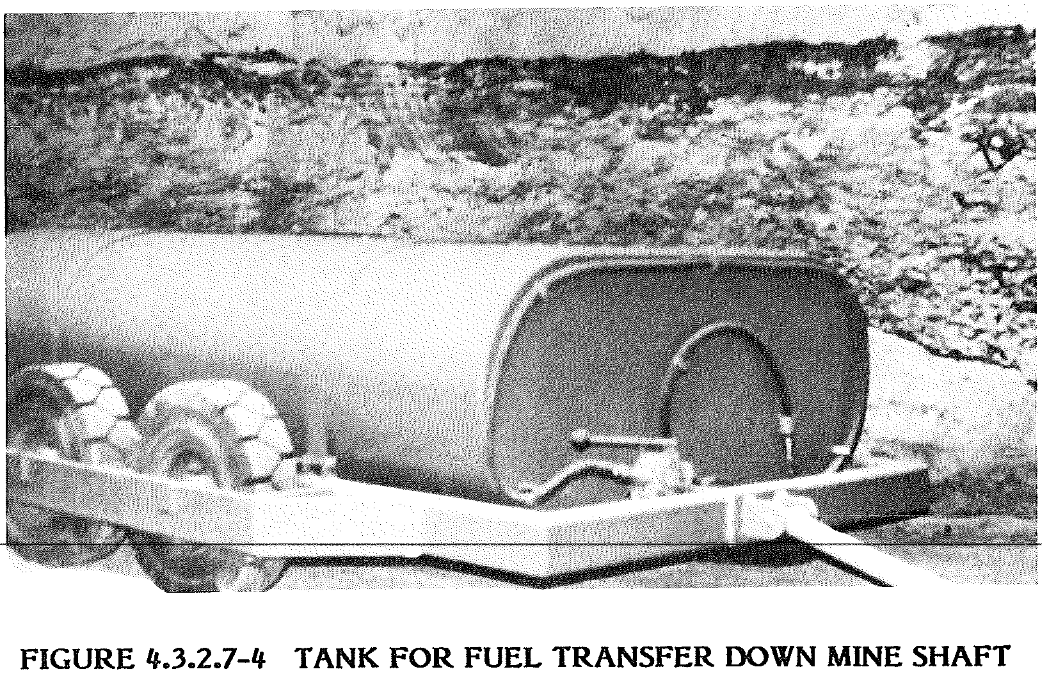

FIGURE 4.3.2.7-4 TANK FOR FUEL TRANSFER DOWN MINE SHAFT

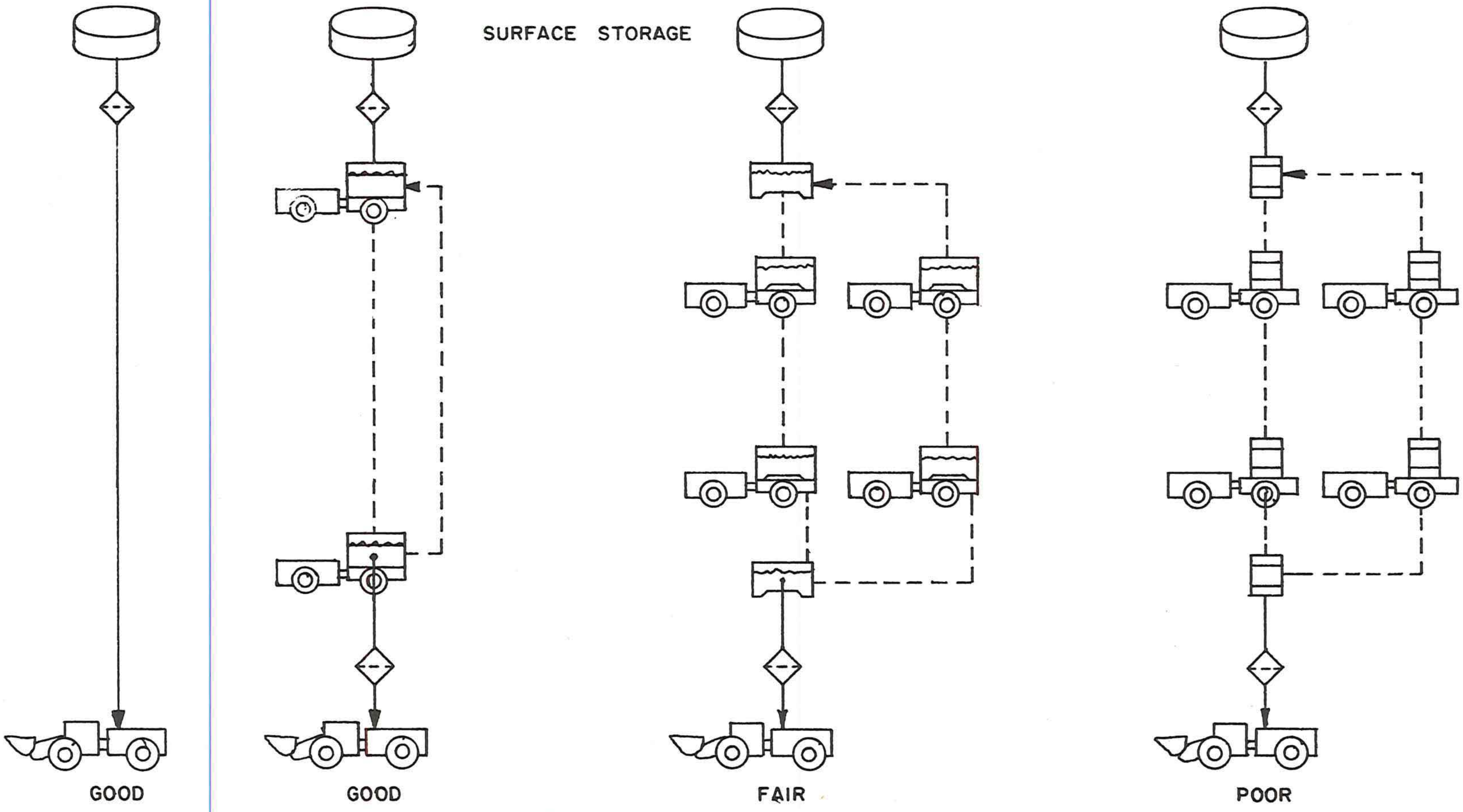

FIGURE 4.3.2.7-5 FUEL HANDLING FOR ADIT OR DRIFT MINES

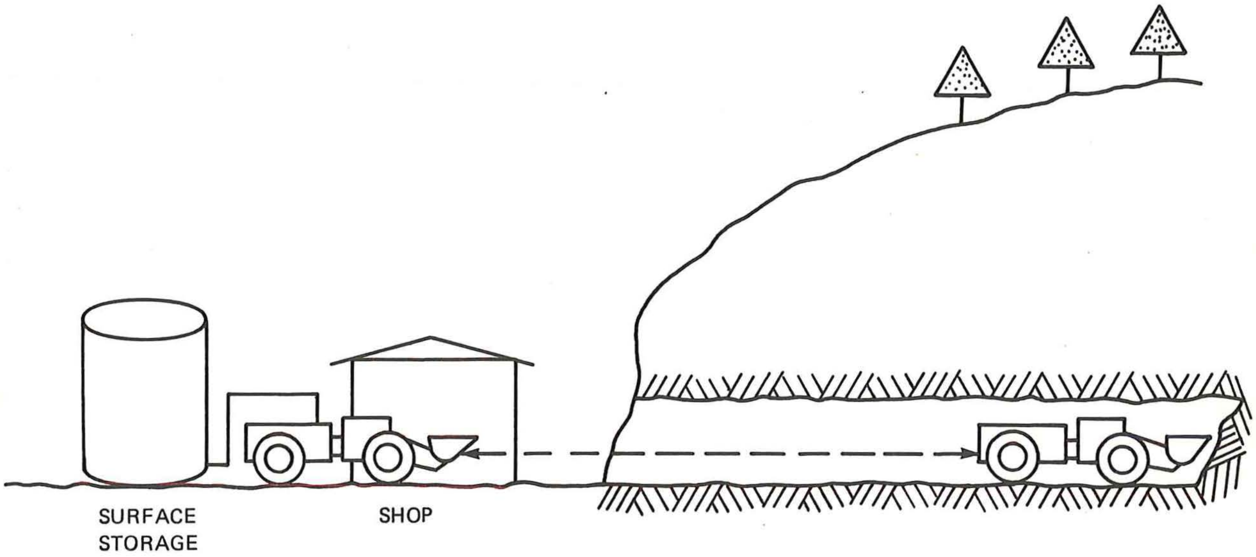

FIGURE 4.3.2.7-6 A FUELING METHOD FOR ADIT OR DRIFT MINES

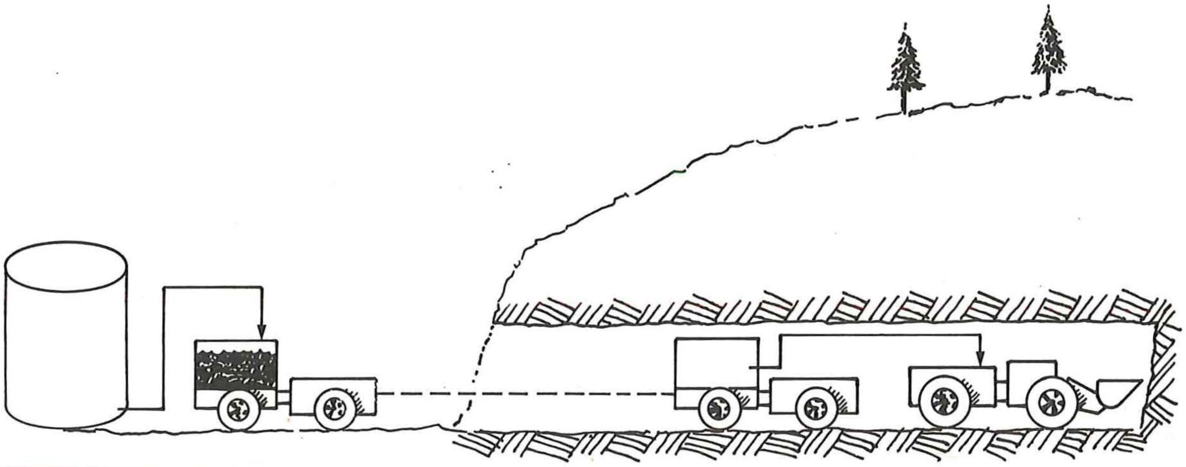

FIGURE 4.3.2.7-7 FUEL TRANSFER FOR LARGE DRIFT MINES

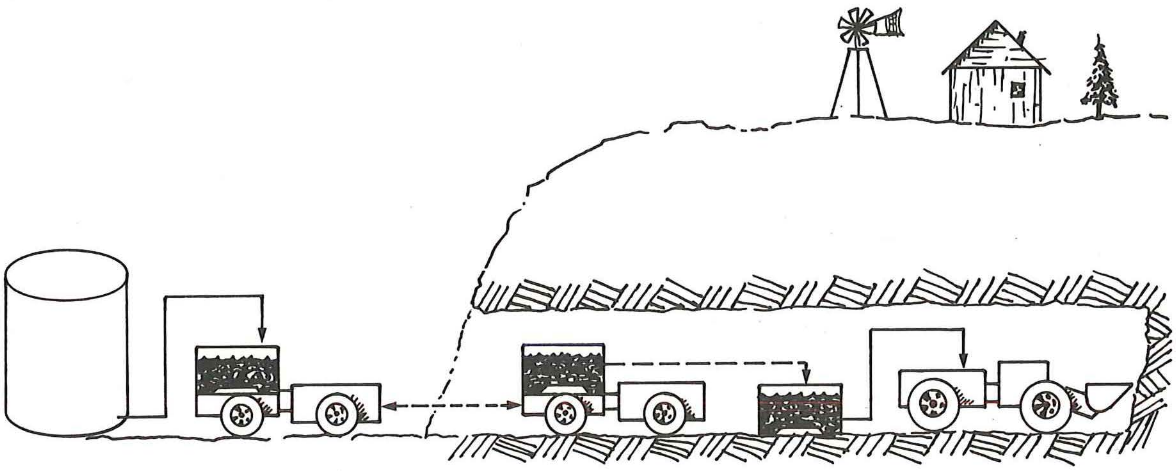

FIGURE 4.3.2.7-8 DOUBLE TRANSFER FUELING IN DRIFT MINES

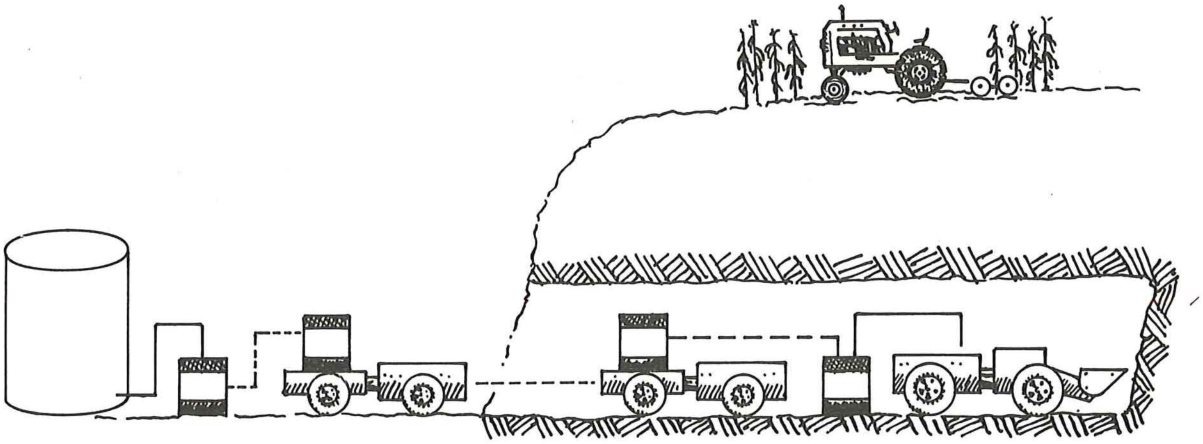

FIGURE 4.3.2.79 FUEL TRANSFER BY DRUM SYSTEM

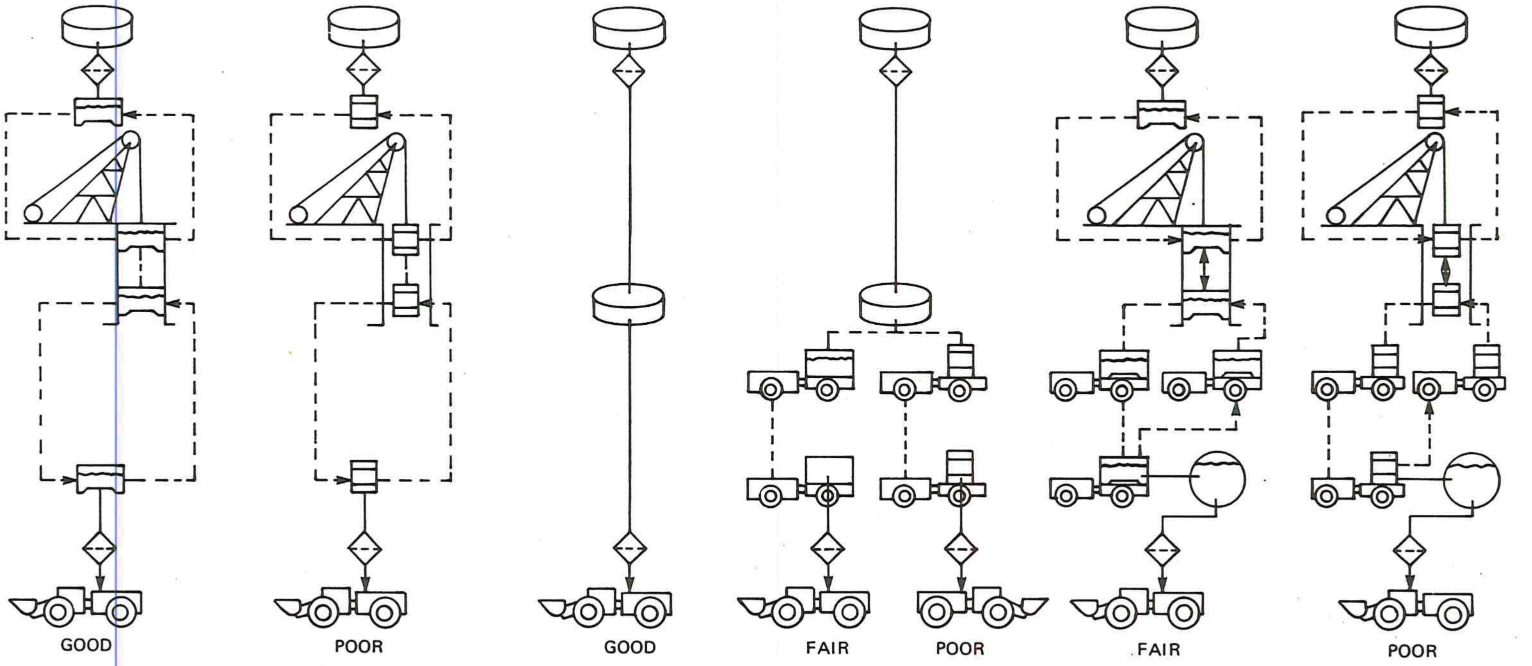

FIGURE 4.3.2.7-10 FUEL HANDLING FOR SHAFT MINES

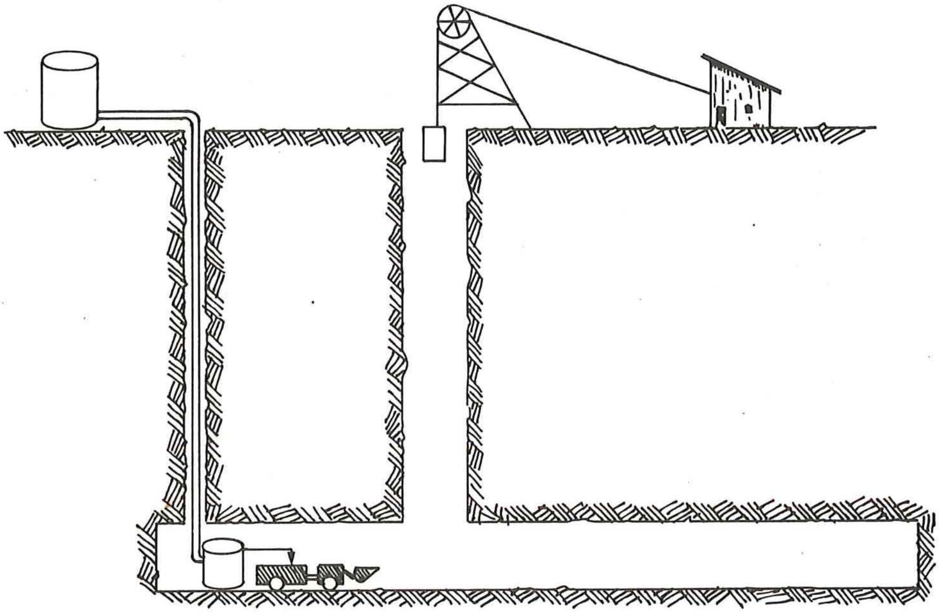

FIGURE 4.3.2.7-11 PIPELINE FUEL TRANSFER METHOD FOR SHAFT MINES

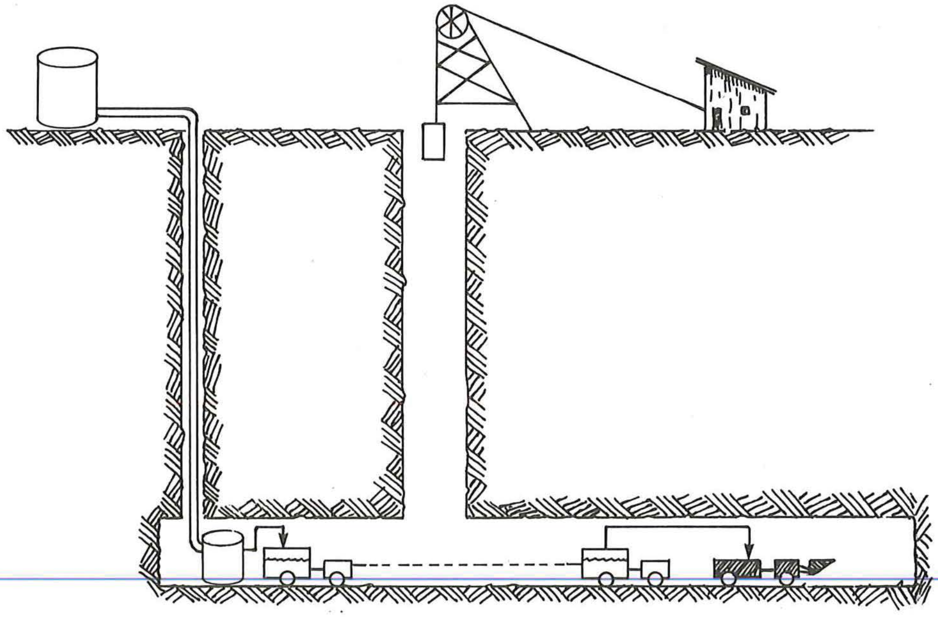

FIGURE 4.3.2.7-12 PIPELINE FUEL TRANSFER TO TANK TRUCK IN SHAFT MINES

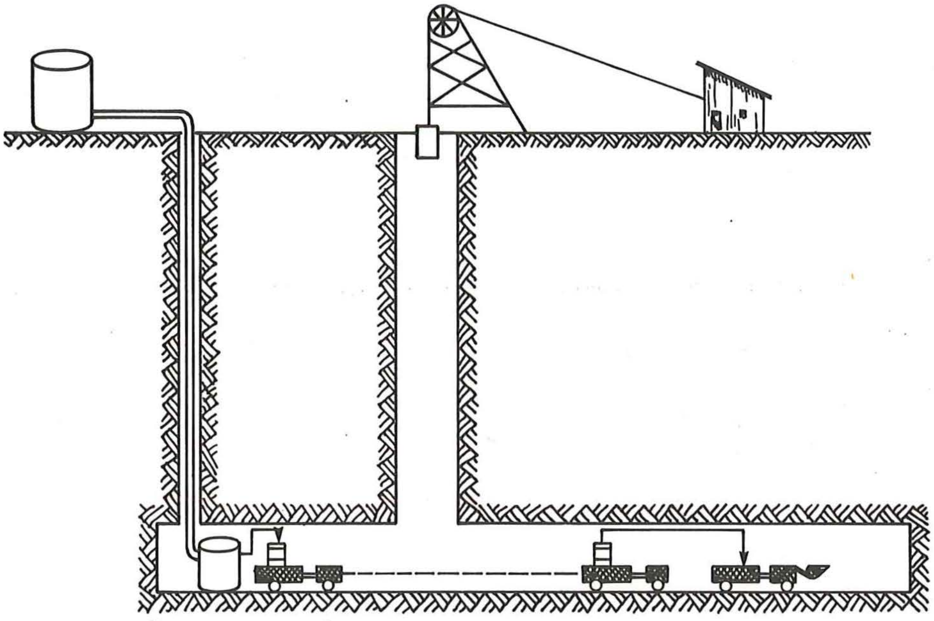

FIGURE 4.3.2.7-13 PIPELINE TRANSFER TO 55-GAL DRUMS IN SHAFT MINE

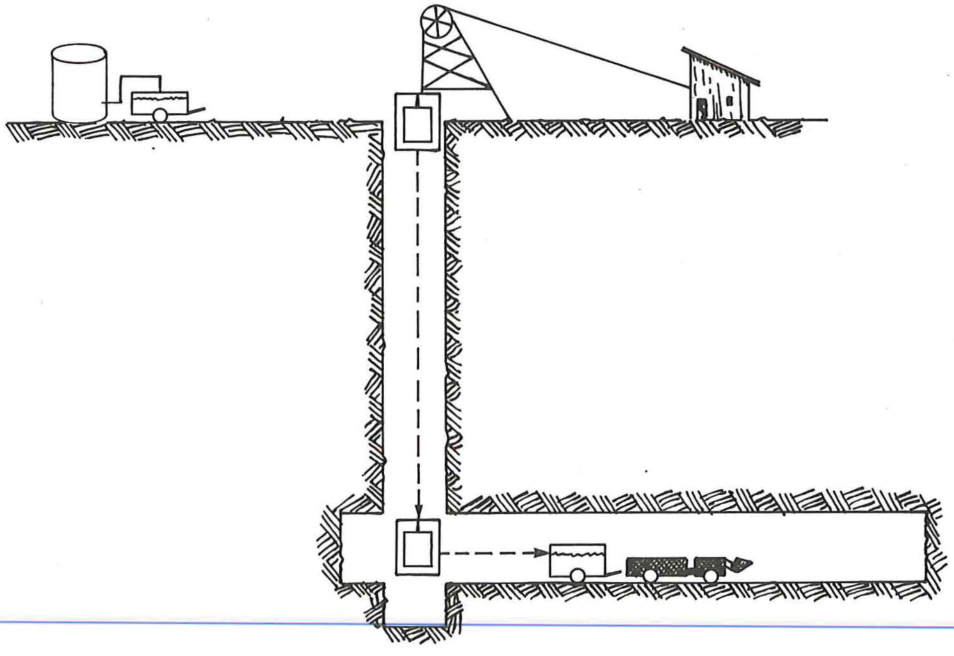

FIGURE 4.3.2.7-14 SPECIAL TANK DOWN SHAFT TRANSFER

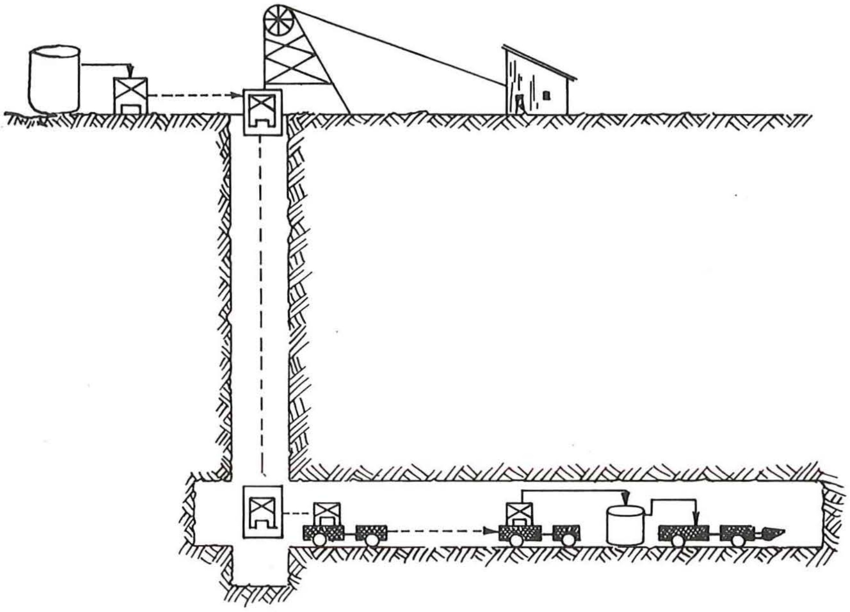

FIGURE 4.3.2.7-15 SPECIAL TANK DOWN SHAFT DOUBLE TRANSFER

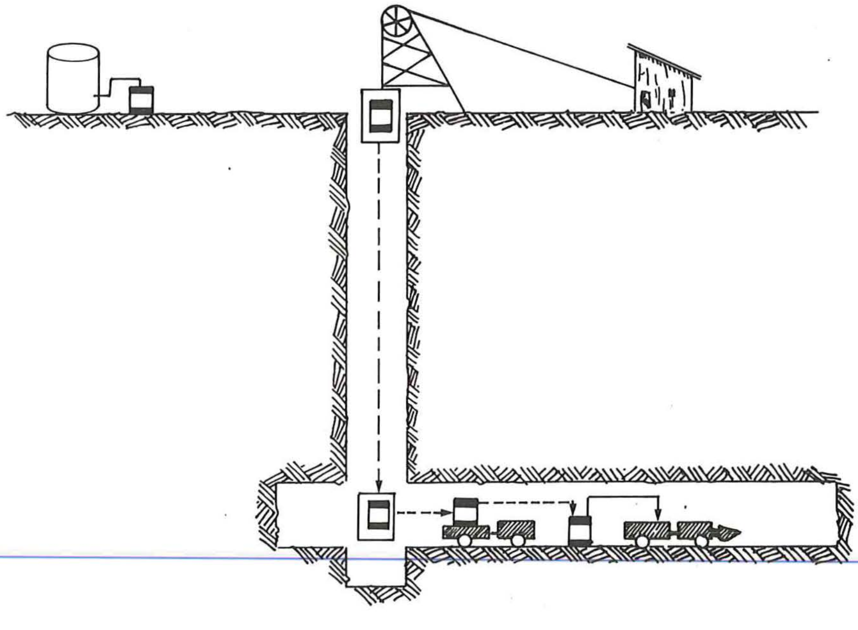

FIGURE 4.3.2.7-16 DRUM SYSTEM DOWN SHAFT TRANSFER

Figure 4.3.2.7-16, mix-up, contamination and intermixing of fluids can almost certainly be expected.

4.3.3 Cooling System

4.3.3.1 Effect of Cooling System Problems on Emissions

No direct effect of any consequence on emissions can be expected from cooling system failure. Overheating of the engine would be the only short term effect. Engine overheating can cause engine wear and damage. Loss of cooling is caused by either a failure or problem within the cooling system itself, or failure of some associated component. Long-term effects include cylinder wall scuffing, cracked or warped heads, and burned valves. Emission mechanisms related to the engine cooling system are related in Figure 4.3.3.1-1

4.3.3.2 Cooling System Operation

Overheating has been reported as a major cause of engine failures. About half of all underground engines are air-cooled Deutz engines; the remainder are water-cooled Caterpillar, Ford, Perkins, Kubota and several other makes. Air-cooled engines require less cooling system attention than do liquid-cooled engines, and are preferred at many mining operations. At present, no approved air-cooled engine complies with the CFR 30 surface temperature limitation for operation in the face area of a gassy mine; consequently, no air-cooled engines are found in coal mines.

