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CONTROL OF DIESEL EXHAUST EMISSIONS IN UNDERGROUND MINES

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Engelhard Corporation

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BUREAU OF MINES
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FOREWARD

This report was prepared by Engelhard Corporation, Specialty Chemicals Division, Menlo Park, New Jersey under USBM Contract number H0199021. The contract was initiated under the Bureau of Mines Health & Safety Program. It was administered under the technical direction of Pittsburgh Research Center with Mr. Edward D. Thimons acting as Technical Project Officer. Mr. Oliver H. Snyder, III was the contractor administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period May 10, 1979 to July, 1985. This report was submitted by the authors on May, 1986.

TABLE OF CONTENTS

		PAGE
I.	GENERAL INTRODUCTION	6
II.	ONTARIO RESEARCH FOUNDATION FINAL REPORT NO. 2828 FOR PHASES I AND II	21
III.	ONTARIO RESEARCH FOUNDATION FINAL REPORT NO. 3974 FOR PHASE III	239

GENERAL INTRODUCTION

Diesel engines are currently used in underground mines in many parts of the United States and particularly widely in so-called hard rock or non-gassy mines. Extensive use is made of diesel powered vehicles in Canadian mining as well as in major European countries. There is general interest in further extending the applications of diesel engines to underground mining operations. The motivation is primarily economic since diesel powered work vehicles offer greater economy in operation when their increased work efficiency and flexibility are considered as compared to alternate existing methods such as cable fed electric vehicles.

Along with the interest in extending diesel engine application underground has been the need to more adequately deal with the possible health effects dangers of diesel exhaust emissions. Toxic exhaust emissions from underground diesel equipment in the U. S. fall under the regulations of the Mine Safety and Health Administration (MSHA). These are directed at limiting pollutant levels to specified threshold limit value (TLV)* concentrations in the ambient air of the working environment. Diesel engines used in underground mines are derated by resetting fuel pump adjustment. This provides a lower fuel/air ratio and reduces exhaust pollutants caused by incomplete combustion of diesel fuel in the engine, at the expense of some engine sizing. In addition, mine ventilation standards are provided and these serve to dilute tailpipe pollutant concentrations.

However, environmental health standards and concerns are in process of change. Lower TLV's for carbon monoxide and nitrogen dioxide have been proposed.** No mine standard yet exists which is specifically directed at

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* "TLV's" are a trademark of the American Conference of Governmental and Industrial Hygienists (ACGIH)

* CO from 50 to 35 ppm; NO_2 from 5 to 3 ppm.

diesel particulate emissions*. Data is available which describes typical emissions in the exhaust from diesel engines used in underground mines[1, 2]. Rates of pollutant emissions, although reduced through engine derating, nevertheless leave considerable cause for concern as to the health impact on underground mine workers.

There is special concern over the negative synergism which could result from exposure to the array of combined pollutant concentrations. This is particularly true of diesel particulates which can act as carriers for other exhaust pollutants including unburned hydrocarbons and sulfur compounds.

One solution to this problem is to increase the mine ventilation to ensure the safest air dilution levels possible. However, this must be limited by economic and practical considerations and also cannot always account for problems of localized or short term pollutant concentrations. Therefore, it is necessary that techniques for directly controlling emissions on the engine be developed to allow effective but reasonable and economical ventilation levels and the maximum use of diesel equipment in a given mine.

This report covers a three part project directed to the development of exhaust emissions controls for underground diesel powered vehicles. The emphasis in this project is on the development of diesel exhaust after treatment devices and other control techniques and as such is part of a comprehensive program by the U. S. Bureau of Mines to minimize hazards associated with diesel operations in underground mines.

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* It has been recommended in a Canadian health effects survey study that the TLV for respirable diesel particulate in mine air be 75% of the present standard of 2 mg/m^3 TLV for respirable coal dust or 1.5 mg/m^3. (Reference 6)

Phase I was concerned with an experimental survey of existing exhaust emission control techniques and devices. The purpose of this phase was to uncover promising after treatment devices and techniques for mining diesels and especially to discover positive combinations of devices which might provide new possibilities in attacking diesel exhaust pollution. Phase II was designed to pursue in greater depth the characterization and development of the most promising approaches defined in Phase I. The objective of Phase III was to translate the results of the earlier work into practical, field-useable hardware for actual testing and qualification in a mine environment.

In pursuing solutions, in this project, to the problem of exhaust emissions control in underground diesels, a system approach has been emphasized addressing the totality of diesel exhaust pollutants. The commission for the project from the Bureau of Mines included the instruction that "Efforts will be directed to optimize control so that all exhaust species are reduced to the lowest practical level". The work has dealt not only with an evaluation of individual pollution control devices, any single one of which is alone incapable of addressing the entire array of exhaust pollutants, but with combinations of devices.

The selection of a balanced pollution control system is complicated by the fact that successful use of a technique to reduce one pollutant often causes an increase in other pollutants. In addition, all polluting emissions are not considered equally undesirable. This is due to perceived differences in the relative seriousness of known or suspected health effects and the threshold levels at which these effects operate relative to existing levels of emissions. Oxides of nitrogen (NO_x: effectively NO and NO_2) and particulate matter or soot are generally considered to be the most important diesel exhaust constituents requiring control. These two diesel pollutant species are considered particularly troublesome due to relatively high levels noted in the exhaust, their sensibly noxious nature and difficulties encountered in reducing their levels.

Much attention has been focused recently on diesel particulate emissions. This is largely due to the interest in, and increase of, diesel engines in above ground vehicles. There are from 50 to 100 times more particulates emitted from a diesel engine than from a comparable spark ignition engine. The size of the overwhelming bulk of these particles are in the submicrometer range and they are capable of adsorbing toxic constituents from the exhaust stream or mine environment and thereby may act as carriers providing entry and residence of harmful substances into the lungs. Known carcinogens and mutagenic hydrocarbon species have been identified in diesel particulate. Recent extensive studies have been made on the potential carcinogenic effects of exposure to diesel particulates(3, 4). For these reasons, and because no practical solutions for their reduction have yet been proven, particulate emissions are generally considered to be the number one diesel exhaust pollutant of concern.

A number of studies over the last several years have concentrated on the chemical and biological character of diesel soot. The soluble organic fraction of soot contains hydrocarbons which are adsorbed on the solid respirable particulate. Some hydrocarbons from among the class of polynuclear aromatics (PNA's or PAH's) are known to have carcinogenic properties. For this reason, studies have pursued the identification of particular PNA compounds in diesel soot and their quantification. In addition, the Ames Salmonella/microsome bioassay has been widely used as a short method to determine the mutagenic character of diesel soot(5). It is generally felt that these studies will clarify the important question of diesel soot health effects with regard to potential carcinogenicity.

Analysis of changes in the chemical and biological nature of diesel soot emissions have not been included as a part of this study. The scope and character of the present project was not meant to include the additional dimension which such analyses would require. Continuing parallel studies in this area are expected to provide this additional information. The conclusion drawn from the present study is not inconsistent with generally accepted conclusions so far drawn from Ames Test or PNA analysis studies.

Two techniques for control of diesel particulate emissions were examined in this program. Water scrubbers were tested early in the program but were considered less than satisfactory due to their impracticability and the limitations of their effectiveness, usually less than 30% reduction. Attention then was focused on mechanical filtration, using first, a mesh filter largely developed by the Bureau of Mines and secondly, a monolithic ceramic honeycomb device made by Corning. Use of the Corning type of particulate filter is emerging as the single most effective new pollution control device for underground diesels.

A great deal of attention, in this project, has also been given to NO_x reduction. A three way conversion (TWC) catalyst system technique with its use of stoichiometric air/fuel operation has been successfully applied to spark ignition engines to reduce NO_x along with CO and hydrocarbons. This is not suited to diesel engines, however, which operate in the lean A/F regime. For NO_x reduction, investigation has been made of exhaust gas recirculation (EGR) and water-fuel emulsification techniques. Both of these can substantially reduce NO_x emissions but with the penalty of increased hydrocarbons and, with EGR, increased CO and particulates. The use of a particulate filter along with NO_x reduction techniques has been examined as a way of counteracting negative effects of the latter and achieving a balanced system control of both NO_x and particulates. The addition of an oxidation catalyst to this system, to control the increased CO and hydrocarbons, was also of some interest especially since sulfates which may form across the catalyst were found to be substantially reduced by the mesh filter (on which this feature was tested).

There has been recognition of the need to address the overall impact of pollutants of all kinds on mine air quality. Air containing at one time, quantities of carbon monoxide, gaseous hydrocarbons, oxides of nitrogen, soot and sulfur compounds should not be assessed on the basis of standards presented as if each pollutant was alone present. An integrated standard for overall air quality is needed to prevent overloading by several pollutants, each of which may be within its allowed limit, and also to recognize important interactive effects between pollutants. A single figure of merit is desirable to provide an index of overall air quality while taking cognizance of the above considerations. An important contribution has been made in this direction by the emergence of an air quality index (AQI)* calculated as the sum of terms defining the levels of each pollutant in a given case, as a multiple of its threshold limit values (TLV) as follows[6].

$$AQI = \frac{(CO)}{TLV_{CO}} + \frac{(NO)}{TLV_{NO}} + \frac{(RCD)}{TLV_{RCD}} + 1.5 \left[\frac{(SO_2)}{TLV_{SO_2}} + \frac{(RCD)}{TLV_{RCD}}\right] + 1.2 \left[\frac{(NO_2)}{TLV_{NO_2}} + \frac{(RCD)}{TLV_{RCD}}\right]$$

The above is the original version of the AQI formula and was used in Phase I and II of this study to develop hypothetical comparisons among various pollution control approaches. A more recent, modified version of the formula was used in the final Phase III comparison evaluations.

In the original formula, the presence of RCD (respirable combustible dust - refers to diesel particulate emissions in this case) in combination with SO_2 or NO_2 is considered to have extra potency and is penalized by a factor of 1.5 and 1.2 respectively. A bracketed expression is understood to go to zero if SO_2 or NO_2 are not detectable. Of course, no term may exceed 1, since no TLV may be exceeded, giving a nominal maximum AQI of 8.4. The authors of this expression have recommended that an index of 3 not be exceeded to ensure a safe mine atmosphere.

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* originally designated as a "Health Effects Index" by its authors.

Although the AQI formula is meant to be used on ambient mine air measurements, the temptation exists, in researching emission control approaches, to apply it by plugging in available laboratory engine test data on undiluted exhaust emissions. The result is a composite calculation which has generated interest in comparing different emission control approaches. Used in this manner the formula is considered as an "exhaust quality index" (EQI) and a dilution factor must be applied to allow nominal comparison to an ambient air quality standard. Since a maximum AQI of 3 is indicated, a determination of the EQI may be used to calculate the amount of ventilation air required by calculating the dilution ratio EQI/3 and multiplying by known exhaust flows. The air quality index has a number of important limitations especially when used as an exhaust quality index. The conversion of data arising from dynamometer run engine tests to real life field operating conditions undoubtedly involves more than the application of an appropriate dilution factor. The pattern and extent of exhaust emissions' impact on ambient air quality is significantly affected by factors present in the mine environment. These include the effect of duty cycle patterns, transients, and exhaust emissions interactions with the mine environment such as removal of NO_2 or SO_2/SO_3 by water or by plating out on mine tunnel surfaces.

The bracketed terms of the AQI/EQI provide a severe penalty for the presence of SO_2 and NO_2 together with diesel particulate. This reflects the concern that the fine particulate, capable of deep entry into the lungs will act as a carrier for adsorbed NO_2 and SO_2 thus synergistically increasing the negative health impact of these pollutants when taken alone. A double penalty is involved since not only are the penalty factors of 1.5 and 1.2 applied but the measured particulate is added once again for the presence of SO_2 and again for NO_2. However, for an EQI calculation on undiluted exhaust data, in the event of a high particulate measurement in the presence of a very low NO_2 or SO_2 measurement (say 1 ppm or less), a question may be raised as to the meaning of the resulting inflated EQI number. Here, the small NO_2 or SO_2 measurement would undoubtedly not be detectable in the ambient air for an AQI calculation.

Some of these considerations were addressed in the later version of the AQI formula(7):

AQI (Total) = AQI (Gas) + AQI (Particulate)

where, $$\text{AQI (Gas)} = \frac{CO}{TLV_{CO}} + \frac{NO}{TLV_{NO}} + \frac{NO_2}{TLV_{NO_2}}$$

and, AQI (Particulate) =

$$\frac{RCD}{TLV_{RCD}} + \left[\frac{SO_2}{TLV_{SO_2}} + \frac{RCD}{TLV_{RCD}}\right] + \left[\frac{NO_2}{TLV_{NO_2}} + \frac{RCD}{TLV_{RCD}}\right]$$

Here NO_2 has been added as a separate term in the gaseous pollution group, and the extra penalty factors on particulate of 1.5 (when SO_2 is present) and 1.2 (when NO_2 is present) have been dropped.

This, more recent formula, is used in the EQI comparisons done in Phase III of the program.

Generally, an air quality index type of approach is necessary to allow quantitative assessment of overall ambient mine air quality. Much new health effects information has been generated since this formula was first presented in 1978. Also, current research and development is working on new underground emissions control techniques and is focusing on more advanced measurements of actual mine ambient air pollution content.