Oil, dust and engine exhaust often combine to fill the air spaces between the cylinder fins of air-cooled engines and interfere with cooling air flow. Several severe examples were found at an engine dealer's rebuild facility. An engine washing program at one mine failed to prevent the build-up. Conditions are not as severe at other mines. A problem such as this was solved by one mine by periodically steam cleaning the engine with the cowling removed.

Flow restrictions in the body of mobile equipment can obstruct the cooling air flow into, through, and out of the machine. Air density reduction at high altitude and the further reduction due to induced (exhaust) mine ventilation reduce cooling capability of the engine cooling fan. Attention to the cooling air flow and exhaust gas flow is necessary to prevent recirculation of hot cooling air or exhaust gases through the cooling system.

Liquid-cooled engines are most often used where Schedule 31 approval limits surface temperatures to 150°C (302°F), but are also found in uncertified diesel equipment. A water-cooled engine usually requires more attention and maintenance of the cooling components than an air-cooled engine. If untreated water is used in the cooling system, scale deposits can form inside the radiator and the engine. Cavitation damage to the cylinder sleeves and other engine parts, as well as seal failures, are common results. Table 4.3.3.2-1 shows an analysis of a sample of mine water as it was used in diesel engines.

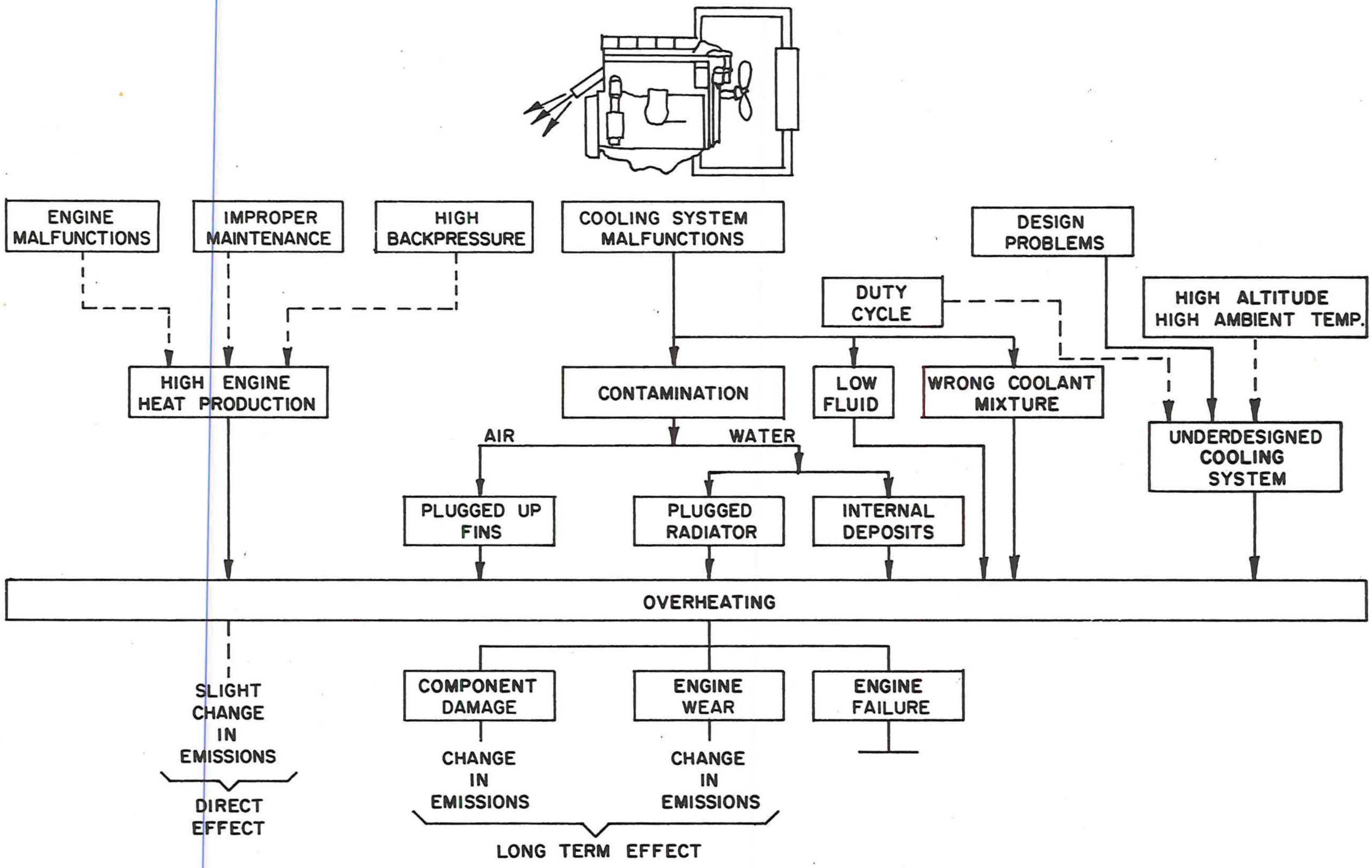

FIGURE 4.3.3.1-1 RELATIONSHIP OF COOLING SYSTEM FAILURES TO ENGINE EMISSIONS

Table 4.3.3.2-1. Measured and Recommended Properties of Water Used in Water-Cooled Engines

	Measured	Recommended
Measured pH	8.11	7
Conductance, Micromolar/cm	2470	
Total Salts as TDS mg/l	1464	500
Magnesium as Mg, mg/l	90	
Calcium as Ca, mg/l	75	
Hardness as Ca CO_3, mg/l	548	
gram/gal	16.6	10.5
Sulfates as SO_4, mg/l	893	200 max.
Chloride as CL, mg/l	25	10
Bicarbonates as HCO_3, mg/l	288	200 max.

When antifreeze is used, the proper mixture should be maintained since higher concentrations (above 50 percent) of antifreeze reduce the heat transfer capability of the mixture. A 100 percent concentration of antifreeze has only 60 percent of the heat transfer capability of a 50-50 mixture. A solution to the cooling water and antifreeze problem was developed and successfully implemented by several mines. Antifreeze is premixed with treated (distilled) water at a 50 percent concentration and only this mixture is added to the cooling system. Such a method prevents improper concentrations and contamination by dirty mine water.

Many mines do not clearly understand the function and proper use of coolant antifreeze. A common misconception is that it only prevents freezing of the coolant. Mines that do not experience sub-freezing temperatures sometime believe antifreeze is unnecessary for their engines. It is not well known that a 50/50 mixture of water and antifreeze (ethylene glycol) is a better coolant than 100 percent water or antifreeze. Antifreeze constituents also prevent rust and corrosion inside an engine. When antifreeze is mixed with clean, distilled water, it helps prevent cavitation and scale formation.

While the antifreeze itself does not "wear out", additive constituents such as rust inhibitors do. The system should be backflushed and the coolant changed yearly. The extent to which these measures are neglected is demonstrated by the extent of scale deposits found inside about two out of three engines returned from underground mines to an engine dealer for rebuild. According to one antifreeze manufacturer, a typical 1/16 inch of scale build-up inside an engine is equivalent in heat transfer resistance to about 4-1/4 inches of cast iron. This substantiates the relationship between scale deposits, overheating, and engine deterioration. Stop leak tends to choke cooling system passages. Its use is discouraged by antifreeze manufacturers.

All equipment certified by MSHA for operation in gassy mines (Schedule 31) incorporates liquid-cooled engines with water-jacketed manifolds and exhaust pipes. With this type of arrangement, additional energy from the water-jacketed exhaust system will be carried through the radiator system.

A Caterpillar 3306 engine, rated at 146 HP, normally rejects 6150 BTU/min (42 BTU/hp/min) to the coolant and 2140 BTU/min (14.6 BTU/hp/min) to the exhaust. With a water-jacketed exhaust system, most of the exhaust energy is absorbed by the coolant, Figure 4.3.3.2-1. Under such conditions, considerable additional heat from the water-cooled exhaust manifold needs to be transferred and removed through the radiator. As a result it is even more important to properly maintain the cooling system.