The EQI evaluations and comparisons made in this study for catalyzed diesel particulate filters (DPFs) are based on the initial existing catalyst formulations used for this study. Recent tests on new catalyst formulations for DPFs (done since the completion of this study) show greatly reduced sulfate formation with standard fuel sulfur content. This development should greatly influence the validity of DPF catalyzation as an effective method of ensuring DPF regeneration in practical applications.

It should be noted that the work covered in this report reflects two different types of measurements. First, steady state measurements under various operating conditions, were taken directly on the exhaust of dynamometer controlled diesel test engines. This was the method used in Phases I and II and was typical of work done in this complex field to enable controlled parametric studies during early analytic stages. The effect, however, of diesel exhaust pollutants on mine working personnel is a function of ambient air quality at the work site. The conversion of data arising from steady state dynamometer run engine tests to real life field operating conditions undoubtedly involves more than the application of an appropriate dilution factor to laboratory data. In the development of practical emission control systems, a prime factor to consider is the actual duty cycle over given time periods of diesel powered vehicles at work, since exhaust pollutant patterns and the effectiveness of control techniques vary greatly with engine operating conditions. For this reason, a second type of measurement, based on simulated duty cycle testing, was used extensively in Phase III. This was done using a computer controlled dynamometer facility with the capability of duplicating known duty cycles characterized from field operating data or capable of simulating hypothetical duty cycles.

Nevertheless, conclusions drawn from laboratory test stand studies of any kind are subject to refinement. Consideration must be given to "field variables" which may influence the impact of exhaust emissions on operational air quality, that is, on the air that is actually breathed by working personnel. These variables include actual mine ventilation patterns, mine geometry, exhaust pollutant interactions after emission, pollutant levels from other sources, type and extent of diesel powered vehicles, etc. Many of these factors may vary among mines and among types of mines. Finally, the effectiveness of a particular control method is usually quite sensitive to the diesel engine used and to the state of maintenance and repair of that engine.

It is for the above reasons that the conclusions arising from the test stand data have been applied to the creation of field useable test hardware for application in actual field testing under Phase III and in associated parallel programs. The major, concluding part of Phase III was an application field demonstration of Corning diesel particulate filters on a working ST5 scoop-tram at the Kidd Creek zinc mine in Timmins, northern Ontario province. The demonstration was made in two separate parts to show the effectiveness of both catalyzation of the filters and also of use of fuel additives to enable continuous regeneration of the filters. Field operation was successfully demonstrated for a period of about 250 hours for each method.

The Bureau of Mines - Engelhard - ORF contract relationship helped provide an important basis for, and a means of implementing, a United States - Canadian Cooperative Planning Committee for coordinating research in underground diesel emissions control. This Committee is now a means for coordinating the interfaces of programs of the U. S. Bureau of Mines, the Canadian Centre for Minerals and Energy Technology (CANMET) and the Ontario Ministry of Labour (MOL). The Engelhard - ORF program has been closely coordinated with the activities of other groups and related to underground field testing of various emissions control hardware and systems on LHD vehicles under relatively standardized and cross-calibrated conditions.

It should be noted that the Phase I and II activity by ORF on the one hand and Phase III on the other were presented as separate reports during the course of the program. These two reports are presented here as originally written. The Phase III report is current and incorporates the up to date evaluations and conclusions. Overall the central result is the emergence of the ceramic diesel particulate filter (DPF) as a very effective diesel pollution control device. The DPF, by substantially reducing diesel particulate emissions shows a profound improvement in the overall Air Quality Index. Current efforts are directed to perfecting the DPF regeneration mechanism and proving applicability by broader field trials. It should be noted that, as presently fabricated and tested, DPFs are not permissible for coal mine use.

This project was undertaken by Engelhard Corporation, under contract to the Bureau of Mines, so as to contribute to the development of diesel exhaust pollution control systems in the important area of underground mines. Engelhard's interest derives from its industry position in catalysts and catalytic purification systems and its extensive work in development of catalysts for automotive emission control. Engelhard's activities also include involvement in catalytic purification systems and related hardware for off-the-road and underground mining vehicles. The program has been developed and carried out with the Ontario Research Foundation (ORF) of Canada acting as a major subcontractor, and utilizing their considerable experience in this area to provide independent testing and analysis. Involvement of ORF provided the opportunity of integrating activity under this program with parallel ORF work being pursued for Canadian Federal and provincial governmental agencies and has greatly expanded, for both sides, the potential for achieving effective results. This increased effectiveness, as a result of creating a bridge between similar U. S. and Canadian programs turned out to be well worth the efforts, by all concerned, in overcoming the attendant legal and administrative problems in arranging a contract program of this type.

Parts of the work done in this study have also been reported in sessions of the Society of Automotive Engineers[8,9] and to the Canadian Institute of Mining and Metallurgy (CIMM)[10]. In addition, a series of Technology Transfer papers have been prepared summarizing the overall work of the joint U.S.-Canadian research effort for diesel emission control in undergroundmines, of which this study has been a part[11, 12, 13, 14, 15, 16]. A single paper reporting the work of the joint program has also been prepared for presentation to the American Mining Congress during October, 1986[17].

The report which follows on the activities of this study is of the testing and analysis carried out by the Ontario Research Foundation.

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SUBCONTRACT REPORTS

BY

ONTARIO RESEARCH FOUNDATION

CONTROL OF DIESEL EMISSIONS IN UNDERGROUND MINES

Section II of U. S. Bureau of Mines Report
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For Phases I and II

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TABLE OF CONTENTS

Page

EXECUTIVE SUMMARY 32

1. INTRODUCTION 47

2. CURRENT AND PARALLEL TECHNOLOGY DEVELOPMENT

2.1 Literature Review 48

2.2 Parallel Research Effort at ORF 49

2.3 Other Technology Development 50

3. BASELINE

3.1 Test Engines 52

3.2 Analytical Techniques 53

3.3 Baseline Emissions 53

3.3.1 Deutz 714 Engine 53

3.3.2 Deutz 413 Engine 54

4. EXHAUST GAS RECIRCULATION (EGR) 64

4.1 Deutz 714 Engine 64

4.2 Deutz 413 Engine 65

4.3 Conclusions on EGR Application 65

5. PTX CATALYST

5.1 Test Conditions 74

5.2 Emission Testing for SO_2/H_2SO_4 74

5.3 Emission Testing for Hydrocarbons, Carbon Monoxide and Oxides of Nitrogen 75

5.4 Conclusions on PTX Catalyst Performance 77

TABLE OF CONTENTS (cont'd)

Page

6. WATER SCRUBBER AND WATER SCUBBER SYSTEMS

6.1 Scope 97
6.2 Domino Catalyst/Water Scrubber System 97
6.3 Gaspe Water Scrubber Systems 99
6.4 Conclusions 101

7. FILTERS AND TRAP OXIDIZERS

7.1 USBM Filter

7.1.1 Cooled Filter 113
7.1.2 Uncooled Filter 115
7.1.3 Conclusions on USBM Filter 119

7.2 Corning Filter 119
7.3 Filter Comparison Summary 122

8. WATER-FUEL EMULSIONS

8.1 Deutz F6L-714 Engine 148
8.2 Deutz F8L 413 Engine 149

9. COMBINED SYSTEMS

9.1 Catalyst/Filter Combinations 159
9.2 EGR Combined Systems

9.2.1 EGR/Catalyst/Mesh Filter Combinations 161
9.2.2 EGR/Corning Filter Combination 163

9.3 Emulsification Combined Systems

9.3.1 Emulsification/Catalyst/Filter Combination - 714 Engine 169
9.3.2 EGR/Emulsification - Corning Filter - 413 Engine . . 170

9.4 Conclusions on Combined Systems 171

TABLE OF CONTENTS (cont'd)

Page

10. SYSTEM COMPARISONS

10.1 Exhaust and Air Quality Indices 211

10.2 Representation of Emission Control Strategies Relative to Exhaust Quality Indices 213

11. CONCLUSIONS AND RECOMMENDATIONS 219

REFERENCES 222

APPENDIX I Operational Experience with Deutz F8L 413 Engine 225

APPENDIX II Analytical Instrumentation and Methodology . . 229

APPENDIX III Analysis of Glass Fibre Emissions from Operation of the USBM Filter 233

LIST OF TABLES

		Page
TABLE 3.1	Deutz F6L 714 Characteristics & Deutz F8L 413 Characteristics	55
TABLE 3.2	Gulf Oil Canada Limited Diesel 40 Fuel Specifications	56
TABLE 3.3	A Comparison of 27 vs 24^{o} BTDC Injection Timing Particulate Emission Rates	57
TABLE 3.4	A Comparison of the Particulate Emissions from the Left and Right Exhaust Banks of a Deutz F6L 714 Diesel Engine	58
TABLE 3.5	Baseline Gaseous Emissions from Deutz F6L 714 Engine	59
TABLE 3.6	Catalyst and Engine Characteristics	60
TABLE 3.7	Baseline Particulate Emission Rates from a Deutz F8L 413 Engine	61
TABLE 3.8	CO and THC Gaseous Emission Characteristics from a Deutz F8L 413 Engine	62
TABLE 3.9	NO, NO_2 and NO_x Gaseous Emission Characteristics from a Deutz F8L 413 Engine	63
TABLE 4.1	Effect of EGR on Engine Performance	67
TABLE 4.2	The Effect of Various % EGR on the Gaseous Emissions of a Deutz F6L 714 Diesel Engine	68
TABLE 4.3	The Effect of Various Percentages of EGR on the Particulate Emissions of a Deutz F6L 714 Diesel Engine	69
TABLE 4.4	Gaseous Emissions - Baseline and with EGR Application	70
TABLE 4.5	Particulate Emissions from the Deutz F8L 413 Engine with EGR Applications	71
TABLE 5.1	Catalyst and Engine Characteristics	78
TABLE 5.2	Engelhard PTX-623D Catalytic Purifier Sulphur Emissions	79
TABLE 5.3	Engelhard PTX-623D Catalytic Purifier THC & CO Gaseous Emissions	80
TABLE 5.4	Engelhard PTX-623D Catalytic Purifier NO_x Gaseous Emissions	81
TABLE 5.5	Engelhard PTX-623D Catalytic Purifier Emission Reductions	82

LIST OF TABLES (Cont'd).

		Page
TABLE 6.1	Control Device Parameters - Domino Combined Water Scrubber/Catalyst	102
TABLE 6.2	A Comparison of the Uncontrolled and Domino Scrubber Gaseous Emissions from a Detuz F6L 714 Diesel Engine	103
TABLE 6.3	A Comparison of the Uncontrolled and Domino Scrubber Controlled Emissions from the Left Bank of a Detuz F6L Diesel Engine	104
TABLE 6.4	A Comparison of the Particulate Emissions from the Right Bank of the Deutz F6L 714 Diesel Engine at Normal and High Back Pressure	105
TABLE 6.5	The Effect of the Gaspé Scrubber on the PTX Catalyst Controlled Gaseous Emission of a Deutz F6L 714 Diesel Engine	106
TABLE 6.6	The Effect of EGR on the Gaseous Emissions of a Deutz F6L 714 Diesel Engine Controlled by the PTX Catalyst/Gaspé Scrubber Combination	107
TABLE 6.7	The Efficiency of the Gaspé Scrubber on the PTX Catalyst Controlled Particulate Emissions with Various Percentages of EGR, Deutz F6L 714 Diesel Engine	108
TABLE 7.1	The Effect of the USBM Filter on the Particulate Emissions of a Deutz F6L 714 Diesel Engine	123
TABLE 7.2	Particulate Test Results Run No. 2. For Bale 1 (Used Filter Bale) 2300 RPM 130 kW - Deutz F8L 413	124
TABLE 7.3	ΔP Characteristics (cm H_2O) for USBM Filter for Sulphate Tests	125
TABLE 7.4	Particulate Collection Efficiency of USBM Filter	126
TABLE 7.5	Variation of Insoluble Particulate Removal Efficiencies with Pressure Drop Across the USBM Filter	127
TABLE 7.6	Variation of Total Particulate Removal Efficiency with Pressure Drop Across USBM Filter	128
TABLE 7.7	Bale Endurance - USBM Filter	129
TABLE 7.8	Baseline Particulate Emissions from the Bare Engine - Deutz F8L 413	130
TABLE 7.9	Particulate Emissions from the Engine Equipped with Corning Filters Deutz F8L 413	131
TABLE 7.10	Average Particulate Removal Efficiencies - Corning Ceramic Filter	132
TABLE 7.11	Filter Comparison Summary	133

LIST OF TABLES (Cont'd).