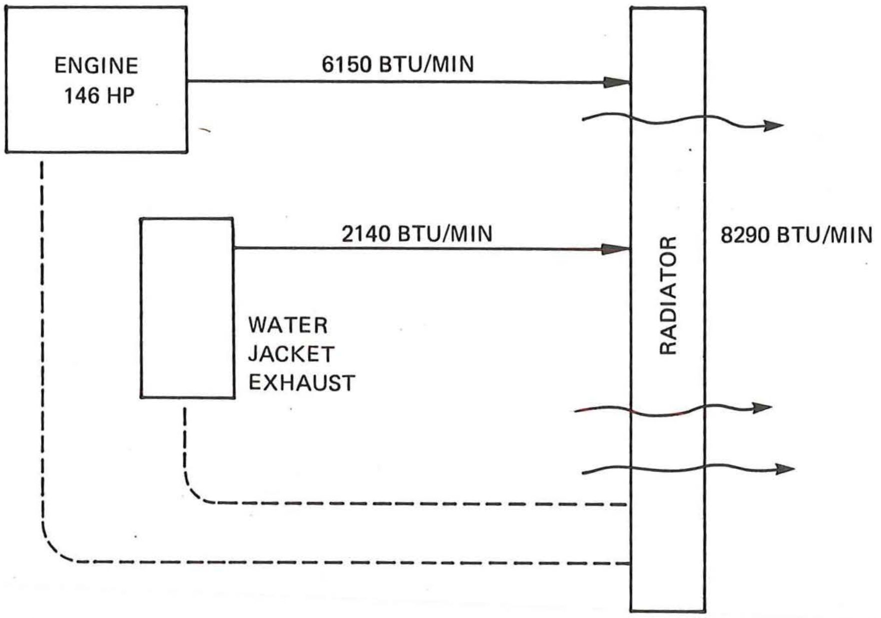

FIGURE 4.3.3.2-1 ENGINE HEAT DISSIPATION TO COOLING SYSTEM

4.3.3.3 Maintenance of a Cooling System

The cooling system of a liquid-cooled engine should be checked periodically for proper fill and for chemical composition. Fluid should be added or changed periodically as required, and only treated water and antifreeze should be used. The radiator should be washed down periodically to prevent accumulation and buildup of foreign matter on external surfaces. Whenever possible, oversized radiators should be designed into the system to compensate for possible deterioration of cooling system capacity in service.

4.3.4 Exhaust Systems and Exhaust Treatment

4.3.4.1 Exhaust System Description

The affect of the exhaust system on exhaust emissions is diagrammed in Figure 4.3.4.1-1. The purpose of exhaust treatment is to reduce emissions and lower the exhaust temperature at the discharge point. The effectiveness of present exhaust treatments is limited as shown in Table 4.3.4.1-1. Schedule 31 certification requires exhaust treatment for temperature control. Some states require exhaust treatment for all underground equipment. However, no requirement exists for the effectiveness of emissions reduction.

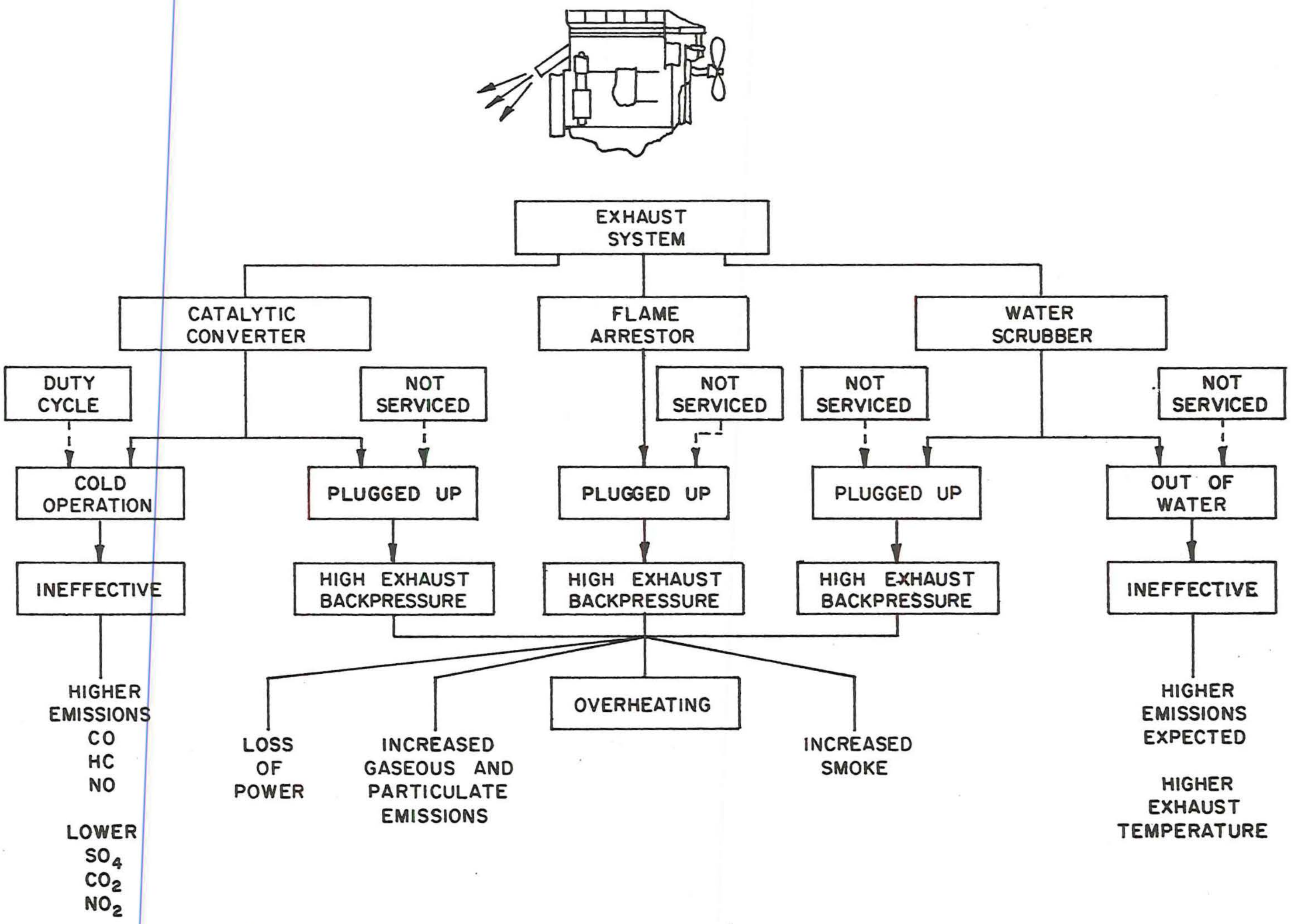

FIGURE 4.3.4.1-1 RELATIONSHIP OF EXHAUST SYSTEM FAILURES TO ENGINE EMISSIONS

Table 4.3.4.1-1. Effect of Different Exhaust Treatments on Temperature and Emissions

	Discharge Temperature	Emissions Affected
Water Scrubber	Lowered	Smoke Smell water vapor
Catalytic Converter	Raised slightly	CO and UBHC lowered at high temperature
Water Spray	Lowered	Unknown
Dilution	Lowered	Gaseous and Particulates Emissions change in concentration
Water-cooled Manifold	Lowered	Unknown

Catalytic Reactors - The main function of a catalytic reactor is to convert CO into CO_2. Up to 90 percent reduction at exhaust temperatures above 400°F is claimed by manufacturers. In addition, a "significant" reduction in hydrocarbons, acrolein and formaldehydes is claimed. However, oxidation increases exhaust gas temperature downstream from the converter. Oxidation of NO into more highly toxic NO_2, and SO_2 into SO_3 and SO_4, are undesired side effects. Use of high sulfur fuel can poison a catalytic reactor, impairing its operation. In addition, catalytic reactors are totally ineffective at exhaust gas temperatures below 400°F. This occurs during idle or low load operation. Converters have been observed that were almost completely plugged, as shown in Figure 4.3.4.1-2. High exhaust back pressure experienced with this condition leads to engine overheating. Other results are engine power loss, increased smoke, and a change in gaseous emission composition.

Water Scrubbers - A water scrubber has little effect on gaseous emissions, but tends to reduce particulate emissions and odor. Its main effectiveness is in reduction of exhaust temperature at the tail pipe, which accounts for the use of wet scrubbers on all Schedule 31 equipment. If improperly serviced, the water could be depleted, which would result in excessive exhaust gas temperature and high emission levels. Schedule 31 equipment has built-in safety devices to shut down the engine when low water level occurs; however, these devices malfunction at times. A plugged scrubber will increase the exhaust back pressure. The results are similar to those experienced with plugged catalytic converters. Water scrubbers are constructed of stainless steel. Almost every manufacturer uses a different design, but all direct the exhaust gases through a water bath. One such device is shown in Figure 4.3.4.1-3.

Water Spray - Some units spray water directly into the tailpipe. The effect on emissions is not documented. Claims of reduction in particulates and smoke are not quantitatively supported. Since such systems reportedly require more frequent attention and maintenance than water bath scrubbers or catalytic converters, many mines and manufacturers have avoided such a system. At one mine that was visited, such a water spray system of the mine's own design was the only type of exhaust treatment used.

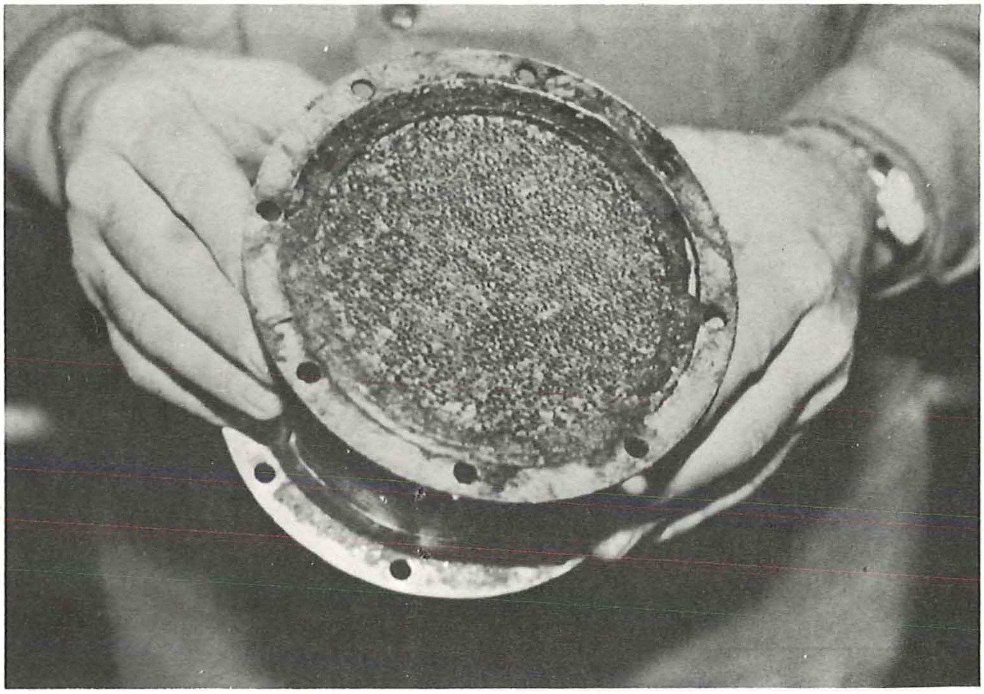

FIGURE 4.3.4.1-2 PLUGGED CATALYTIC CONVERTER

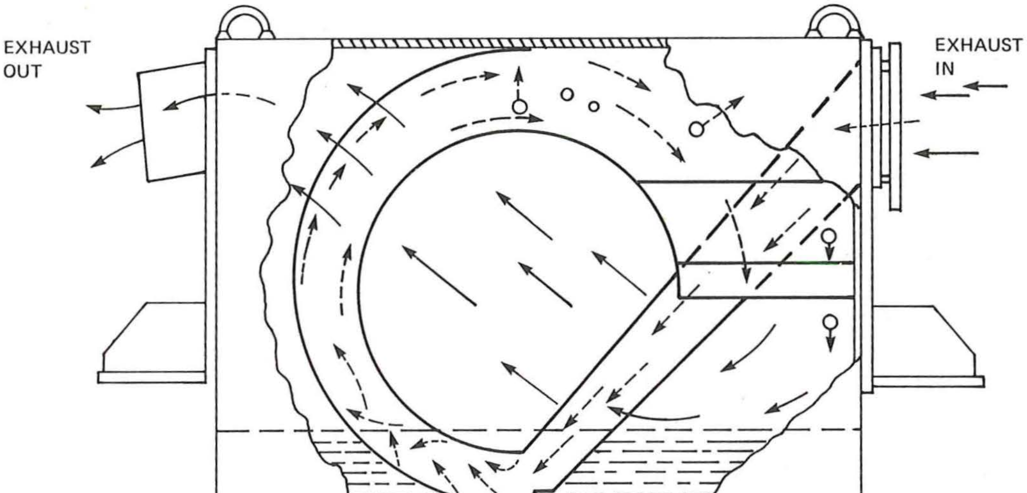

FIGURE 4.3.4.1-3 DESIGN FOR "CYCLONIC SCRUBBING"

Dilution of Exhaust - Most manufacturers use some type of dilution system to either divert the exhaust stream or discharge it into the air stream of the radiator. This cools the gases and lowers their concentration. The lowered temperature also changes the state of the unburned hydrocarbons and particulates, stimulating certain interactions, agglomerations and particulate growth.

Water-Cooled Manifold - Maximum surface temperature limitation for Schedule 31 equipment makes it necessary to cool the exhaust manifold surface temperature to the required 302°F. This is done through use of specially designed water-cooled exhaust manifolds and pipes. These manifolds are custom built by the equipment manufacturers and are generally stainless steel weldments. Since exhaust gases are cooled, some emissions characteristics changes may occur.

Exhaust Flame Arrester - An exhaust flame arrester is required for gassy operations. Its only function is that of a safety device. It does not alter emissions, but it can be plugged by soot and lead to increased exhaust back pressure.

4.3.4.2 Maintenance of an Exhaust Treatment System

Maintenance of water scrubbers is extensive. Their effectiveness depends on keeping them filled and on periodic flushing. This is considered the major disadvantage of water scrubbers in a mining operation. For this reason, their use is avoided whenever possible and catalytic converters are used instead. However, for Schedule 31 operations, water scrubbers are needed to control exhaust gas temperatures. Some mines visited have very extensive programs for filling, flushing, and inspection. The maintenance required by water scrubbers has possibly been a factor in some mine operators' decisions to use electric face equipment.

Catalytic converters are often referred to as the "maintenance free" alternative to water scrubbers. Some types use pellets, others a precious metal honeycomb design. The pellets are recycled periodically or replaced as required by operating conditions. The honeycomb type is renewed by replacement of the catalyst section of the converter. The problem with the catalytic converter is inability to determine if it is working properly. Rate of deterioration or life expectancy is not accurately known at present and should be investigated. The only real means presently available for checking a catalyst is exhaust backpressure measurement.

4.3.5 Fuel Injection System

Most failures of a fuel injection system stem from poor fuel or fuel contamination, and will result in changes in exhaust emissions as illustrated in Figure 4.3.5-1. Water in the fuel can cause injection tips to be eroded. The resulting poor spray pattern results in emission changes. Injector plugging will result in engine power loss, but may not cause emissions to change significantly. Problems such as these are usually satisfactorily corrected by replacement of faulty components with preadjusted components.

Adjustments to the fuel injection system, such as fuel rate setting or injection timing, if performed by untrained mechanics without proper equipment, can lead to significant changes in all emissions. Exhaust emissions are very sensitive to changes in

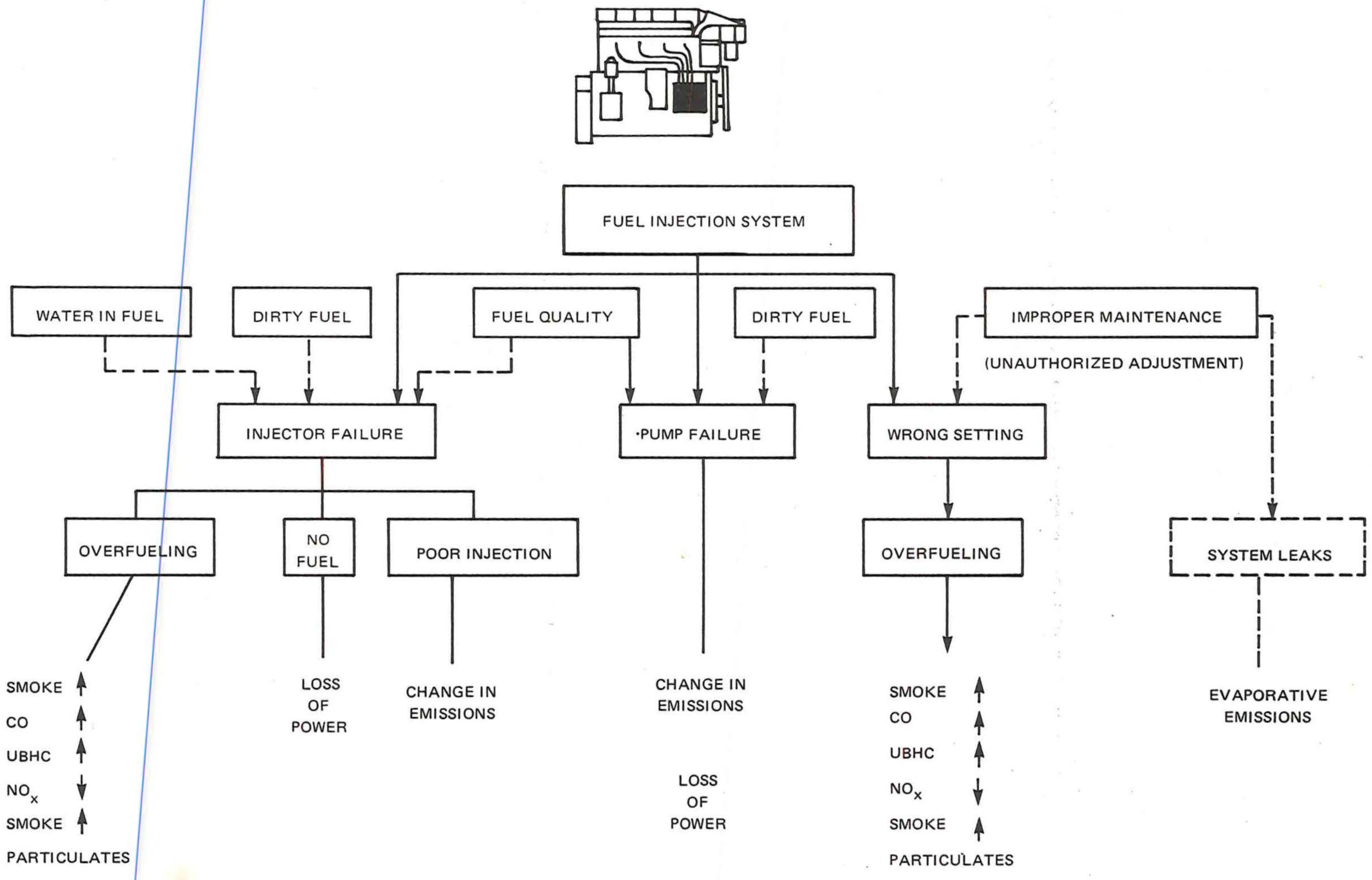

FIGURE 4.3.5-1 RELATIONSHIP OF FUEL INJECTION TO EMISSIONS

fuel injection timing. Retarding the injection by 4° from the proper setting can result in a:

- 300 percent increase in unburned hydrocarbons
- 50 percent increase in carbon monoxide
- 1000 percent increase in particulates.

Advancing the injection timing by 8° can result in a:

- 100 percent increase in unburned hydrocarbons
- 50 percent increase in nitric oxides
- 30 percent increase in particulates.

Changing the fueling rate can also greatly affect exhaust emission characteristics. Overfueling a diesel engine by 20 percent can cause a:

- 200 percent increase in carbon monoxide
- 175 percent increase in particulates

Even larger increases in all of the above can be expected if, in addition, the engine air filter is loaded. This will be discussed in greater detail later in this report.

Some mines attempt to adjust fueling rate and injection timing. However, no mines were observed to have the tools and instruments to properly perform this task. As a result, the engines will almost certainly be set improperly, resulting in higher than normal production of regulated exhaust gas components. Failures of the fuel injection system will be minimized if the delivery components are adjusted correctly and the fuel is clean. Adjustments should be performed by trained personnel with the necessary tools. If either is not available, the task should be contracted to the local engine dealer or representative. Implementing one of the good fuel handling procedures discussed previously will help prevent fuel contamination. Additionally, equipping the vehicles with dual-fuel filters and a water trap will prevent any foreign solids or water from reaching the injectors.

4.3.6 Lubrication System

4.3.6.1 Effect of Lubrication System on Emissions

Lubrication system failures are generally caused by one or more of the following:

- Lubrication system mechanical failure
- Lubricant failure or contamination
- Engine overheating

Each of these will ultimately lead to the same result; engine wear, emissions changes and engine failure. The mechanisms of emission changes are depicted in Figure 4.3.6.1-1.

Mechanical system failures obviously will reduce or eliminate lubrication, usually leading to engine damage or failure in a short time. Improper lubricants such as

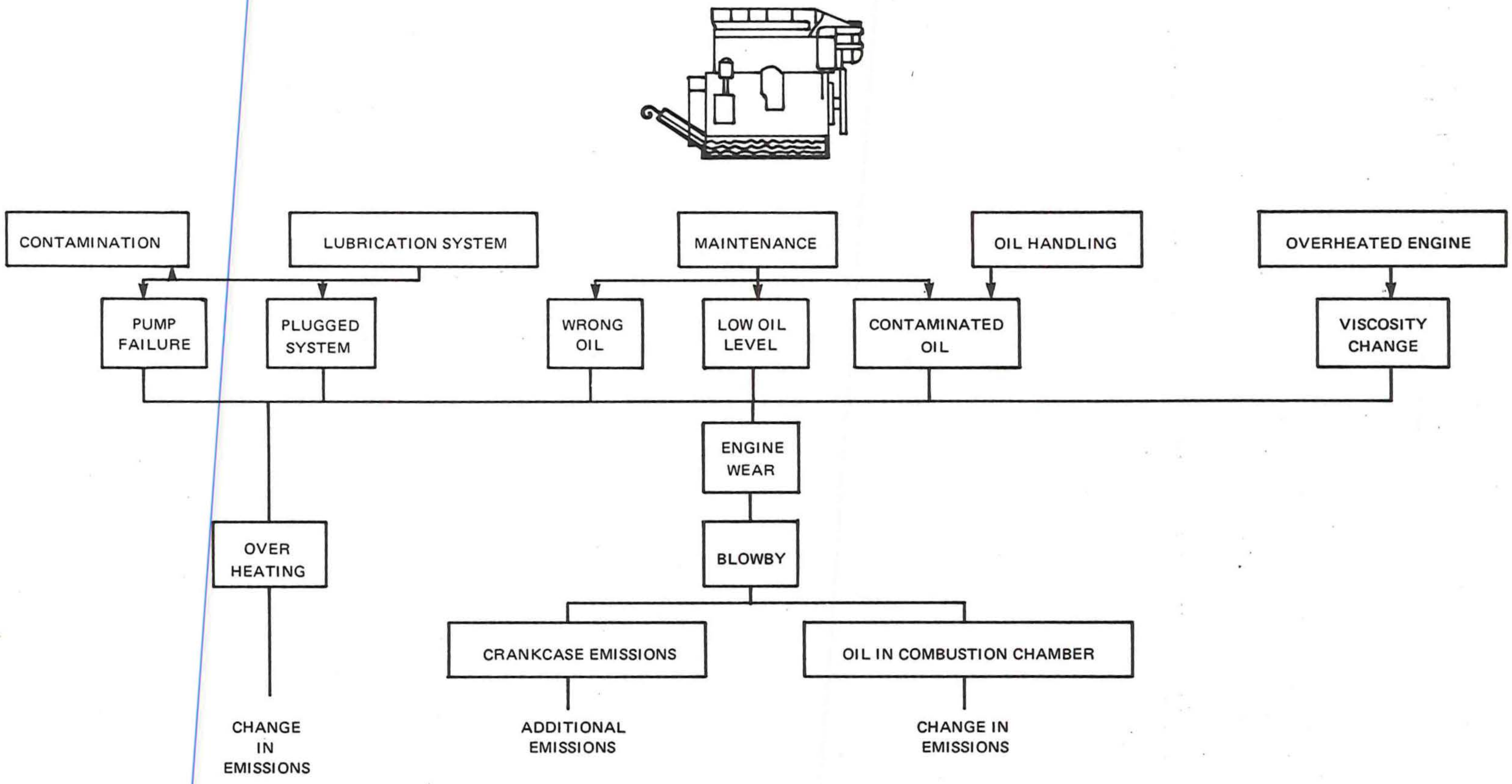

FIGURE 4.3.6.1-1 RELATIONSHIP OF LUBRICATION TO EMISSIONS

light pneumatic tool oil or transmission oil are less effective than recommended engine lubricants. Neither do they contain the proper additives to counteract the acids produced during the combustion process. Water, which is sometimes introduced intentionally or inadvertently, follows the same pattern of wear and failure, but usually at a catastrophic rate. Contamination of the crankcase oil with solids such as sand can cause ring wear, but can also lead to lubrication system mechanical failure.

Engine overheating, regardless of its initial cause, will reduce the viscosity of the engine oil, leading to increased engine wear. Excessive engine wear is the result of all lubrication system related failures. It will occur mainly at the pistons and rings. Wear will also occur at the lower end of the engine, but perhaps to a lesser degree. Ring wear will allow additional engine oil to be admitted to the combustion chamber and upper cylinder wall areas. Engine wear effects most noticeable will be higher particulate and unburned hydrocarbon emissions. A secondary effect of ring wear is emission of fuel and lubricant vapors from the crankcase blowby tube. Quantitative data on blowby emissions could not be found since all engine emission tests and certification runs are performed with new engines in which these excessive conditions are not experienced.

All engines have oil filters designed to remove solid contaminants. However, if large amounts of contaminants are present in the oil, or if filters are not changed, a built-in relief valve will allow oil to bypass the filter. If this condition persists, increased engine wear will result.

Proper training of service personnel and proper storage of crankcase oil in labeled containers will reduce the possibilities of having transmission oil, pneumatic tool oil, or diesel fuel or water added to the crankcase. Proper storage and handling will also reduce contamination of the oil. Engine and equipment manufacturers recommend various oil change intervals. In mines where conditions are more severe, manufacturers' recommendations should be observed as a minimum. Many mines have gone to 50 or 100 hour oil change intervals. Checking the oil daily is important, warning lights or shutdown devices are helpful in engine damage prevention but must be heeded immediately.

4.3.6.2 Used Oil Analysis Program

Many mines have implemented a used oil analysis program as a method of monitoring engine conditions. Some report significant reduction in overhaul costs since initiation of such a program; however, others have not seen any benefit. The difference in results may be explained in the level of effort expended in utilizing the data. Regardless of the results, it shows effort by mine management to improve maintenance. Such a program does not prevent damage, but it can give clues that may result in preventing serious damage or total engine failure. It will almost certainly lower the average cost for an overhaul. Additionally, the ability to track engine wear allows the mine to change engines according to a scheduled program and not according to unexpected breakdowns.