		Page
TABLE 8.1	The Effect of ∿ 14% w/w Water/Fuel Emulsion on the Gaseous Emissions of a Deutz F6L 714 Diesel Engine	151
TABLE 8.2	The Effect of 14% w/w Water/Fuel Emulsion on the Particulate Emissions from a Deutz F6L 714 Engine	152
TABLE 8.3	Water Emulsion Gaseous Emissions for a Deutz F8L 413	153
TABLE 8.4	Water Emulsion Gaseous Emissions for a Deutz F8L 413	154
TABLE 8.5	Particulate Emissions from Bare Engine and Engine Run on Water Emulsion	155
TABLE 9.1	Effect on $SO_2/SO_4^=$ Emissions	174
TABLE 9.2	Effect of Uncooled Catalyst/Filter Combination on $SO_2/SO_4^=$ Emissions	175
TABLE 9.3	Effect of Uncooled Catalyst/Filter Combination on SO_2/SO_4 Emissions	176
TABLE 9.4	Comparison of Particulate Removal Efficiencies of USBM Filter with and without the Catalyst Installed	177
TABLE 9.5	The Effect of the PTX Catalyst, USBM Filter and 21% EGR on the Particulate Emissions of a Deutz F6L 714 Diesel Engine	178
TABLE 9.6	The Effect of the USBM Filter on the Gaseous Emissions of a Deutz F6L 714 Diesel Engine - Emission Control Devices - PTX, USBM Filter, 21% EGR	179
TABLE 9.7	The Effect of 21% EGR on the Gaseous Emissions of a Deutz F6L 714 Diesel Engine - Emission Control Devices - PTX, 21% EGR	180
TABLE 9.8	Gaseous Emissions - Baseline and with EGR/Filter	181
TABLE 9.9	Baseline Particulate Emissions from the Bare Engine Deutz F8L 413	182
TABLE 9.10	Particulate Emissions from the Engine Equipped with Corning Filters Deutz F8L 413	183
TABLE 9.11	Particulate Emissions from the Engine with EGR Application Deutz F8L 413	184
TABLE 9.12	Particulate Emissions from the Engine with EGR/Corning Filter - Deutz F8L 413	185
TABLE 9.13	Test Data EGR and Corning Filter	186

LIST OF TABLES (Cont'd).

		Page
TABLE 9.14	The Effect of the PTX Catalyst, USBM Filter and Water/Fuel Emulsion on the Particulate Emissions of a Deutz F6L 714 Diesel Engine	187
TABLE 9.15	The Effect of the PTX Catalyst on the Gaseous Emissions of a Deutz F6L 714 Diesel Engine - Emission Control Devices - PTX, ∿14% w/w Water Emulsion	188
TABLE 9.16	Particulate Emissions from Bare Engine Equipped with Corning Filter, EGR, Water Emulsion	189
TABLE 9.17	Baseline Gaseous Emissions vs Emissions with Engine Equipped with Corning Filter, EGR, Water Emulsion	190
TABLE 9.18	Baseline Gaseous Emissions vs Emissions with Engine Equipped with Corning Filter, EGR, Water Emulsion	191
TABLE 9.19	Average % Changes in Steady State Emissions Relative to Bare Engine, Assignable to Various Combination Control Systems	192
TABLE 9.20	Comparison of Emission Reduction Effect of Various Emission Control Strategies Applied to the Deutz F8L 413 Engine	193
TABLE 10.1	Composite EQI Values for Comparison of Various Emission Control Strategies - F6L-714 Engine	217
TABLE 10.2	Composite EQI Values for Comparison of Various Emission Control Strategies - F8L-413 Engine	218

LIST OF FIGURES

		Page
FIGURE 4.1	View of Air Intake and EGR Control Valve	72
FIGURE 4.2	Effect on Emissions of 20% EGR at Full Load versus 20% EGR at Off Full Load	73
FIGURE 5.1	Space Velocity versus Engine Speed and Load Engelhard PTX-623D Catalytic Purifier	83
FIGURE 5.2	Post Catalyst Sulphate and Sulphur Dioxide Emission Rate (gm/hr) versus Catalyst Temperature - Engelhard PTX-623D Catalytic Purifier	84
FIGURE 5.3	Post Catalyst Sulphate and Sulphur Dioxide Emission Rate (gm/kW.hr) versus Catalyst Temperature - Engelhard PTX-623D Catalytic Purifier	85
FIGURE 5.4	% Conversion SO_2 to $SO_4^{=}$ versus Catalyst Temperature and Fuel/Air Ratio - Engelhard PTX-623D Catalytic Purifier	86
FIGURE 5.5	Equilibrium Conversion of Eighteen ppm Inlet SO_2 to SO_3 at 1 atm Pressure as a Function of Catalyst Temperature for Various Oxygen Concentrations	87
FIGURE 5.6	% Reduction versus Catalyst Temperature of CO and THC Engelhard PTX-623D Catalytic Purifier	88
FIGURE 5.7	% Reduction versus Fuel/Air Ratio - Engelhard PTX-623D Catalytic Purifier	89
FIGURE 5.8	THC Emissions versus Engine Speed and Load - Engelhard PTX-623D Catalytic Purifier	90
FIGURE 5.9	THC Emissions versus Engine Speed and Load - Engelhard PTX-623D Catalytic Purifier	91
FIGURE 5.10	CO Emissions versus Engine Speed and Load - Engelhard PTX-623D Catalytic Purifier	92
FIGURE 5.11	CO Emissions versus Engine Speed and Load - Engelhard PTX-623D Catalytic Purifier	93
FIGURE 5.12	NO_x Emissions (gm/kW.hr) versus Engine Speed and Load - Engelhard PTX-623D Catalytic Purifier (Inlet)	94
FIGURE 5.3	NO_x Emissions (gm/hr) versus Engine Speed and Load - Engelhard PTX-623D Catalytic Purifier (Inlet)	95
FIGURE 5.14	NO_2 Concentrations versus Catalyst Temperature	96

LIST OF FIGURES (Cont'd).

		Page
FIGURE 6.1	Domino Catalytic Scrubber	109
FIGURE 6.2	Domino Scrubber Test Set-up	110
FIGURE 6.3	Gaspé Copper Mines - Scrubber	111
FIGURE 6.4	Gaspé Scrubber/EGR Test Set-up	112
FIGURE 7.1	USBM Filter Installation	134
FIGURE 7.2	Close-up of USBM Filter Installation and Water Spray Location	135
FIGURE 7.3	Histogram of Insoluble Particulate Matter Removal from Water Cooled Exhaust Using USBM Filter, Preliminary Results	136
FIGURE 7.4	Variation in Removal Efficiency with Increase in Pressure Drop due to Loading of Filter with Particulate 1625 rpm 70 kW	137
FIGURE 7.5	Particulate Collection Efficiency and Load-up Time of USBM Filter. 185 kg/m^3 Bulk Density. Detuz F8L 413 Engine	138
FIGURE 7.6	Relationship of Pressure Drop vs Distance from Inlet of Bale	139
FIGURE 7.7	Variation of Particulate Removal Efficiency with Pressure Drop across the Filter - 2300 rpm 138 kW	140
FIGURE 7.8	Corning Filter Element	141
FIGURE 7.9	Corning Filter Installed on Deutz Engine	142
FIGURE 7.10	Close-up View of Corning Filter	143
FIGURE 7.11	Corning Ceramic Filter - Variation in Engine Back Pressure During Operation at 2000 rpm 63 kW	144
FIGURE 7.12	Corning Ceramic Filter - Variation in Engine Back Pressure During Operation at 2300 rpm 104 kW	145
FIGURE 7.13	Corning Ceramic Filter - Variation in Engine Back Pressure During Operation at 2300 rpm 138 kW	146
FIGURE 7.14	Load-up and Regeneration of Corning Ceramic Filter	147
FIGURE 8.1	Schematic of the Modified Deutz Diesel Engine Fuel System which Allows Operation on Water/Fuel Emulsion or Neat Fuel	156

LIST OF FIGURES (Cont'd).

		Page
FIGURE 8.2	Fuel Discharge HydroShear	157
FIGURE 8.3	Emulsion Fuel System Schematic for the Deutz F8L 413	158
FIGURE 9.1	Schematic of the Test Rig for the EGR/PTX Catalyst/USBM Filter Emission Control Package	194
FIGURE 9.2	Engine Test Configurations	195
FIGURE 9.3a	EGR Intake System	196
FIGURE 9.3b	EGR Control Valve on EGR/Filter System	197
FIGURE 9.4	Gaseous Emissions - Baseline vs EGR/Filter	198
FIGURE 9.5	Gaseous Emissions - Baseline vs EGR/Filter	199
FIGURE 9.6	Effect of Various Emission Control Strategies on the Particulate Emission Rates 2300 rpm 138 kW	200
FIGURE 9.7	Effect of Various Emission Control Strategies on the Particulate Emission Rates 2300 rpm 104 kW	201
FIGURE 9.8	Effect of Various Emission Control Strategies on the Particulate Emission Rates 2000 rpm 63 kW	202
FIGURE 9.9	Comparison of the Efficiencies of EGR/Filter and Filter only for the Reduction of Particulate Emissions	203
FIGURE 9.10	Engine Back Pressure Composite - Corning Filter vs EGR/Corning Filter	204
FIGURE 9.11	Engine Back Pressure vs Time at 2300 rpm 104 kW. Corning Filter and EGR/Corning Filter	205
FIGURE 9.12	Engine Back Pressure vs Time at 2000 rpm 64 kW. Corning Filter and EGR/Corning Filter	206
FIGURE 9.13	Engine Back Pressure vs Time at 2300 rpm 138 kW. Corning Filter and EGR/Corning Filter	207
FIGURE 9.14	Particulate Burn-offs with and without EGR. Engine Back Pressure vs Time	208
FIGURE 9.15	Effect of Various Emission Control Strategies on the Particulate Emission Rates 2300 rpm 104 kW	209
FIGURE 9.16	Effect of Various Emission Control Strategies on the Particulate Emission Rates 2000 rpm 63 kW	210

EXECUTIVE SUMMARY

This report covers Phase I and II of a three part project directed to the development of exhaust emissions controls for underground diesel powered mining vehicles. The direction is to emphasize the development of diesel exhaust after treatment devices as well as other techniques.

Phase I covers an experimental survey of existing exhaust emission control techniques and devices. This includes limited laboratory engine testing of selected devices and systems for the purpose of surveying and identifying promising candidates. A survey is also made of the relevant literature and of parallel research efforts in this field. Based on the results of Phase I, the development is continued in Phase II utilizing more directed engine testing for fuller characterization of selected techniques. The results of both phases are presented together in combined form in this report so that the presentation of data and results is organized by the type of emissions control device.

The diesel exhaust emissions requiring control and addressed in this study include, carbon monoxide, gaseous hydrocarbons, nitric oxide, nitrogen dioxide, sulphur dioxide and soot or particulate matter. Particulater matter includes insoluble organic matter and usually a soluble organic fraction (SOF) and may also include sulphates. These three constituents of particulate matter are often addressed individually.

Diesel exhaust emission control techniques examined in the course of Phases I and II, include water scrubbers, catalysts, particulate filters, exhaust gas recirculation, water-fuel emulsification and various combinations of these applied as systems.

Two test engines were employed:

(1) Deutz F6L-714 9.5 litre, V-6 during Phase I testing;
(2) Deutz F8L-413 12.8 litre, V-8 for Phase II testing.

Both engines employ indirect injection and are air cooled. The 714 series engine is a presently discontinued model but still widely used in hard rock, non-gassy mines. The F8L-413 is of a relatively new model series generally considered as a replacement to the older 714 models.

Functional problems were encountered in use of the new 413 engine during the early part of the Phase II testing. These problems were cleared up, however, and were not considered to influence the overall conclusions arising from the work. Testing was carried out on an engine test stand employing a Clayton 700 C.E. water-brake dynamometer at steady-state load/speed points typically including all or some of the following:

- Full rated speed and full, 3/4, 1/2 load;
- 1900 rpm and full, 3/4, 1/2 load;
- 1600 rpm and full load.

Gulf Diesel 40 fuel with a sulphur content of 0.16% was used for all testing.

Measurement of emissions was carried out on sample streams of the undiluted exhaust using conventional instrumentation for gaseous analysis. Particulate measurements were made using a modified EPA Method 5 source sampling train consisting of filter and multiple impingers. Measurements of SO_2 and sulphate were made using a controlled condensation sampling system.

Table S.1 shows the main types of combination systems examined on the Deutz F8L-413 and the F6L-714 engines, and indicates the average percent change in emissions assignable to each of these systems. The numbers assigned are based on average data assembled from the various test runs and shown for one load/speed condition only for each engine (at full rated speed and 3/4 or full load).

The mesh filter proved very effective in particulate removal. (See Table S.1). The mesh filter consists of a knitted multiple strand material of stainless steel wire and fibreglass yarn. Sheets of this material were packed and arranged for testing with the exhaust gas flowing perpendicular to the sheets and also parallel to the sheets. The parallel flow arrangement with a packed bulk density of 150 kg/m^3 proved optimum in terms of particulate reduction vs operating time before clogging. Particulate reduction seemed generally effective with water spray or run dry. However, SO_2 emissions were substantially depressed with the water spray but not with the dry filter. When combined with a catalyst, effective reduction of CO and THC are also seen for the system. Substantial reduction of sulphate was apparent with the filter run both wet and dry thus reducing sulphate emissions which could be expected to generate across the catalyst. Net sulphate emissions were virtually eliminated with the wet filter at 2200 rpm and 73 kW. However, in general, some sulphate impact is expected to remain with this sytem, so that a judgement is required as to whether it is beneficial to reduce CO and THC emissions at the expense of a small increase in sulphate, or whether it is better to avoid any increase in sulphate at the expense of allowing uncontrolled CO and THC emissions.

The catlyst/filter combination, does not address NO_x reduction. The addition of water-fuel emulsification to this sytem reduces NO_x about 35% and also contributes to particulate reduction as can be seen when comparing emulsification with catalysts both with and without the mesh filter. In the latter case, total particulate reduction is at about the 40% level. An increase in THC had been noted when emulsification was operated alone but this was apparently compensated for when operated with the catalyst. There is perhaps, more justification for using a catalyst in combination with a water emulsion and filter system, in order to reduce increases in CO and THC emissions.