Engine oil analysis programs are offered by oil companies, engine manufacturers, and independent laboratories. Results range from a mere list of contaminants to a written analysis and recommendations concerning engine conditions. The effectiveness of these programs varies greatly in quality and timeliness. Engine oil analysis results are best utilized by observing trends in the concentrations of the various wear metals. When one or more of these components suddenly increases, a failure may be imminent. Table 4.3.6.2-1 gives several elements and compounds which when appearing in high concentrations may portend the failures or conditions shown.

Table 4.3.6.2-1 Engine Diagnostics by Used Oil Analysis

Wear Metal/Oil Component Having Elevated Concentration	Possible Problem Components or Systems
Aluminum (Aℓ)	Bearings, pistons, torque converter, auxiliary drives
Barium (Ba)	Oil additive
Boron (B)	Cooling system leak
Calcium (Ca)	Oil additive, coolant leak
Chromium (Cr)	Rings, liners, coolant leak
Copper (Cu)	Bushings, bearings, valve guides, piston pins, rocker arms, transmission, auxiliary drives
Iron (Fe)	Pistons, rings, liners, valve guides, rocker arms, transmission, auxiliary drives
Lead (Pb)	Bearings, mixing with leaded gasoline
Magnesium (Mg)	Bearing race
Nickel (Ni)	Valve train
Phosphorous (P)	Oil additive, coolant leak
Silicon (Si)	Intake air system, oil additive
Silver (Ag)	Bearings, bushings
Sodium (Na)	Coolant leak
Tin (Sn)	Bearings
Titanium (Ti)	Bearing Race
Zinc (Zn)	Oil additive, bushings
Water	Coolant leak
Fuel	Fuel delivery system, excessive engine lugging
Carbon, varnish	Oil breakdown, engine misfiring

5. TEST EQUIPMENT DESCRIPTION

5.1 FIELD TESTING

5.1.1 Performance and Diagnostic Equipment

Performance equipment and instrumentation is defined as a general category of tool used to measure how well the engine is operating and is used during actual running of the engine. Diagnostic equipment measures the current general health of the engine. Since there are many parameters that affect the operation of and emissions from a diesel engine, many instruments are required to properly monitor these parameters. This section lists the parameters relevant to engine testing, discusses how they affect engine performance, and overviews the instrumentation used to measure those parameters.

- **Engine Speed** - Two methods were used to measure engine speed. The primary device was an AVL injection timing light. This instrument counts injection pulses from the engine's fuel pump and displays engine rpm on a digital meter. The system is accurate to within 10 rpm.

  The second device used to measure engine speed was one that was built into the portable dynamometer. The dynamometer driveshaft that loaded the engine was equipped with a 60-tooth gear and magnetic pickup. Each time a tooth of the metal gear passed the face of the magnetic pickup, an electrical pulse was developed. These pulses were counted for a one-second time interval and displayed as rpm on a digital light-emitting diode indicator. This system is accurate to within one rpm but measures dynamometer speed which often was different from engine speed due to torque converters and gear boxes.

- **Engine Output Torque** - It was determined in Phase I of this program that close monitoring of the engine output level was critical in accurately determining engine emission characteristics. To accurately, repeatably, and steadily load a diesel engine under field conditions, a portable dynamometer was required. Most dynamometers available on the market are stationary laboratory-type devices. However, a portable dynamometer marketed by A&W Dynamometer, Inc., was available and was capable of the speeds and loads expected in our testing. This dynamometer is illustrated in Figure 5.1.1-1.

  The dynamometer applies load to the engine under test via a driveshaft that connects to the engine flywheel or vehicle driveshaft. The dynamometer has three large drum brakes that serve to apply a load to the engine. The outer hub of the brake drum rotates at the same speed of the driveshaft. For cooling, the drums are immersed in water. If immersion of the brakes in water creates excessive drag, the brakes can be cooled by means of a water spray provided by a built-in spray bar. If the load brakes are immersed in water, the dynamometer can effectively absorb 900 hp at a speed between 1500 and 3000 rpm. To apply load to the engine, the brake pads inside the drum brakes are hydraulically forced against the hub. The output torque required of the engine under test is proportional to the force applied to the brake pad. The hydraulic system that drives the brake pads is controlled by a spool valve which is adjusted by the operator.

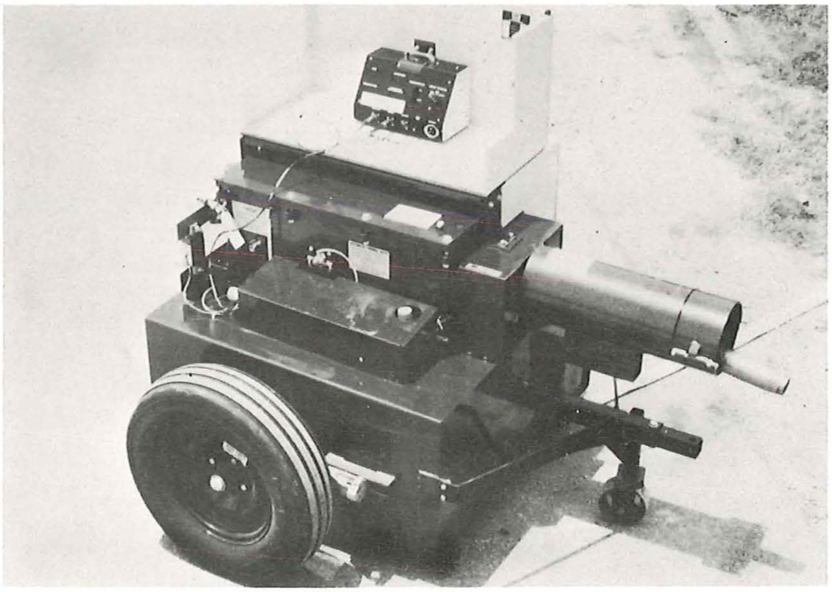

FIGURE 5.1.1-1 PORTABLE DYNAMOMETER USED DURING DIESEL ENGINE TESTING

The cylinder block that provides pressure to the brake pads is connected to a splined shaft, which is in turn tied to a lever arm. The end of the lever arm is connected to an electrical load cell. The load cell in this configuration measures the output torque of the engine under test. The signal from the load cell is sent to the dynamometer electronic package where it is conditioned, digitized, and displayed on an LED meter in units of ft-lb torque. The dynamometer electronics multiplies the load shaft speed by the load shaft torque, applies the appropriate constants, and calculates output horsepower. The output horsepower is also displayed on a digital LED meter. System calibration was accomplished by attaching a load arm and NBS traceable weights to the load cell lever arm.

- **Fuel Flow Rate** - To determine how efficiently a diesel engine is operating, it is desirable to monitor engine fuel consumption. A Fluidyne volume flow meter was chosen due to its ruggedness and long-term accuracy without recalibration. Being a volume flow device, both fuel temperature and specific gravity corrections must be made in each reading. The specific gravity of No. 2 diesel fuel at 85°F is approximately 0.841. Its specific gravity at 115°F is 0.830. This is a change of 1.3 percent over a temperature range of 30°F. This small error in using a volume flow device rather than a mass flow device justifies its use.

The volume flow sensor was used in the fuel measurement system shown in Figure 5.1.1-2. It is seen from this figure that only one fuel flow is measured. A storage tank with a needle valve on its fuel inlet line acts as a summing junction for the fuel delivered to the engine and the fuel returning from the engine. The fuel consumed is displayed on a digital meter. The system was calibrated in the SwRI laboratory in a manner that allows direct readout of fuel flow in lbs per hour. This, of course, assumes a fixed density of the diesel fuel.

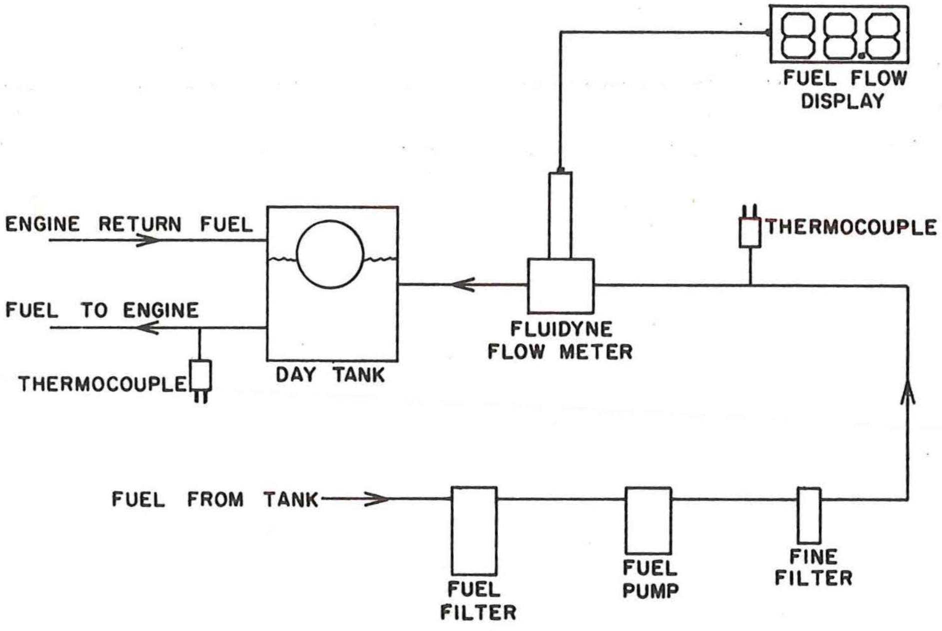

FIGURE 5.1.1-2 DIESEL FUEL FLOW MEASUREMENT SYSTEM FOR FIELD TESTING

- **Engine Intake Air Flowrate** - Engine intake air flow is another parameter that affects both engine output power and exhaust emissions. The intake air flowrate was calculated by measuring the pressure drop across a laminar flow element (LFE). The laminar flow element looks like a honeycomb and forces the airflow into a laminar regime. With a laminar flow, the curves that relate pressure drop to air flow are well-behaved (nearly linear in the region of interest). The laminar flow element was calibrated at SwRI against a known airflow source. The pressure gauges used to measure the pressure drop across the LFE were also calibrated at SwRI before being used in the field.

- **Injection Timing** - The timing of the diesel fuel injection into an engine strongly affects the production of nitric oxides. The injection timing can also have an effect on the production of other emissions as well as engine output power. Injection timing is measured in degrees before or after top dead center. The device used senses fuel injection into the No. 1 cylinder through a pressure sensor clamped on the fuel line to the No. 1 injector. The operator adjusts a strobe light to synchronize the flash of the light to the top dead center mark on the harmonic balancer. Knowing when injection occurs and when top dead center occurs, the instrument calculates and displays the number of degrees of crank rotation between injection and top dead center.

- **Barometric Pressure** - The amount of oxygen available in a given volume of air is a function of the barometric pressure. Therefore, barometric pressure is one parameter required in the correction of observed brake horsepower corrected for standard conditions. A barometer was used to measure the barometric pressure underground at the field test site. The barometer was calibrated at the nearest airport. Since airport barometer readings are corrected for sea level, all of the barometric pressure readings had to be adjusted to reflect the proper altitude.

- **Relative Humidity** - Moisture in the air displaces oxygen, thereby affecting engine output power. Relative humidity, like barometric pressure, is used to correct the observed brake horsepower to brake horsepower at standard conditions. Relative humidity was measured with a psychrometer. This psychrometer uses a battery-powered fan to create an air flow across wet bulb and dry bulb mercury thermometers. With the wet bulb and dry bulb temperatures, psychrometric charts can be used to determine relative humidity.

- **Compression Tester** - It was deemed necessary to measure cylinder cranking pressures since reduced compression can result in a reduction in output power. The compression tester used has a mechanical pressure sensor that is connected to a swinging arm. This arm moves across a piece of pressure sensitive graph paper leaving a line the length of which indicates cylinder pressure. To test the compression of a cylinder, the injector nozzle or glow plug in the cylinder head is removed and a fitting is screwed in its place. When the engine is cranked, the pressure is transmitted to the mechanical pressure transducer which moves the marking arm, leaving a pressure trace on the graph paper.

- **Injector Nozzle Tester** - Faulty injector nozzles can result in engine knock at high loads, reduced horsepower, and it can also cause an increase in carbon monoxide and hydrocarbon levels in the exhaust gases. The injector nozzle tester is a device that can pressurize diesel fuel and force it through an injector nozzle fitted onto the tester. A pressure gauge on the tester indicates the pressure at which the nozzle cracks open. When the injector nozzle cracks open, a quick eye or a synchronized camera can show up faulty spray patterns.

5.1.2 Gaseous Emission Measurements

Design and development of the emissions carts was initiated after several visits to prospective mines to develop design criteria for cart fabrication. Once the basic design for the emissions measurement system was developed, specific instrument selection was made. Beckman instruments were selected based on proven field durability, existing availability of repair parts, experience in custom cart fabrication, equipment warranty and assurances of immediate response to field repair parts requirements. The instrument model numbers and available ranges are presented in Table 5.1.2-1.

The instrument cart was fabricated by Beckman Instruments based on design criteria provided by SwRI. The basic carts were built using quarter-inch steel plate to protect the instruments from any potential external inadvertent contacts with mining equipment. The gaseous emissions measurement system was designed to incorporate the use of two separate carts. One cart was the interface cart, which contained the interface oven and Beckman 402 hydrocarbon analyzer. The second cart contained the remainder of the emissions instrumentation, namely, CO, CO_2, NO_x, and O_2 analyzers. The two carts were designed to operate in tandem with a minimal distance between the two. The flow schematic of the gaseous emissions instrumentation is presented in Figure 5.1.2-1. Several views of the emissions instrumentation are presented in Figure 5.1.2-2 through Figure 5.1.2-5. The calibration and zero gases are located in the adjacent particulate cart.

Table 5.1.2-1 List of Emissions Equipment

Instrument Description	Exhaust Component	Detection Method	Instrument Ranges
Beckman Model 402	HC	FID	0-50, 0-100, 0-500, 0-1000, 0-5000 ppm C
Beckman Model OM-11EA	O_2	Polargraphic	0-25%, 0-5%
Beckman Model 865	CO_2	NDIR	0-2%, 0-8%, 0-16%
Beckman Model 865	CO	NDIR	0-500 ppm, 0-1500 ppm, 0-3000 ppm
Beckman Model 955	NO_x	Chemiluminescent	0-1000 ppm, 0-250 ppm, 0-100 ppm
Soltec Recorder Model 3315	--	--	10 mv

The instrument frame and panel supporting the CO, CO_2, NO_x, and O_2 instruments is shock mounted on aircraft-type shock absorbers to minimize vibrations. Full size automotive tires are used on each cart to allow easy movement on rough floors, provide additional shock resistance and give sufficient ground clearance for routine inter-mine transportation. The carts have locking front and back doors to ensure security of the instruments during non-testing periods. The front door has Lexan^R windows to allow visual access to the instruments without opening the doors.

The system was originally designed to hold eight size two cylinders in the HC cart. However, during the design of the particulate cart it became apparent that the particulate system would also require zero air bottles. It was decided to include cylinder storage space for 12 size 150 aluminum cylinders in the particulate cart. Since the mechanical components of the "mini-tunnel" could be designed into a relatively small portion of the cart, the design and fabrication of the particulate cart was expanded to include full size cylinders. There were several distinct advantages to using the size 150 aluminum cylinders in lieu of the smaller steel cylinders. The larger cylinders would last five times longer and would be more cost effective in the long term, both in terms of purchasing replacement gases and in naming the new gases. The gases used in this study were named in reference to NBS SRM gases. Calibration curves

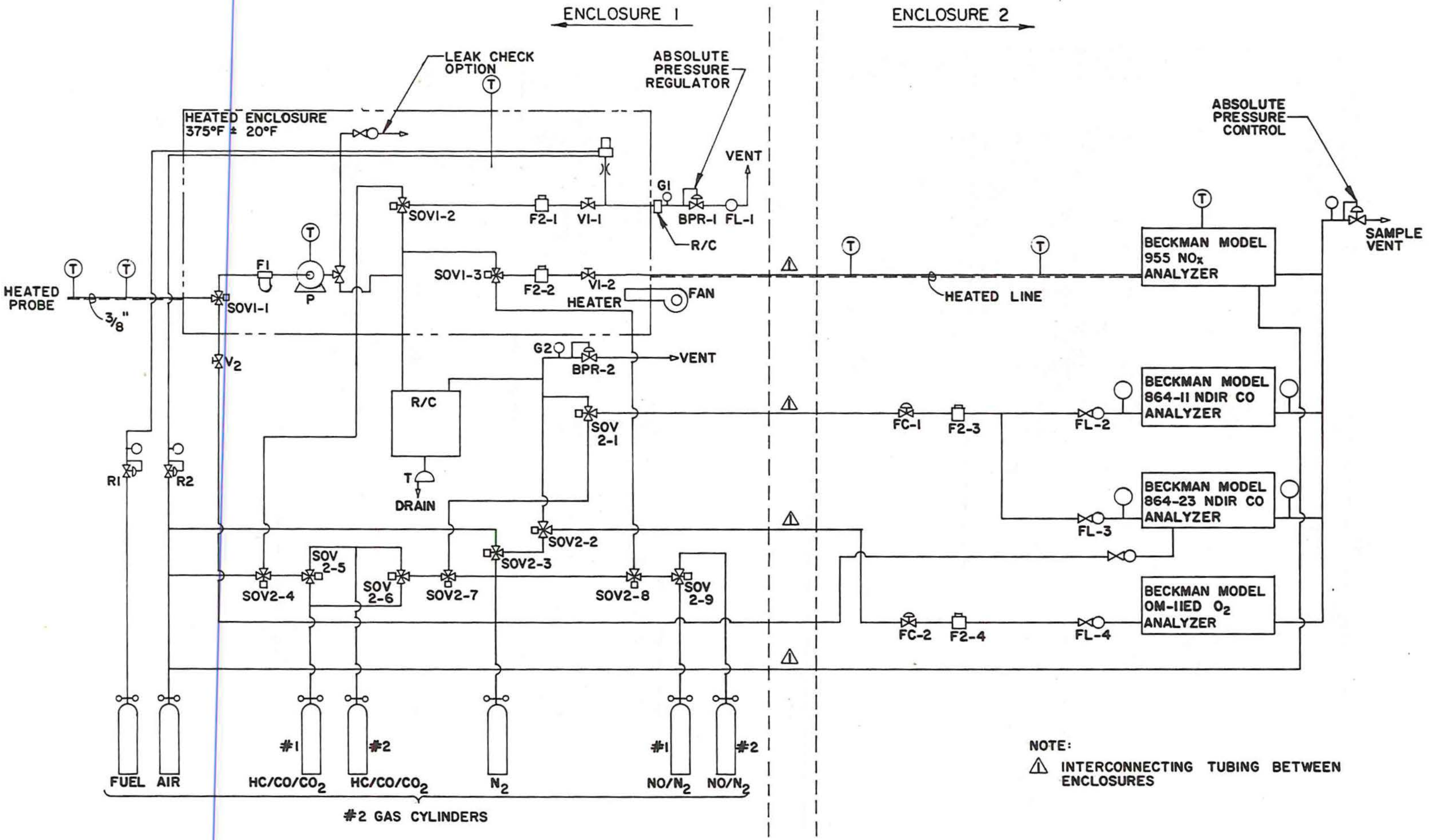

FIGURE 5.1.2-1 GASEOUS EMISSION ANALYSIS FLOW SCHEMATIC

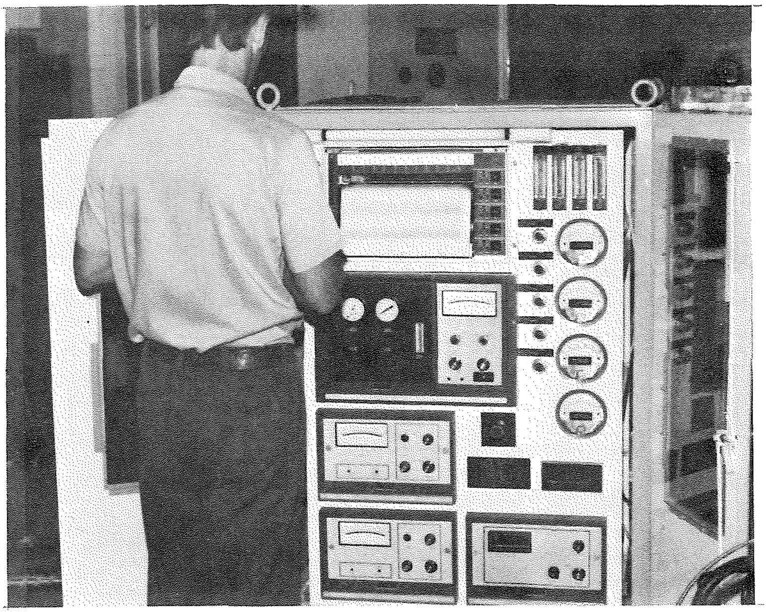

FIGURE 5.1.2-2 GASEOUS EMISSIONS CART - CO, CO_2, NO_x, O_2

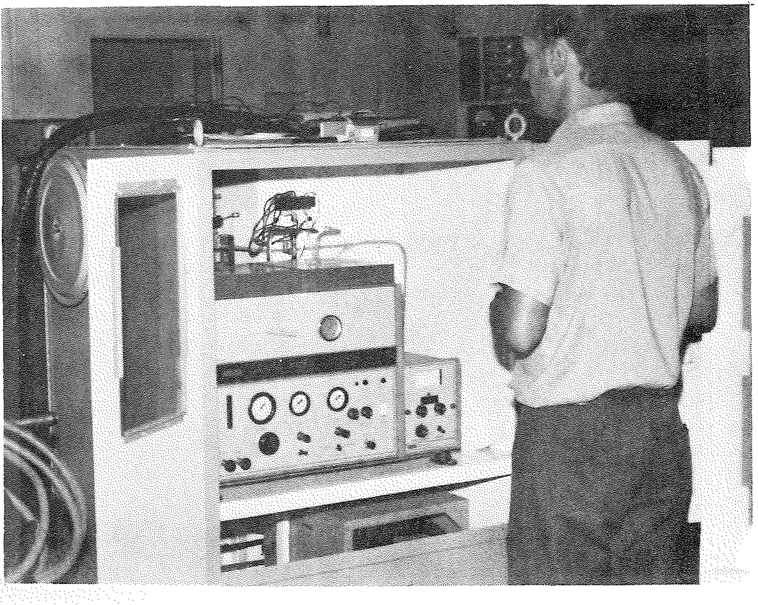

FIGURE 5.1.2-3 GASEOUS EMISSIONS CART - HC AND INTERFACE OVEN

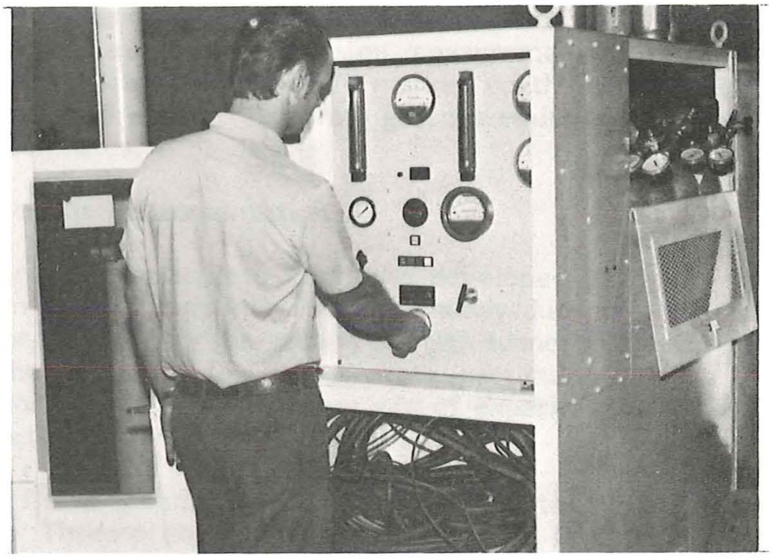

FIGURE 5.1.2-4 PARTICULATE (AND CYLINDER) CART

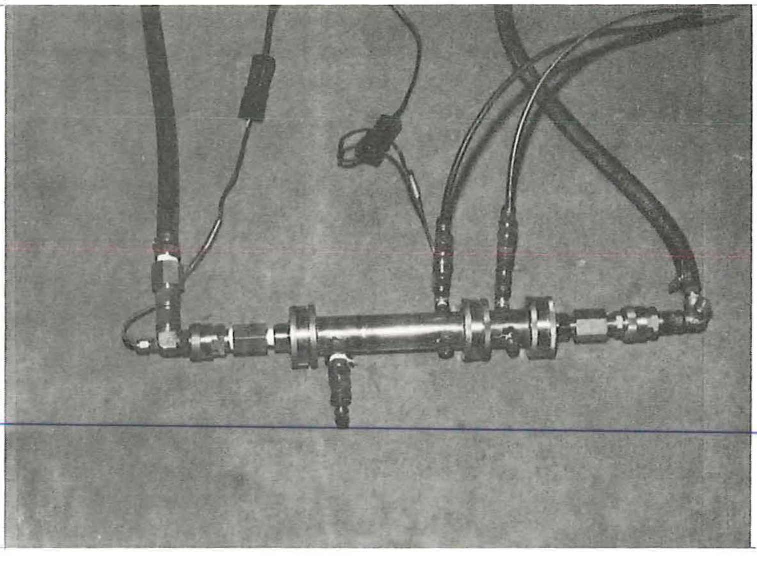

FIGURE 5.1.2-5 CLOSE-UP OF "MINI-TUNNEL"

were generated for each range on each instrument using curve fit techniques used in EPA certification of heavy-duty diesel engines.