Water-fuel emulsification applied in the program was limited to in-situ unstabilized emulsification generated by a mechanical device, the HydroShear. This device, previously developed by the Ontario Research Foundation, was custom installed in both the F6L-714 and F8L-413 Deutz engines for this program.

On the Deutz F6L-714 engine, the Gaspe water scrubber showed modest particulate reduction capability. Good reduction of CO and THC* was offered when the scrubber was combined with a catalyst. In addition, the scrubber was found to provide good removal of SO_2, as well as about 30% of the sulphate which was generated over the catalyst. However, NO_x emissions remain unchanged and also some undesirable NO to NO_2 formation was observed through the water scrubber. Addition of EGR to this system provides the expected control of NO_x emissions to a level of about 75% reduction with the penalty, however, of greatly increased particulate emissions. In general, these effects were greater at higher EGR (20%) and at high speed, full load operation and were moderated at lower EGR and off-full load conditions. With 10% EGR, total particulate was increased by only 15% at the load/speed condition of 1625 rpm/70 kW. However, less effective NO_x control also resulted, with about a 45% reduction in NO_x from baseline levels.

The Corning Cellular Ceramic Diesel Particulate Filter, although previously known for possible application to light duty surface diesel passenger cars, became available for heavy duty underground diesel testing late in the contract program. This device is basically a ceramic honeycomb monolith structure with numerous parallel flow-through "cells' or passageways. As a filter, alternate passageway openings are blocked on inlet and outlet faces so that the exhaust flow is forced through the extra porous walls of the passageways. The large units tested in this program (about 12 inch diameter) consist of several shaped segments cemented together. The Corning filter exhibited excellent particulate reduction capability and was teamed with EGR to provide NO_x reduction, The EGR/Corning Filter combination shows capability for good control of both NO_x and particulates simultaneously with only relatively modest increases in CO and THC. The tendency of EGR to increase particulates especially at high load/speed conditions is generally cancelled by the filter. Increases in CO and THC due to EGR could be controlled, if necessary, with a catalyst in the system. In an EGR/catalyst/filter system, sulphates generated across the catalyst, are reduced by the particulate filter. Sulphate capture was measured across

* THC (Total Hydrocarbons).

the mesh filter and it is considered likely that the Corning filter would function similarly. However, in this respect, the collected sulphates may be dumped all at once, if the Corning filter is operated with a periodic on-board thermal regeneration technique. Undesirable NO and NO_2 conversion which can occur across the catalyst was not observed when in combination with EGR.

In judging the desirability of a catalyst as a component in the above systems, sulphate generation, deriving from fuel sulphur content, as well as the possibility of undesirable NO to NO_2 formation across the catalyst must be considered as against the advantage of CO and THC control. CO and gaseous hydrocarbons from well maintained diesel engines are often considered adequately controlled by mine ventilation which is otherwise supplied. However, in given circumstances such as in poorly ventilated drifts and especially when increases of these pollutants due to EGR or water-fuel emulsification are indicated, their danger should not be underestimated.

A catalyst was not tested with the EGR/Corning combination due largely to concern of the added pressure drop burden this would place on the operating life of the filter, between regenerations, and also in part to practical reasons, since the Corning filter test sequence was started late and added on to the program. The over-riding interest at this stage was to determine the effectiveness of the Corning filter in handling increased particulate from EGR and in its ability to regenerate by "spontaneously" burning off collected particulate deposits under these circumstances. With respect to the latter consideration, a catalyst may offer its greatest potential for being included in an emission control system, if it can assist in filter regeneration. Capability of a catalyst coated filter to improve filter regeneration may prove to be a more important contribution of a catalyst system, than the capability to reduce CO and THC emissions. This will be investigated in the next phase of the present project.

A test was also run on the Corning filter combined with both EGR and water-fuel emulsification (on the F8L-413 engine). The result, however, although offering good NO_x reduction (to 75%) also gave excessive increases in THC and CO. The THC and CO increases were much lower at off full load conditions. Further work is required on water emulsion application to the 413 engine, since the results on the 413 were less attractive than on the 714 engine, and the reason for this is not yet fully understood.

Both the mesh filter and the Corning filter seem effective in particulate reduction. The main concern in application is with service durability of the filters and particularly with operating time between cleaning or regenerations. The mesh filter in its optimized version (parallel flow, 150 kg/m^3 density), seems capable of up to about 30 hours before cleaning. Cleaning requires an off-board wash and flush operation. The fibreglass yarn in the mesh filter seems delicate and attrition of the yarn was noted over a period of several cleanings. Application of the mesh filter to engines of the size tested, requires a rather large filter box about 2.6 cubic feet (15 x 15 x 20 inches or similar volume).

The Corning filter was applied in two units (one for each engine outlet manifold) with a combined volume of less than 1.5 cubic feet. Operational time between cleanings could not be determined after 26 hours of testing due to the very slow rate of Δp increase. This was apparently a result of self-regeneration of the filter due to exhaust temperatures reaching the filter regeneration burn-off temperature of 550°C when the F8L-413 engine was run at 2300 rpm and 142 kW load. Depending upon the duty cycle, therefore, the Corning filter may be capable of continuing in operation for extended periods of service without removal for servicing. For the above reasons, the Corning filter seems favoured as a more practical alternative.

In an assessment of emission control net effectiveness, a simple inventory of the increase or decrease of each individual pollutant is not fully satisfactory as a basis for reaching conclusions from this study. It is necessary also to account for the overload impact of several pollutants present and acting simultaneously even if each is below its TLV and for interactive effects between pollutants. For these reasons, an exercise was carried out to apply an air quality index (AQI) to steady state engine exhaust data collected during the program. The AQI has been fomulated for ambient air quality as:

$$V = \frac{(CO)}{50} + \frac{(NO)}{25} + \frac{(RCD)}{2}\,\frac{(H_2SO_4)}{1} + 1.5\left[\frac{(SO_2)}{3} + \frac{(RCD)}{2}\right] + $$
$$+ 1.2\left[\frac{(NO_2)}{3} + \frac{(RCD)}{2}\right]$$

where:

(CO) = Carbon monoxide concentration (ppm)

(NO) = Nitric oxide concentration (ppm)

(SO_2) = Sulphur dioxide concentration (ppm)

(NO_2) = Nitrogen dioxide concentration (ppm)

(RCD) = Respirable combustible dust (mg/m^3)

(considered equivalent to the particulate level of diesel exhaust).

The two bracketed terms indicate the synergistic effect of SO_2 and NO_2 respectively with diesel particulate. This reflects the ability of the diesel particulate to increase exposure to SO_2 and NO_2 by deposition of particulate, containing the adsorbed gases, on the lung membrane. The term V(ventilation factor) originally used by the originators, is currently best described as an Air Quality Index which is recommended not to exceed a value of 3. The above expression was designed for use with ambient mine air pollutant concentrations. If tailpipe emission data is applied to the same expression, then it is possible to consider that an Exhaust Quality Index (EQI) will result. The expression $\frac{EQI}{3}$ then indicates the required dilution ratio, and the dilution ratio multiplied by the engine (or engines) exhaust volume results in a value for the recommended quantity of fresh ventilating air required in the mine.

There are, however, limitations to this approach. Since the expression was designed as an air quality index, the use of tailpipe undiluted emission values creates a different impact on the EQI values, due to the lack of accountability for the ultimate fate of emission components which are emitted to the mine atmosphere. For example, NO emissions will be oxidized to NO_2 at a rate dependent on mine air residence time, and environment. NO_2 may subsequently be removed from the mine atmosphere by interactions with water. Similar considerations apply to H_2SO_4 emissions. An accurate assessment can only be made, therefore, by applying pollutant concentrations actually measured underground. A further limitation is evident with the synergistic terms of the expression which are capable of making a large impact on the AQI/EQI. For example, it is a matter of judgement as to whether the same synergistic health impact will result from exposure to a large concentration of particulate matter when only low concentrations of SO_2 and NO_2 are present. The weighting factors of these terms under such conditions might become unduly severe. In effect one must judge whether the NO_2 or SO_2 values ever become zero, and the synergistic terms disappear from the expression. This will be illustrated later when the EQI is discussed.

Despite these limitations, the expression is probably the best tool presently available, in order to compare the different impacts on exhaust quality of various emission control strategies. It is considered appropriate and relevant, but not necessarily conclusive, therefore, to use EQI values to preview the ranking of different emission control approaches, and try to assess which approaches show the greatest benefits in improving the exhaust quality, and therefore also the mine air quality.

Using steady state data contained in this report, (and data from relevant literature where available in this report), EQI values were calculated at two engine load/speed conditions, and for two engines. The EQI values vary with engine type and load/speed condition, but for the same engine and the same load/speed conditions, it is possible to compare EQI values of the controlled versus the baseline uncontrolled engine. Table S.2 shows EQI values for the Deutz F6L 714 engine at two different load/speed conditions, with the application of various emission control devices.

At 2200 rpm/full load, the worst strategy is the application of 21% EGR alone to the the engine, which results in an EQI value 530% greater than the baseline value. A catalyst/scrubber system used in combination with the EGR, does not overcome the high particulate impact of EGR application, even although the NO_x is considerably reduced, and the EQI values remain greater than the baseline value. Similarly, the emulsification/catalyst system appears a poor combination, with the test stand H_2SO_4 data impact of the catalyst overwhelming the advantages of reduced NO_x and particulate created by the water emulsion, even though the catalyst effectively reduced the increased CO and THC emissions created by the emulsion application. Emulsion application alone produced a better result with an EQI 67% of the baseline value. Using exhaust gas cooled by water injection, the mesh filter, and catalyst mesh filter combination, both produced EQI values 36-39% of the baseline engine value. However, the disadvantage of storing water on board may tend to offset the advantage of the low EQI value when used in non-gassy mines.

The same consideration applies to the water emulsion/catalyst/mesh filter system, although in this case the water may be used for the dual purpose of water emulsion application, and exhaust cooling. This system produced the lowest EQI value for the 714 engine at 2000 rpm/93 kW.

Table S.2 also shows a set of data in parenthesis for the three EGR systems. These data were calculated assuming that the term

$$1.2 \quad \frac{(NO_2)}{3} + \frac{(RCD)}{2}$$

was absent. This shows the powerful effect of the synergistic term which makes a difference in the EQI values of as much as 300 units. Whether the synergistic term should have so great a weighting factor when there is a large particulate concentration, but only a small NO_x concentration, remains a subject to be resolved. It should be noted, however, that even if the synergistic term is ignored, the ranking of exhaust treatment devices remains the same.

Table S.2 also shows a similar set of EQI values for the 714 engine at rated speed and three-quarter full load condition. Because the engine is operating at off full load condition, the EGR penalty is less severe, and the EGR/catalyst/scrubber combination, for example, now performs with an EQI value 93% of the baseline. The 21% EGR/mesh filter combination performs with an EQI value 36% of baseline. It is clear from the earlier set of data that such a technique is more likely to be successful at full load condition, when the quantity of EGR application is reduced.

Table S.3 shows EQI values calculated for the controlled and uncontrolled Deutz F8L-413 engine, at two load/speed conditions, rated speed/full load, rated speed/three-quarter load. In this case, emulsification, catalyst and EGR techniques, used alone, are unattractive at either load/speed condition. At full load/speed condition, the Corning filter and EGR/Corning filter system produce the best performance, reducing the EQI values to 33% and 29% of baseline values respectively. This result, by itself would seem to indicate that there is no great advantage in combining EGR with the Corning filter, since the addition of EGR further reduces the EQI value by only 4 percentage points, while the complexity of the device is significantly increased. However, when the EQI values are examined at 2300 rpm/103 kW, it is apparent that there is now a significant improvement in the EQI value when the EGR is added to the Corning filter to form a combined system. This shows the significance of assessing EQI values at different load/speed conditions, and the need for performance evaluation over a typical underground vehicle duty cycle. The latter will be included in a follow-up phase to this project. It is to be concluded, therefore, that for the 413 engine, the EGR/Corning filter system offers the best opportunities, in terms of effectiveness and minimum complexity, for development into field usable hardware.

The following conclusions and recommendations are made from this study,

1) The Air Quality Index (AQI) as a single index number to evaluate overall air quality is an important breakthrough in providing a useable formula for this purpose.

However, because of present limitations, particularly when used as an Exhaust Quality Index (EQI) of undiluted tailpipe emissions data from steady state engine operation, EQI comparisons should be used as guides to further investigations rather than for definitive conclusions in the absence of data from real duty cycle conditions.

2) The EGR/Corning filter has shown the promise of the best improvement in exhaust quality with the least complexity. It is considered the most likely to achieve earliest commercial development.

3) A water-fuel emulsion/catalyst/mesh filter system shows emission control potential at a similar level to an EGR/ Corning filter system. This type of system, although needing further development in the area of mesh filter durability and emulsion system optimization, may be of special interest for gassy and coal mines where on board water boxes for flame proofing scrubbers already exist.

4) Based on steady state engine test data, some devices have shown the negative potential of deteriorating overall exhaust quality in underground mine applications. These include EGR and catalysts when used alone without other control elements.

   Since results based on steady state engine data can vary, it is important for all candidate systems to test control techniques under actual duty cycle and field conditions and to carefully match control system components for positive results.

5) Further evaluation of the viable pollution control approaches should be carried out over complete mine vehicle duty cycles and under real field conditions.

6) Further studies of regeneration aids for operation of the Corning filter and to determine the nature of emissions produced during regeneration, are important tasks in establishing this promising device.