During gaseous emission tests, every effort was made to ensure accurate emissions data acquisition in the field. The sample line was leak checked prior to measurements, sample line and oven operating temperatures confirmed, flows checked, etc., before any emissions measurements were initiated. All ranges were zeroed and spanned before and after each emission measurement to confirm the validity of each data point. Each emission was clearly marked on the recorder chart paper as to type, range, date, run, and engine. The raw gaseous emissions were used to calculate brake specific emission rates.

5.1.3 Particulate Instrumentation

A portable particulate cart was developed using the principles of the EPA double dilution system currently used in heavy-duty diesel transient testing. This technique incorporates only the second dilution tunnel to measure particulate emissions. The use of the approach for steady-state particulate measurements had not been previously reported and required a variety of experiments to demonstrate equivalency to full dilution tunnels.

The flow schematic of the particulate "mini-tunnel" is presented in Figure 5.1.3-1. Three prime areas of concern were investigated during the correlation experiments: temperature of the sample at the filter face, repeatability and accuracy of measurement relative to conventional full dilution tunnels. The results of bench mark tests showed ± 10 percent total repeatability and accuracy when the dilution ratio was held below 11:1.

The mini-tunnel was found to be quite rugged and did not need any special mounting shock absorbers in the portable particulate cart. The particulate cart was fabricated with 1/8 inch steel plate. The floor was reinforced to provide sufficient strength for the calibration cylinders. Each side panel of the particulate cart was designed with steel lattice windows to ensure adequate ventilation. All cylinder regulators were removed during transportation.

The particulate cart and mini-tunnel are illustrated in Figure 5.1.2-4 and Figure 5.1.2-5. The dilution tunnel is 1-1/4 inch OD by approximately 12 inches long and uses two 47mm SS Gelman filter holders to collect particulate. A single 47mm SS Gelman filter holder is used to filter the zero dilution air. All 47mm filters are Pallflex T60A20. This is the same filter media as that used in EPA diesel particulate studies.

During the initial particulate cart check-outs, there was concern over the potential of exceeding the 125°F maximum temperature at the filter face. Exhaust temperatures during the initial check-out were less than those anticipated on some of the larger mining engines. In order to ensure consistent operation at less than 125°F filter face gas stream temperatures, cooling fins were added to the short length of 3/8 inch tubing between the exhaust pipe and the mini-tunnel. A small instrument ventilation fan provided air movement over the fins to slightly reduce the exhaust gas temperature prior to entry into the mini-tunnel. After installation of the cooling fins, gas stream temperatures were well below the 125°F maximum.

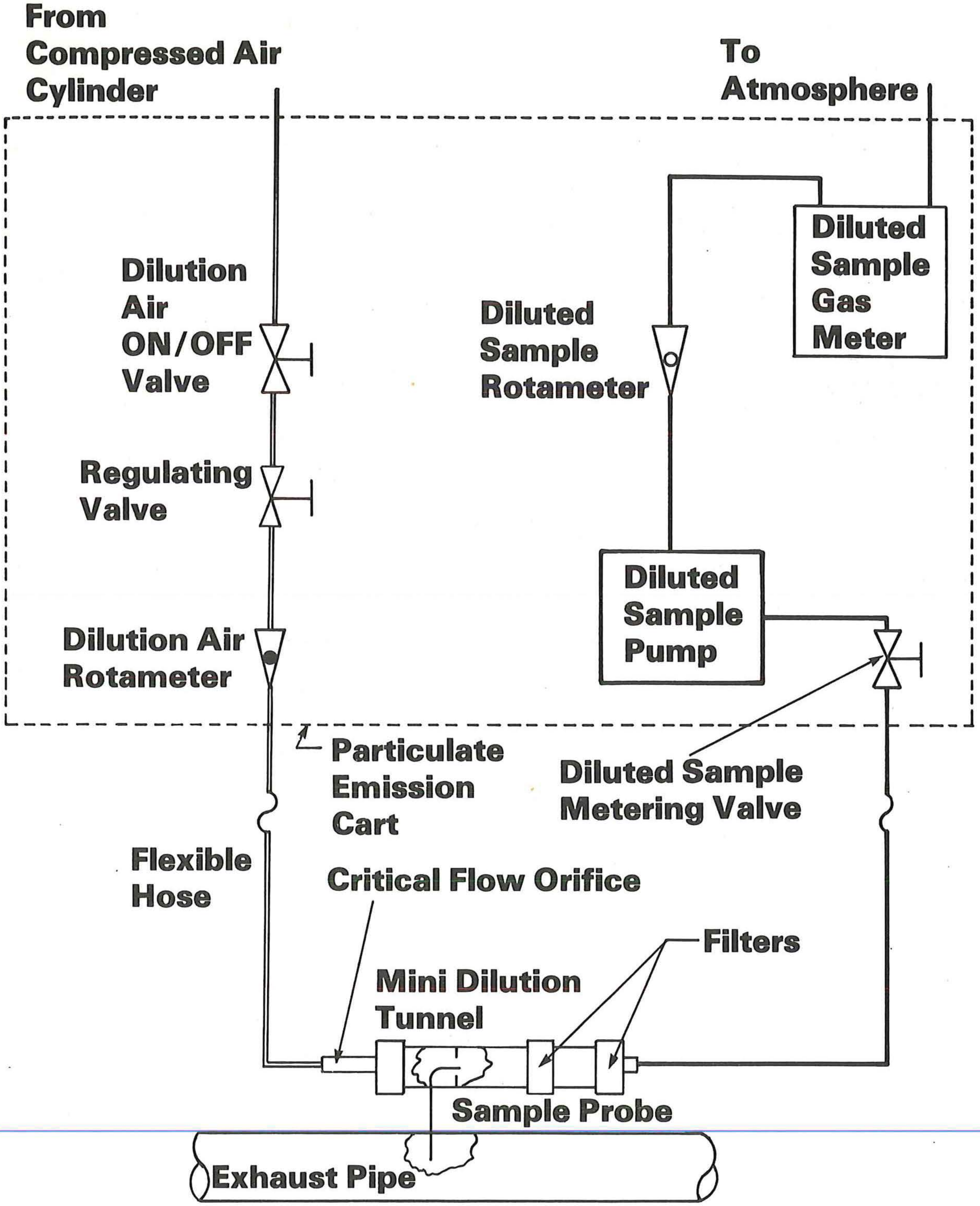

FIGURE 5.1.3-1 MINIATURE DILUTION TUNNEL USED FOR FIELD PARTICULATE MEASUREMENT

The accuracy of the particulate measurement is directly influenced by the dilution ratio. The quantity of exhaust sample collected is determined by the volumetric difference between the dilution air and the diluted exhaust sample. At high dilution ratios, the sample volume accuracy decreases because the sample is calculated as the difference between two large values. The mini-tunnel accuracy is greatest at dilution ratios less than 11:1 (depending on critical flow orifice size). Since field tests were within the recommended range, it is felt the particulate emission measurement accuracy was satisfactory.

5.2 USED ENGINE AND INDUCED FAULT LABORATORY TESTING

5.2.1 SwRI Laboratory Test Equipment

Three different test cells were utilized for the used engine testing and the induced faults phase of this program. The test cell floor plan of these cells is shown in Figure 5.2.1-1. Appropriate sized eddy-current dynamometers were used for each engine with electronic speed controllers to maintain a constant desired speed. Engine speed was determined by using a magnetic pickup in close proximity to a 60-tooth gear on the dyno shaft. An air actuator was used to control rack or throttle position, thus allowing any speed-load condition to be held stable during testing. Intake air flow was determined using a Merriam laminar flowmeter. Fuel flow was measured with a Flo-Tron linear mass flowmeter. This instrument uses the principle of a hydraulic Wheatstone bridge and displays fuel consumption directly in pounds per hour without the need for temperature or density correction factors.

Temperatures were measured with iron-constantan thermocouples and a combination of gauges and manometers provided pressure data. Wet and dry bulb temperatures were recorded and used to calculate relative humidity. Crankcase blowby measurements were made with a bellows-type dry gas meter attached to the engine's crankcase vent tube. Smoke numbers were obtained by using a conventional Robert Bosch sample pump and filter meter. Engines were tested with minimum intake restrictions and exhaust back pressures except during portions of the induced faults testing. A baffle in the exhaust system downstream of the sampling probes was used, however, to correct for small changes in exhaust back pressure caused by the particulate tunnel as sample rates changed.

5.2.2 Gaseous Emissions Instrumentation

Instrumentation for measuring gaseous emissions (CO, CO_2, NO_x, and HC) was selected to conform to requirements as specified by EPA in the 13-Mode emissions certification of heavy-duty diesel engines. CO and CO_2 were measured using non-dispersive infrared (NDIR) analyzer. NO and NO_x were measured by a heated chemiluminescent analyzer. HC was measured using a heated hydrocarbon analyzer (375°F) with a flame ionization detector (FID).

5.2.3 Particulate Emissions Measurements

Exhaust particulate measurements were accomplished using a splitter-system dilution tunnel. This splitter-system takes a portion of the exhaust under steady-state engine operation and dilutes it with filtered ambient air to keep the diluted exhaust gas temperature below 125°F at the filter face. The stainless steel dilution tunnel is

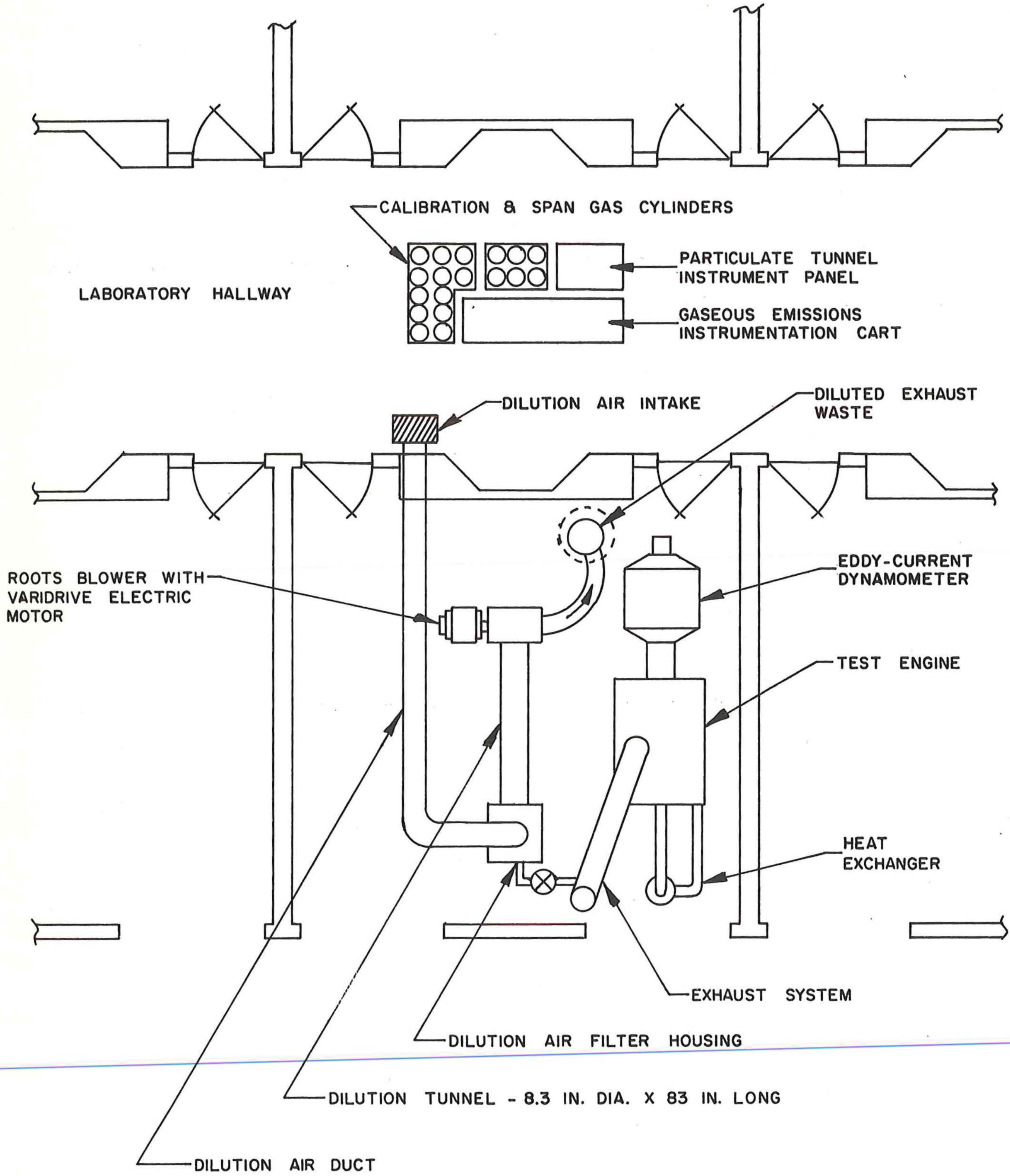

FIGURE 5.2.1-1 LABORATORY TEST CELL AND EQUIPMENT LAYOUT

8.3 inches in diameter and 7 feet long. Four individually controlled 47mm filter collection systems were available as needed. Particulate samples of diluted diesel exhaust were collected under steady-state operation and exhaust concentrations (mg/SCM) were calculated using dilution tunnel test parameters. Brake specific particulate emission rates were calculated using engine air and fuel rates and measured brake horsepower.