TABLE S.1

Average % Changes in Steady State Emissions Relative to Bare Engine Assignable to Various Control Systems

	Particulates				Gaseous			
	Insol.	SOF	Total	SO_2/H_2SO_4 Conversion	NO_x	NO/NO_2 Conversion	CO	THC
Deutz F8L-413 Engine (at 2300 rpm/104 kW)								
• Corning Filter	-84%	-43%	-69%	0%	0%	0%	0%	0%
• 10%* EGR/Corning Filter	-90	-90	-90	0	-30	0	+5	+15
• 15% EGR/Corning Filter	-90	-85	-90	0	-50	0	+10	+55
• 15% H_2O Emuls/15% EGR/ Corning Filter	-50	-25	-45	0	-75	0	+670	+2300
• Catalyst	0	0	0	+58	0	14	-85	-65
• Catalyst/Mesh Filter (dry, parallel flow)	-80	**	-55	20->44	0	-	-85	-65
• Mesh Filter (dry, parallel flow)	-90	**	-85	0	0	0	0	0
Deutz F6L-714 Engine (at 2200 rpm/93 kW)								
• H_2O Emulsion	-41	+3	-40	0	-35	0	+2	+36
• 15% H_2O Emuls/Catalyst/ Mesh Filter (wet, pendicular flow)	-90	-45	-88	0	-35	-	-95	-90
• Catalyst/Mesh Filter (wet, perpendicular flow)	-85	-5	-80	0	0	-	-95	-90
• Mesh Filter (wet, perpendicular flow)	-80	**	-83	0	0	0	0	0
• 15% H_2O Emuls/Catalyst	-40	-5	-40	+55	-35	0	-95	-90
• Catalyst/Gaspe Scrubber	-30	-15	-25	+40	-15	+5->25	-95	-75
• 20% EGR/Catalyst/Gaspe	+370	-40	+270	+40	-80	0	-65	-60

* All % EGR and water emulsification settings are approximate

** SOF reductions for this test series were highly variable and ranged from 0 to 50%

Note: SOF refers to Soluble Organic Fraction.

TABLE S.2

Composite EQI Values for Comparison of Various Emission Control Strategies

(derived from data from steady state engine test stand data)

(Deutz F6L-714 Engine)

RPM/kW	Device	EQI	% Baseline
2200/93	21% EGR	944 (653)	530%
	21% EGR/Cat/Scrubber	747 (262)	419%
	10% EGR/Cat/Scrubber	363 (254)	204%
	Emulsification/Catalyst	220	124%
	Baseline	178	100%
	Gaspe Scrubber	135	76%
	Emulsification	120	67%
	Cat/Mesh Filter (Wet)	69	39%
	Mesh Filter (Wet)	64	36%
	Emuls/Cat/Mesh Filter (Wet)	50	28%
2200/71	21% EGR	151	102%
	Base Engine	148	100%
	21% EGR/Cat/Scrubber	137	93%
	Gaspe Scrubber	114	77%
	21% EGR/Cat/Mesh Filter (Cooled)	72	49%
	21% EGR/Mesh Filter (Cooled)	54	36%
	Limiting EQI Value (CO_2 dilution)		

TABLE S.3

Composite EQI Values for Comparison of Various Emission Control Strategies

(derived from data from steady state engine test stand data)

(Deutz F8L-413 Engine)

RPM/kW	Device	EQI	% Baseline
2300/138	PTX Catalyst	364	131%
	10% EGR	332 (295)	118%
	Emulsification	281 (205)	100%
	Baseline	279	100%
	Cat/Mesh Filter (Dry)	131	47%
	Mesh Filter (Dry)	107	38%
	Corning Filter	92	33%
	10% EGR/Corning Filter	82	29%
	Limiting EQI value (CO_2 dilution)	56	
2300/103	Emulsification	251	174%
	PTX Catalyst	235	163%
	Baseline	144	100%
	10% EGR	123	86%
	EGR/Emuls/Corning Filter	86	60%
	Corning Filter	71.9	50%
	10% EGR/Corning Filter	40	28%
	Limiting EQI Value (CO_2 dilution)	47	

1. INTRODUCTION

Diesel engines are used extensively underground in Canada and in many parts of the U.S.A. The possibility of increased dieselization of North American mines has raised concern over the possible health impact, on underground workers, of exposure to diesel exhaust emissions. In view of this it would seem necessary to ventilate the mine to as safe a level as possible. Since there are limits to the amount of ventilation air which can be employed, it is important to develop diesel emission control technology in order to reduce ventilation costs, and allow more equipment to work within a given area.

The General Introduction and Executive Summary relating to this report deals in more detail with these considerations and discusses some of the emission control approaches and the problems of assessing the relative merits of these approaches.

2. CURRENT AND PARALLEL TECHNOLOGY DEVELOPMENT

2.1 Literature Review

At the commencement of the project, a literature review was carried out to determine that all pertinent material had been collected relevant to this work area. It was apparent at that time that there was little material of direct interest and relevance to diesel exhaust control with water scrubbing and filtration techniques. Most information related to catalyst control, or to engine modifications (injector, timing variations, etc.) which affect exhaust emission characteristics[(4)(5)(6)]. Engine maintenance is also extremely important in its effect on exhaust emissions. Some information was obtained on fabric filters for sub-micron particulate[(7)], which showed that very high collection efficiencies could be achieved with large (>10 microns) and very small (<0.1 micron) particles. Even at the worst size range of 0.4 microns, however, efficiencies of 90% were possible. In contrast, electrostatic precipitators generally exhibit poor collection efficiencies for sub-micron particles, which would require the control device to be impractically large for on-board use. 90% particulate removal efficiency is claimed by a Japanese invention which comprises a water vapourizer, cooling pipe, and exhaust filter. Water droplet formation in the cooling pipe is claimed to improve the efficiency of the downstream filter.

For venturi scrubbers, removal efficiency is largely a function of the energy consumed in the particle to liquid contact. Since this is achieved by passing the liquid and particles through the venturi throat where the velocity is increased dramatically, the efficiency is largely a function of the pressure drop across the throat. Efficiency increases with increased pressure drop and decreases with decreased particle size. For submicron particles, efficiencies of 90% are possible at the higher pressure drops.

2.2 Parallel Research Effort at ORF

Parallel studies carried out at ORF at the commencement of this project included:

- Analysis of Diesel Exhaust Emitted from Water Scrubber and Catalytic Purifiers. [8]
- Emission Control of a Detroit Diesel 8V-71N Engine Derated for Underground Use. [9]
- Emission Control of a Deutz F6L-714 Diesel Engine, Derated for Underground Use, by Application of Water/Oil Fuel Emulsion. [10]
- Development of an Emission Control System for Underground Diesel-Powered Equipment; Performance Data. [11]

A summary of the findings of these projects is outlined below.

Conventional Water Scrubbers and Catalysts

Conventional water scrubbers already in use in some mines, principally as flame proofing devices, are only marginally effective in reducing diesel particulate emissions. Removal efficiencies of 30% are achieved on average. These scrubbers have no effect on CO or NO_x emissions, but will absorb 90% of the SO_2. Hydrocarbon removal efficiencies parallel those of particulate removal.

Catalysts tested were monolithic Englehard PTX converters. These were found to be extremely effective in reducing CO and THC emissions (90% reduction). NO was however, oxidized to NO_2, and SO_2 was oxidized to SO_3 and H_2SO_4, which could be a disadvantage of using catalysts alone as an emission control device for underground diesel engines at their particular range of exhaust temperature operation.

Combination of the catalysts with a conventional water scrubber showed additional benefits. Particulate removal efficiency in the water scrubber improved to 50% and, in addition, about 30% of the H_2SO_4 produced by the catalyst was removed by the water scrubber. This illustrates the benefits of employing combined systems for emission control.

Venturi Scrubber

Tests carried out on the efficiency of a venturi scrubber for diesel particulate removal [11], showed, however, that while collection efficiencies of >50% were possible at 40" pressure drop, the back pressure in engine exhaust increased particulate formation, so that the overall control efficiency, relative to a bare engine, was closer to 30% at some load/speeds. That is, despite the apparently good potential of the venturi scrubber for fine particle removal, it is limited by the back pressure effect on the engine. The increased design complexity of the venturi scrubber would not therefore be justified for use in hard rock mines, but may be justified in coal mines where flame proofing is required.

Water Emulsions

Unstabilized water/diesel fuel emulsions, applied to a Deutz F6L 714 diesel engine, were found to be effective in controlling both NO_x and particulate emissions. This is the only method known which can control both of these emission components with one technique. About 50% reduction in both NO_x and particulate emissions could be achieved with 15% w/w H_2O/diesel emulsions. Some penalty in the form of increased CO and THC emissions occurred, especially at intermediate load/speed conditions. Details of the techniques employed, and results obtained, are contained in SAE and CIM publications [12][13].

2.3 Other Technology Development

During the course of this project, other developments in the field were closely monitored. It was found possible to incorporate some of these developments into the project in order to maintain the objective of employing best available technology. Developments are summarized below.

Advanced Venturi Scrubber

Follow on work by CANMET from that carried out at ORF has led to the development of a model which may allow the achievement of higher particulate collection efficiencies than that of the earlier ORF work. A scrubber, based on this model, has been constructed by CANMET, and is scheduled for testing by ORF in future programs.

Johnson Matthey Catalyst Trap Oxidizer

Early work by Ricardo[14] on spiral soot scrubbers, and parallel studies by Johnson Matthey has led to the development of a catalyst trap oxidizer system [15]. This system comprises a catalyst coated wire mesh located in the exhaust manifold. The mesh traps particulate matter, and the catalyst aids the periodic combustion of the particulate as the trap loads up with particulate, according to the load/speed condition of the engine. High filtration efficiencies are claimed with their latest model (JM 10), with satisfactory combustion and minimum "blow-off" of particulate matter. This system merits investigation over a typical mines duty cycle, to assess the products of combustion during regeneration, and determine how much H_2SO_4 may be produced. It is expected that this will be carried out by ORF in a future parallel contract.

Texaco Filter

An Alumina coated metal wool particulate filter has been developed by Texaco for the control of diesel particulate emissions. High efficiency over a wide range of engine speeds and exhaust gas velocities has been reported [16]. Regeneration of this filter was achieved with a catalytic torch fired by propane. This involves placing a catalyst upstream of the filter and injecting propane into the hot exhaust gas upstream of the catalyst. The exothermic reaction of propane on the catalyst raises the exhaust gas temperature in order to initiate combustion of particulate on the filter. Further development of the catalytic torch is required, however, to determine its commercial viability.

Corning Filter

Development of a ceramic filter for diesel particulate has been developed by Corning Glass Division [17]. This is an extension of their work on monolithic ceramic supports for automotive catalysts, and uses similar materials except that alternate channels in the honeycomb are closed, to force the exhaust gas through the walls of the ceramic material which produces the filtering action. This technology was of sufficient interest to allow incorporation of test work within the present project. Furthermore, CANMET, are undertaking field trials of such filters underground in order to assess durability potential. Progress in the development of this technology for underground diesels is reported herein.

3. BASELINE

3.1 Test Engines

Two test engines were used in this project:

- Deutz F6L 714, indirect injection, 9.5ℓ V-6, air cooled;
- Deutz F8L 413, indirect injection, 12.8ℓ V-8, air cooled.

General specifications for both engines are shown in Table 3.1. The F6L 714 engine is representative of mining engines presently in common use and the F8L 413 engine is a late model engine, which is likely to replace the outmoded 714, and may therefore be representative of a typical mining engine which will be in common use in the future.

Serious mechanical problems were experienced with operation of the new 413 series engine including cylinder glazing and ring problems, excessive oil consumption, valve problems, overheating problems, and fuel pump problems. Considerable effort was involved, working with the engine manufacturer, to overcome these problems. Details of the problems experienced, and corrective action taken are included in Appendix I.

Both engines were installed on engine dynamometer test beds (Clayton 700 C.E., water brake). Emission tests were carried out over a range of steady state load/speed conditions, typically:

rated speed,	full, 3/4, 1/2 load
1900 rpm,	full, 3/4, 1/2 load
1600 rpm,	full load

The fuel used throughout the series of tests was Gulf Diesel 40, a typical winter grade diesel fuel commonly used in Canadian mines. Typical fuel specifications are shown in Table 3.2.

3.2 Analytical Techniques

Gaseous analysis was carried out using conventional NDIR and chemiluminescent instrumental techniques. Particulate analysis was carried out using the EPA Method 5 sampling technique with a train manufactured by Joy Manufacturing. Sulphuric acid analysis was carried out using a controlled condensation technique developed at ORF [17]. Details of instrumentation and analytical methodology are provided in Appendix II.

3.3 Baseline Emissions

3.3.1 Deutz 714 Engine

Work on the 714 engine was conducted during the first phase of this project which involved rapid scanning of a number of emission control devices with the objective of selecting only the most promising approach for further study. The number of load/speed conditions employed were therefore smaller than that used in the subsequent phase with the 413 engine.

Table 3.3 shows typical particulate emission rates from the Deutz F6L 714 engine. Two injection timings are indicated 24^{o} and 27^{o} BTDC. 27^{o} BTDC was originally recommended by Deutz Diesel, but the mining industry currently uses 24^{o}. It is clear that emission characteristics are more favourable at 24^{o} BTDC. Table 3.4 shows a comparison of the particulate emissions from the left and right banks of the engine. This data was important in relation to tests of a water scrubber, described later in the report, which was sized for one bank of the engine exhaust only. The right and left bank exhausts are not identical, which complicated a comparison of the left bank scrubber controlled exhaust with the uncontrolled right bank exhaust.

Table 3.5 shows typical uncontrolled gaseous emission characteristics at 24° BTDC* injection timing. CO emission rates range from 25 to 66 g/hr, THC 5 - 14 g/hr and NO_x from 212 to 306 g/hr.

3.3.2 Deutz 413 Engine

More detailed data was obtained on the eight cylinder 413 engine. Table 3.6 shows typical engine operating characteristics for this engine.

During baselining of this engine, engine problems were experienced as described in Appendix I. As a result, the emission characteristics shown in Tables 3.7, 3.8 and 3.9 are abnormal, and represent a condition where high CO and THC emissions may have resulted from oil blowby past the piston rings. Table 3.7 shows particulate emissions rates, characterized by insoluble and soluble organic fractions, as well as total particulate emissions, over seven steady state load/speed conditions. Tables 3.8 and 3.9 show emission concentrations and rates obtained over 12 load/speed conditions for CO and THC emissions, and NO, NO_2 and NO_x emissions respectively.

Because it was considered that the engine was operating abnormally, further baseline tests were conducted during testing of control device efficiency, and the data obtained at that time used as a comparison with that obtained downstream of such emission control systems. It is apparent, for example, that higher CO and THC emissions can be observed at intermediate loads for 2300 rpm in Table 3.8 as compared with Table 9.8.

The following sections examine the effects of various emission control techniques, in modifying the baseline emission characteristics.

* BTDC (Before Top Dead Centre).

TABLE 3.1

Deutz F6L 714 Characteristics

No. of Cylinders	6V
Bore cm (in)	12.0 (4.72)
Stroke cm (in)	14.0 (5.32)
Displacement ℓ (cu.in)	9.5 (579.1)
Compression Ratio	19.2:1
Combustion Process	Swirlchamber
Fuel Injection System	Bosch
Max. Power at Rated Speed	135 BHP @ 2300 RPM

Deutz F8L 413 Characteristics

No. of Cylinders	8V
Bore cm (in)	12.0 (4.72)
Stroke cm (in)	12.5 (4.92)
Displacement ℓ (cu.in)	12.76 (779)
Compression Ratio	19.5:1
Combustion Process	Swirlchamber
Fuel Injection System	Bosch
Max. Power at Rated Speed	185 BHP @ 2300 RPM
Max. Torque at 1500 RPM	500 lb.ft

TABLE 3.2

Gulf Oil Canada Limited

Diesel 40 Fuel Specifications

Specific Gravity	0.818
API Gravity	41.6
Colour	+20
Flash °F	138
Cloud °F	-52
Pour °F	-55
Distillation	
% Recovered	
I.B.P.	320
10	367
50	421
90	503
F.B.P.	545
Recovery	99.0
Residue	1.0
Loss	0.0
C/H Ratio	6.4
Carbon %	86.5
Hydrogen %	13.5
Sulphur %	0.16
Nitrogen ppm	17

TABLE 3.3

A Comparison of 27 vs 24° BTDC Injection Timing Particulate Emission Rates for a Deutz F6L 714

Speed rpm	Load kW	Torque Nm	Inj. Timing ° BTDC	Particulate Emission Rates							
				Total Particulate		Insoluble Matter			Soluble Organic Fraction		
				mg/m^3	g/hr	mg/m^3	g/hr	% of Total	mg/m^3	g/hr	% of Total
2200	93	407	24	58.4	27.2	50.4	23.51	86	8.0	3.71	14
			27	64.8	30.21	58.2	27.13	90	6.6	3.10	10
1625	71	407	24	61.8	21.07	57.2	17.97	85	9.1	3.10	15
			27	93.8	32.0	84.6	28.82	90	9.3	3.20	10
2200	71	305	24	32.4	15.33	21.6	10.21	67	10.8	5.13	33
			27	42.8	19.91	35.5	16.53	83	7.2	3.35	17
1500	32	203	24	28.0	9.81	14.5	5.19	52	13.5	4.62	48
			27	44.7	15.97	19.3	6.89	43	25.4	9.09	57

TABLE 3.4

A Comparison of the Particulate Emissions from the Left and Right Exhaust Banks of a Deutz F6L 714 Diesel Engine

Speed rpm	Load kW	Torque Nm	Engine Bank - Back Pressure cm of H_2O	Particulate Emission Rates							
				Total Particulate		Insoluble Matter			S.O.F.		
				mg/m^3	g/hr	mg/m^3	g/hr	% of Total	mg/m^3	g/hr	% of Total
1850	78	407	L - 17	49.53	20.58	48.17	20.02	97	1.37	0.57	3
			L - 17	53.42	22.20	47.12	19.83	89	5.68	2.36	11
			R - 17	45.06	18.72	40.95	17.02	91	4.11	1.71	9
			L - 13	50.22	17.96	46.47	16.61	93	3.75	1.34	7
			L - 13	48.37	17.27	45.03	16.10	93	3.35	1.20	7
1625	70	407	R - 13	66.76	23.87	56.51	20.20	85	10.25	3.66	15
			R - 13	72.50	25.81	57.87	20.69	80	14.33	5.12	20

L = Left Bank
R = Right Bank

TABLE 3.5

Baseline Gaseous Emissions from

Deutz F6L 714 Engine

Exhaust Component	Speed rpm	Load kW	Torque Nm	Conc. ppm	Emission Rates		
					g/kW.hr	g/hr	g/kg Fuel
CO	2200	93	407	122	0.702	65.5	2.41
	2200	71	305	92	0.724	51.3	2.39
	1625	70	407	60	0.350	24.8	1.28
THC	2200	93	407	40	0.145	13.6	0.498
	2200	71	305	30	0.146	10.35	0.481
	1625	70	407	20	0.0731	5.18	0.267
NO	2200	93	407	530	3.27	305	11.20
	1625	70	407	480	3.00	212	10.94
NO_2	2200	93	407	<1	0.01	<1	0.01
	1625	70	407	<1	0.01	<1	0.01
NO_x	2200	93	407	530	3.27	305	11.20
	1625	70	407	480	3.00	212	10.94

TABLE 3.6

Deutz F8L 413 F/W Engine Characteristics

Speed (rpm)	Load (kW)	Fuel/Air Ratio	Flow Rate, Dry (SCMM)*	Flow Rate, Wet (ACMM)*	% H_2O	Fuel Consumption (kg/hr)
2300	139	0.0433	10.7	32.0	8.9	35.4
2300	103	0.0350	10.5	27.3	7.5	28.1
2300	69	0.0267	11.3	24.8	6.0	22.7
2300	35	0.0192	11.2	20.7	4.7	16.3
2000	132	0.0386	11.0	30.1	8.3	32.6
2000	99	0.0278	11.5	25.6	6.4	24.5
2000	66	0.0240	10.6	21.2	5.6	19.4
2000	33	0.0162	11.0	18.5	4.1	13.3
1600	112	0.0395	8.17	21.8	8.4	25.0
1600	84	0.0302	8.44	18.8	6.7	19.6
1600	56	0.0212	8.66	15.8	5.1	14.1
1600	28	0.0132	9.08	13.6	3.6	8.9

*SCMM - Standard Cubic Metres per Minute

*ACMM - Actual Cubic Metres per Minute

TABLE 3.7

Baseline Particulate Emission Rates from a Deutz F8L 413 Engine

Speed (rpm)	Load (kW)	Fuel/Air Ratio	Particulate Loadings and Emissions											
			Insoluble				Soluble				Total			
			mg/m^3	g/kW.h	g/h	g/kg Fuel	mg/m^3	g/kW.h	g/h	g/kg Fuel	mg/m^3	g/kW.h	g/h	g/kg Fuel
2300	138	0.042	88.8	0.429	59.8	1.65	24.7	0.119	16.6	0.458	114	0.547	76.3	2.11
2300	138	0.042	75.9	0.361	50.4	1.41	18.6	0.088	12.3	0.344	94.4	0.450	62.7	1.75
2300	103	0.032	43.5	0.296	30.5	1.05	38.0	0.259	26.6	0.920	81.5	0.555	57.1	1.97
2300	69	0.023	21.1	0.229	15.9	0.725	25.7	0.280	19.4	0.884	46.8	0.510	35.3	1.61
2000	132	0.040	63.0	0.307	40.6	1.22	7.46	0.036	4.81	0.144	70.4	0.344	45.4	1.36
2000	98	0.028	40.5	0.280	27.6	1.12	7.89	0.055	5.38	0.219	48.4	0.335	33.0	1.34
2000	65	0.022	23.0	0.251	16.3	0.847	29.3	0.318	20.7	1.08	52.3	0.569	36.9	1.92
1600	113	0.043	109	0.475	53.9	1.98	17.0	0.075	8.45	0.311	126	0.550	62.3	2.29

TABLE 3.8

CO and THC Gaseous Emission Characteristics
from a Deutz F8L 413 Engine

Speed (rpm)	Load (kW)	Total Hydrocarbons as Methane				Carbon Monoxide			
		ppm	g/kW.hr	g/hr	g/kg Fuel	ppm	g/kW.hr	g/hr	g/kg Fuel
2300	139	87.5	0.294	40.8	1.15	80.0	0.430	59.6	1.68
2300	103	69.0	0.303	31.2	1.11	45.0	0.321	33.0	1.18
2300	69	79.0	0.544	37.7	1.66	92.0	1.04	72.5	3.19
2300	35	83.5	1.11	38.7	2.38	171.5	3.80	133.0	8.19
2000	132	57.0	0.204	26.9	0.82	140.0	0.805	106.0	3.26
2000	99	61.5	0.301	29.9	1.22	127.0	1.02	101.0	4.14
2000	66	48.5	0.326	21.6	1.12	28.5	0.318	21.0	1.09
2000	33	41.5	0.573	18.8	1.42	26.0	0.605	19.8	1.50
1600	112	57.5	0.181	20.2	0.808	126.0	0.636	71.2	2.84
1600	84	50.5	0.214	18.0	0.924	92.0	0.640	53.9	2.76
1600	56	59.5	0.384	21.5	1.52	96.0	1.04	57.8	4.10
1600	28	101.0	1.32	37.4	4.18	205.0	4.53	128.0	14.4

TABLE 3.9

NO, NO_2 and NO_x Gaseous Emission Characteristics from a Deutz F8L 413 Engine

Speed (rpm)	Load (kW)	Nitric Oxide				Nitrogen Dioxide				Total Oxides of Nitrogen ($NO + NO_2$)			
		ppm	g/kW.hr	g/hr	g/kg Fuel	ppm	g/kW.hr	g/hr	g/kg Fuel	ppm	g/kW.hr	g/hr	g/kg Fuel
2300	139	675	3.88	539	15.2	5	0.05	6	0.2	680	3.93	545	15.4
2300	103	598	4.57	470	16.7	15	0.17	18	0.7	613	4.74	488	17.4
2300	69	430	5.23	363	16.0	15	0.28	19	0.8	445	5.51	382	16.8
2300	35	243	5.76	202	12.4	20	0.73	25	1.6	263	6.49	227	14.0
2000	132	720	4.44	586	18.0	15	0.14	18	0.5	735	4.58	604	18.5
2000	99	585	5.05	501	20.4	10	0.14	13	0.6	595	5.19	514	21.0
2000	66	463	5.53	367	18.9	16	0.29	19	1.1	479	5.82	386	20.0
2000	33	263	6.54	215	16.2	22	0.86	28	2.1	285	7.40	243	18.3
1600	112	630	3.41	381	15.2	3	0.02	3	0.1	633	3.43	384	15.3
1600	84	565	4.21	355	18.1	18	0.20	17	0.9	583	4.41	372	19.0
1600	56	400	4.62	258	18.3	23	0.39	22	1.6	423	5.01	280	19.9
1600	28	185	4.43	124	13.9	45	1.64	47	5.2	230	6.02	171	19.1

4. EXHAUST GAS RECIRCULATION (EGR)

Exhaust gas recirculation is known to reduce NO_x emissions, but has adverse effects on most other exhaust constituents. The effect of EGR on the emission characteristics of both the 714 and 413 engines was therefore investigated to determine the magnitude of the effects created, and establish opportunities for employing EGR together with some other control device.

4.1 Deutz 714 Engine

The EGR system used on the 714 engine test bed is shown in Figure 4.1. The effect of EGR on engine performance is shown in Table 4.1. As the EGR is increased, the OEM rated speed and full load condition cannot be maintained without pro-rating the fuel pump to a higher fuel delivery rate. The effects are small, however, at about the 10-15% EGR level.

The effect of various percentage EGR on gaseous emission rates is shown in Table 4.2. Significant reductions in NO_x are apparent, ranging from 40 - 50% at 10% EGR, to 65 - 70% at 20% EGR. The trade-off occurs with increased CO and THC emissions. At 3/4 full load, and 21% EGR, CO increases of 540% occur. However, the effect on CO emissions at lower load conditions and smaller percentages of EGR is less severe. For example, CO is increased only 30% by 21% EGR at rated speed and half load.

The effect of EGR on the insoluble particulate emission rates is shown in Table 4.3. Again high loads, and high percentages of EGR create very large increases in particulate matter. At lower loads and lower EGR rates, the effect is less severe, but increases of 60 - 80% are still observed.

The overall effect of EGR on gaseous and particulate emissions rates from the 714 engine, is summarized in the bar chart of Figure 4.2. A comparison is made of the effect of 22% EGR under high load conditions versus the effect at lower load conditions. It is clear that the trade-off of increased CO, and particulate emissions, for similar NO_x

reductions, is much less severe at lower load conditions. THC emissions, however, are increased slightly. The NO_2 component of the NO_x in these tests was very low, and not recorded.

4.2 Deutz 413 Engine

Similar effects on emissions have been observed with EGR application to the 413 engine. Table 4.4 shows the effect of various percentages of EGR on CO and NO_x emission rates, under different load/speed conditions. In this case the maximum EGR application was limited to 17% and at full load condition, only 10% EGR was applied. Ten percent EGR at full load was sufficient to reduce NO_x emissions by 40%, while CO increases were limited to about 90% at lower load/speed conditions and 10% EGR, only small increases (10%) in CO emissions were observed. The situation was a little worse at 17% EGR, where a 30% increase in CO emissions occurred at 2000 rpm, half load condition. It should be noted that baseline CO emissions shown in Table 4.4 are greater than that recorded later in this report. This is again due to the 413 engine oil consumption being abnormally high at this stage in the project.

With EGR limited to 10 - 15%, the effects of particulate emissions are much less severe than was observed with the 714 engine. This is clear by examination of Table 4.5 Most of the increase in particulate emissions is due to an increase in the insoluble fraction, while considerable reductions in the soluble organic fraction are evident. This results in the total particulate increasing by 60% at full load/full speed with 8% EGR, and decreasing by 17% at 2000 rpm, half load, with 15% EGR, which also reduced NO_x emissions by 50%.

4.3 Conclusions on EGR Application

Application of EGR lowers NO_x emissions, and increases CO, THC and particulate emissions. Increases observed are greatest at high loads, and high percentages of EGR. At lower load/speed conditions, the effects are much less severe, due largely to the reduction in SOF which becomes a significant fraction of the total particulate at these load/speed conditions.

It is unlikely that EGR could ever be used alone as an emission control approach without the aid of some additional device to minimize increases in CO, THC and particulate emissions, especially under full load/ speed condition.

TABLE 4.1

Effect of EGR on Engine Performance
for a Deutz F6L 714

Speed (rpm)	Load (kW)	Torque Nm	EGR %	Air Intake Temp. °C	Exhaust Temp. °C	Fuel Consumption Rate kg/hr
	93	407	0	28	546	27.2
2200	91	395	11.0	33	556	27.6
	89	388	21.8	42	568	27.5
	70	407	0	31	468	19.4
1625	70	407	10.9	36	479	19.4
	69	403	21.7	42	509	20.1
	71	305	0	34	457	21.5
2200	71	305	10.7	39	460	21.3
	71	305	21.4	42	473	21.4
	48	305	0	-	343	14.0
1500	48	305	10.7	-	342	13.8
	48	305	21.3	-	336	13.6

TABLE 4.2

The Effect of Various % EGR on the Gaseous Emissions of a Deutz F6L 714 Diesel Engine

Speed (rpm)	Load (kW)	Torque Nm	EGR %	Concentrations and Emission Rates (PTX Catalyst Controlled)											
				NO			NO_2		THC			CO			
				ppm	g/hr	% Decrease	ppm	g/hr	ppm	g/hr	% Increase	ppm	g/hr	% Increase	
2200	93	407	0	460	264		<1	<1	40	13.6	67	122	65.5	541	
			11.0	260	132	50	<1	<1							
			21.8	150	67.3	75	<1	<1	80	22.7		>1000	>420		
1625	70	407	0	400	177		<1	<1	20	5.2	69	60	24.8	278	
			10.9	245	97	45	<1	<1							
			21.7	145	50	72	<1	<1	40	8.8		290	93.8		
2200	71	305	0	480	287		<1	<1	30	10.3	89	92	51.3	31	
			10.7	330	176	39	<1	<1							
			21.4	220	103	64	<1	<1	70	19.5		154	67.3		
1500	48	305	0	330	144		<1	<1							
			10.7	210	82	43	<1	<1							
			21.3	150	52	64	<1	<1							

Note: Percentage increase and decrease in pollutants are based on mass emission rate.

TABLE 4.3

The Effect of Various Percentages of EGR on the Particulate Emissions of a Deutz F6L 714 Diesel Engine

Speed (rpm)	Load (kW)	Torque Nm	EGR %	Average Particulate Concentration and Emission Rates — Insoluble Particulate Matter		
				mg/m^3	g/hr	% Increase(1)
2200	93	407	0	52.5	24.2	
			21.6	431.2	186.6	671%
			0	86.0	30.4	
1625	70	407	10.8	178.4	56.3	85%
			21.6	431.4	119.7	294%
2200	71	305	0	26.1	12.5	
			21.6	53.0	19.9	59%

(1) Based on mass emission rates.

TABLE 4.4

Gaseous Emissions - Baseline and with EGR Application

F8L 413 F/W

Speed (rpm)	Load (kW)	EGR %	Total Oxides of Nitrogen ($NO + NO_2$)					Carbon Monoxide				
			ppm	g/kW.h	g/h	g/kg Fuel	% Decrease[(1)]	ppm	g/kW.h	g/h	g/kg Fuel	% Increase
2300	138	-	730	4.36	601	16.6	(Baseline)	340	1.88	260	7.17	(Baseline)
2300	104	-	610	4.83	501	17.6	(Baseline)	163	1.21	125	4.38	(Baseline)
2000	63	-	525	6.94	440	24.1	(Baseline)	81	0.99	62	3.4	(Baseline)
2300	138	9.5	445	2.58	356	9.43	40.8	670	3.63	500	13.2	92.3
2300	138	9.5	445	2.49	343	9.43	42.9	670	3.50	483	13.3	85.8
2300	104	9.1	475	3.41	353	12.4	29.5	185	1.24	128	4.50	2.4
2300	104	9.2	450	3.25	337	11.7	32.7	200	1.35	140	4.86	10.7
2300	104	14.6	330	2.28	236	8.61	52.9	210	1.35	140	5.11	10.7
2300	104	14.6	330	2.29	237	8.61	52.7	210	1.36	141	5.11	12.8
2000	63	10.3	395	4.53	287	16.0	34.8	95	1.02	64.5	3.58	4.0
2000	63	11.3	325	3.65	231	13.2	47.5	95	.987	62.6	3.58	1.0
2000	63	17.3	300	3.13	198	10.7	55.0	130	1.27	80.3	4.34	29.5
2000	63	17.3	300	3.25	206	10.9	53.2	130	1.31	80.3	4.41	34.3

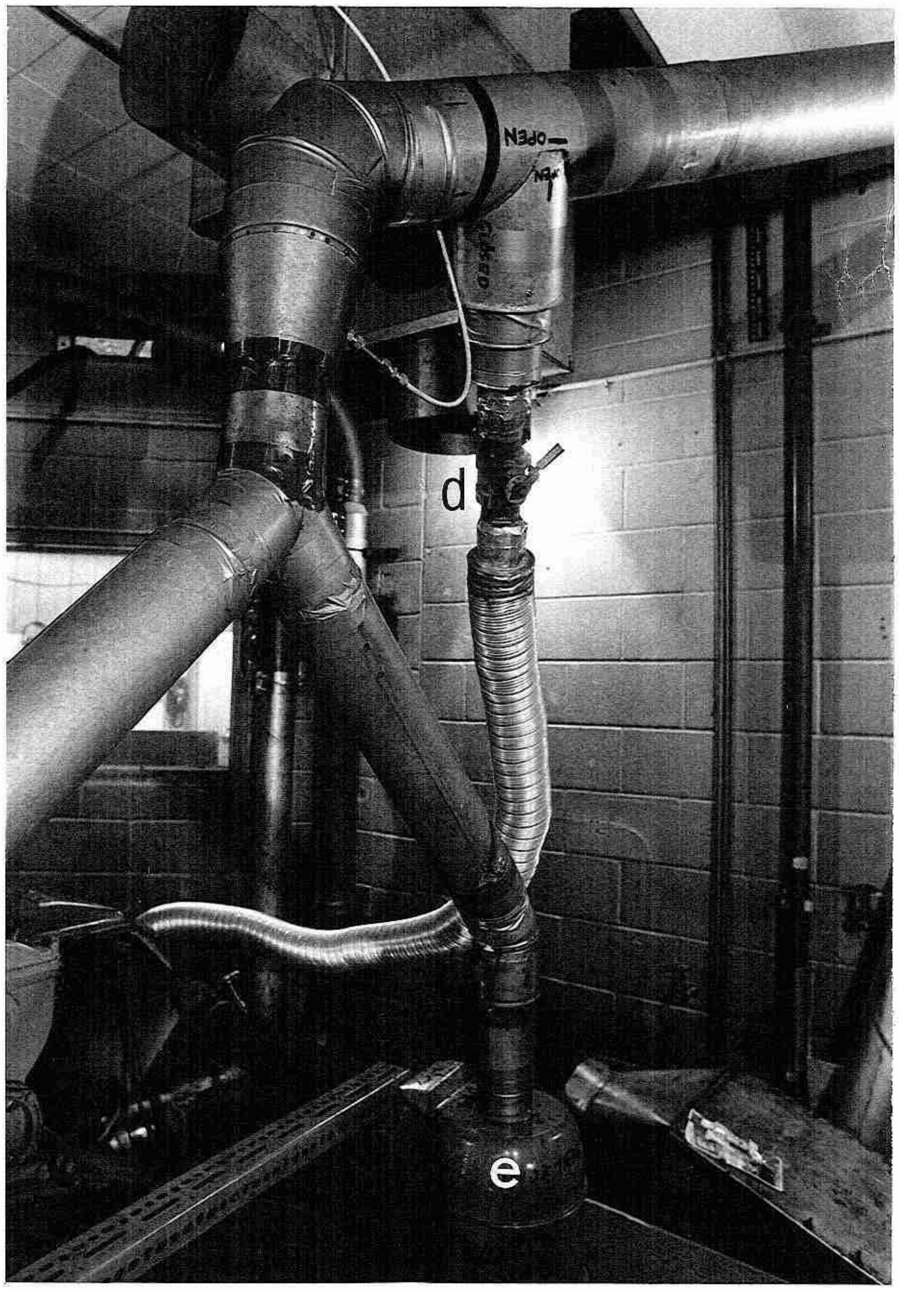
(1) Based on mass emissions

TABLE 4.5

Particulate Emissions from the Deutz F8L 413 Engine with EGR Applications

Speed (rpm)	Load (kW)	EGR (%)	Insoluble mg/m^3	Insoluble g/kW.h	Insoluble g/h	Insoluble g/kg Fuel	% Increase * wrpt Baseline	Soluble mg/m^3	Soluble g/kW.h	Soluble g/h	Soluble g/kg Fuel	% Increase * wrpt Baseline	Total mg/m^3	Total g/kW.h	Total g/h	Total g/kg Fuel	% Increase * wrpt Baseline
2300	138	0	78.4	.373	51.3	4.25		17.5	.083	11.4	.316		95.8	.455	62.8	1.73	
2300	138	8.0	157	.700	96.5	2.58		15.5	.069	9.53	.255		172	.768	106	2.84	
2300	138	7.8	156	.685	94.5	2.58	82.8	11.7	.051	7.08	.193	-31.6	168	.737	102	2.77	61.9
2300	138	7.8	148	.655	90.3	2.44		11.1	.049	6.77	.183		159	.704	97.1	2.63	
2300	104	0	36.9	.234	24.3	.851		14.4	.092	9.5	.332		51.3	.326	33.7	1.18	
2300	104	12.9	53.9	.294	30.5	1.04		10.5	.057	5.93	.203		64.4	.351	36.4	1.25	
2300	104	12.8	45.7	.251	26.1	.886	20.0	9.1	.050	5.19	.176	-32.8	54.8	.301	31.2	1.06	5.3
2300	104	12.8	53.6	.298	30.9	1.04		13.8	.077	7.96	.268		67.4	.375	38.9	1.31	
2000	63	0	21.4	.222	14.1	.772		26.3	.273	17.3	.950		47.6	.495	31.3	1.72	
2000	63	15.4	25.7	.218	13.8	.763		24.7	.200	13.3	.733		50.4	.427	27.1	1.50	
2000	63	15.4	28.7	.243	15.4	.852	15.4	14.9	.126	8.01	.442	-43.8	43.6	.370	23.4	1.30	-17.0
2000	63	15.4	36.4	.309	19.6	1.08		14.6	.124	7.85	.433		51.0	.433	27.4	1.51	

* % increase is calculated using g/h and determined with respect to (wrpt) baseline emissions.

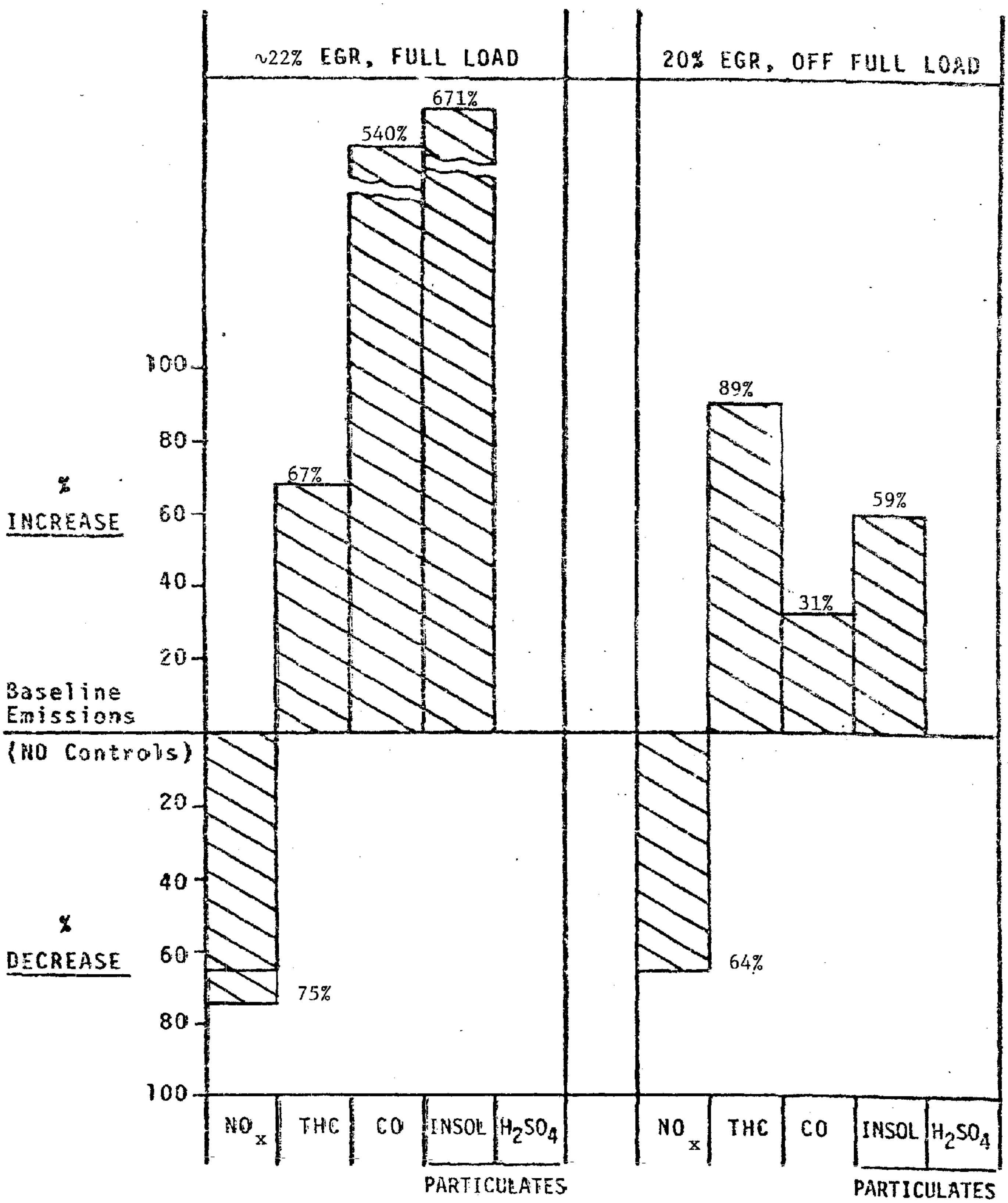


d - EGR Control Valve e - Right Bank Intake Air Cleaner

FIGURE 4.1: View of Air Intake and EGR Control Valve.

FIGURE 4.2:

Effect on Emissions of 22% EGR at Full Load vs 22% EGR at Off Full Load on a Deutz F6L 714



5. PTX CATALYST

5.1 Test Conditions

Engelhard PTX catalysts are presently in common use underground. An assessment is made here of their performance. Similar catalyst performances were obtained on both the 714 and 413 engines. Data is reported here for the 413 engine only. Two Engelhard PTX 623D catalysts were mounted close to the exhaust manifold of the engine, one on each bank of the exhaust. The new catalysts were subjected to an aging period of approximately 30 to 40 hours.

To establish the catalyst performance at various exhaust gas temperatures the following twelve load/speeds were selected:

2300 rpm)
2000 rpm) 100, 75, 50 and 25% load.
1600 rpm)

These engine conditions produced a range of exhaust gas temperatures from 148°C to 536°C (298°F to 997°F). Table 5.1 gives results of the tests showing catalyst temperature, fuel/air ratio, catalyst back pressure, exhaust flows, space velocities, and fuel consumption rate. From this table it can be seen that the higher exhaust temperatures are consistent with higher catalyst back pressures, higher space velocities (actual conditions) and consequently reduced contact times. Figure 5.1 illustrates the relationship of space velocity (standard) versus engine speed and load. Space velocity is the volume of gas passing through a unit volume of a catalyst per unit time under specified conditions.

5.2 Emission Testing for SO_2/H_2SO_4

A total of 10 sulphate tests were conducted during catalyst aging. Tests were conducted at a post-catalyst location using the controlled condensation sampling system. This sytem allows for the quantitative collection of sulphates ($SO_4^{=}$) and sulphur dioxide (SO_2) from hot exhaust gas streams. The sampling system withdraws exhaust gas (11 ℓ/min) through a glass probe maintained at 250°C followed by a glass cooling coil

(@ 70^{o}C). The sulphate fraction is removed in the coil while sulphur dioxide is removed in a set of impingers, downstream of the coil, containing a 3% hydrogen peroxide solution. Solutions are subsequently analyzed using a spectrophotometer to determine the sulphur concentrations. (See Appendix II).

Table 5.2 gives average results of the ten sulphate tests and shows that at higher catalyst temperatures to 450^{o}C there is increased conversion of SO_2 to $SO_4^{=}$. This conversion is reduced considerably at lower temperatures (i.e. <300^{o}C). It seems apparent, therefore, that the conversion is affected more by exhaust temperature than contact time of the exhaust with the catalyst. The accountability of fuel sulphur is very good (∿95%) for the tests conducted.

The relationship of sulphate and sulphur dioxide in g/hr and g/kW-hr, respectively, versus catalyst temperature is shown in Figures 5.2 and 5.3. A significant increase in sulphate emission is apparant in Figure 5.2 at catalyst temperatures of about 350^{o}C to 450^{o}C, which correspond to fuel/air ratios of approximately 0.028 to 0.040.

As shown in Figure 5.4, above 450^{o}C to the last data point at about 540^{o}C, the conversion of SO_2 to $SO_4^{=}$ begins to fall off increasingly. This is consistent with the literature of catalytic oxidation of SO_2 and is apparently well known[18, 19]. Above about 450^{o}C, the reaction is in thermodynamic equilibrium and the decomposition of SO_3 is increasingly favoured. An example of this effect is described in Figure 5.5 for a 300 ppm sulphur content fuel as a function of catalyst temperature and oxygen concentration for temperatures above 400^{o}C.[20]

5.3 Emission Testing for Hydrocarbon, Carbon Monoxide and Oxides of Nitrogen

Concentrations of total hydrocarbons (THC as methane CH_4, carbon monoxide (CO) and oxides of nitrogen (NO_x as NO and NO_2) were measured continuously throughout the catalyst aging procedure. Sampling was conducted before and after the right and left bank catalysts.

Table 5.3 provides concentration and emission rates of both CO and THC emissions upstream and downstream of the catalyst. Plots of the percentage reductions of THC and CO versus catalyst temperature and fuel air ratio are presented in Figures 5.6 and 5.7 respectively. Significant reductions in THC and CO occur above a catalyst temperature of about 250°C and a fuel/air ratio of 0.020.

Figures 5.8 and 5.9 show inlet and outlet THC emissions upstream and downstream of the catalyst, expressed as gram/hr and gram/kW-hr, respectively. Figures 5.10 and 5.11 show similar data for CO emissions. A consistent pattern is evident with respect to improved catalyst efficiency at the higher temperatures. It is clear that at low loads, engine combustion efficiency results in less CO and THC emitted at 2000 rpm than at other speeds. At the lower speeds, however, the catalyst temperature is insufficient to allow significant oxidation to take place.

NO_x concentrations and emission rates are provided in Table 5.4. Emission rates of NO_x as NO_2 in g/hr and g/kW-hr are given in Figures 5.12 and 5.13. Some NO_2 (45 ppm max.) was noticed at the pre-catalyst locations. The NO_2 concentrations at this location increased as the load was decreased for given engine speeds. Post catalyst NO_2 concentrations were generally higher at the higher catalyst temperatures; however, the NO_2 concentrations are lower than pre-catalyst concentrations for lower catalyst temperatures. Both Figures 5.12 and 5.13 show higher emission rates of NO_x for all loads at the 2000 rpm speed. This is probably due to improved combustion at this speed condition which was also noted for THC and CO.

Figure 5.14 shows pre and post catalyst NO_2 emission rates (g/hr) versus temperature. It is interesting to note that at low catalyst temperatures the catalyst appears to convert NO_2 to NO. This occurs up to a catalyst temperature of about 260°C and then NO_2 emission rates are higher after the catalyst.

5.4 Conclusions on PTX Catalyst Performance

Table 5.5 summarizes the performance of the Engelhard PTX catalysts, which are widely used in underground mining operations. Efficiencies for reducing CO and THC emissions are very high, but there is a trade-off in the form of increased NO_2 and H_2SO_4 emissions created by oxidation of NO and SO_2.

It would appear that such catalysts for use on underground diesels would be better applied in combination with some other device or technique which would minimize the NO_2 and H_2SO_4 emissions produced.

TABLE 5.1

Catalyst and Engine Characteristics

Deutz F8L 413 F/W

Speed (rpm)	Load (kW)	Catalyst Temp. (^oC) Inlet	F/A Ratio	Catalyst Back Pressure (cm H_2O)	Flow Rate, Dry (SCMM)*	Flow Rate, Wet (ACMM)*	% H_2O (V/V)	Space Velocity Standard, Dry ($Hr^{-1} \times 10^5$)	Space Velocity Actual, Dry ($Hr^{-1} \times 10^5$)	Fuel Consumption (kg/hr)
2300	139	536	0.0428	36	10.7	32.0	8.9	1.37	4.11	35.4
2300	103	432	0.0350	30	10.5	27.3	7.5	1.35	3.50	28.1
2300	69	333	0.0267	25	11.3	24.8	6.0	1.45	3.18	22.7
2300	35	242	0.0192	20	11.2	20.7	4.7	1.43	2.65	16.3
2000	132	480	0.0386	35	11.0	30.1	8.3	1.41	3.87	32.6
2000	99	348	0.0278	27	11.5	25.6	6.4	1.48	3.29	24.5
2000	66	280	0.0240	22	10.6	21.2	5.6	1.36	2.72	19.4
2000	33	195	0.0162	18	11.0	18.5	4.1	1.41	2.37	13.3
1600	112	447	0.0395	20	8.17	21.8	8.4	1.05	2.80	25.0
1600	84	335	0.0302	15	8.44	18.8	6.7	1.08	2.41	19.6
1600	56	234	0.0212	11	8.66	15.8	5.1	1.11	2.03	14.1
1600	28	148	0.0132	10	9.08	13.6	3.6	1.17	1.75	8.9

*SCMM - Standard Cubic Metres per Minute

*ACMM - Actual Cubic Metres per Minute

TABLE 5.2

Engelhard PTX-623D Catalytic Purifier Sulphur Emissions

Speed (rpm)	Load (kW)	Catalyst Temp. (°C) Inlet	Sample Point	Sulphur Dioxide				Sulphates ($SO_4^{=}$)			
				ppm	g/kW-hr	g/hr	g/kg Fuel	ppm	g/kW-hr	g/hr	g/kg Fuel
2300	69	333	Outlet	27.0	0.701	48.4	2.13	10.5	0.409	28.2	1.24
2000	99	348	Outlet	23.5	0.433	42.8	1.75	21.0	0.580	57.4	2.34
2000	33	195	Outlet	24.5	1.30	42.9	3.26	1.35	0.108	3.55	0.267
1600	112	447	Outlet	18.5	0.215	24.0	0.960	38.5	0.670	75.1	3.00
1600	56	234	Outlet	29.5	0.725	40.6	2.88	2.45	0.085	4.78	0.339

TABLE 5.3

Engelhard PTX-623D Catalytic Purifier THC & CO Gaseous Emissions (F8L 413 F/W)

Speed (rpm)	Load (kW)	Catalyst Temp. (^oC) Inlet	Sample Point	Total Hydrocarbons as Methane				Carbon Monoxide			
				ppm	g/kW-hr	g/hr	g/kg Fuel	ppm	g/kW-hr	g/hr	g/kg Fuel
2300	139	536	Inlet	87.5	0.294	40.8	1.15	80.0	0.430	59.6	1.68
			Outlet	27.5	0.093	1.29	0.380	7.0	0.038	5.27	0.149
2300	103	432	Inlet	69.0	0.303	31.2	1.11	45.0	0.321	33.0	1.18
			Outlet	23.0	0.102	10.5	0.375	6.5	0.047	4.84	0.172
2300	69	333	Inlet	79.0	0.544	37.7	1.66	92.0	1.04	72.5	3.19
			Outlet	30.0	0.208	14.4	0.630	13.5	0.154	10.7	0.471
2300	35	242	Inlet	83.5	1.11	38.7	2.38	171.5	3.80	133.0	8.19
			Outlet	47.5	0.640	22.4	1.40	37.0	0.835	29.3	1.80
2000	132	480	Inlet	57.0	0.204	26.9	0.82	140.0	0.805	106.0	3.26
			Outlet	16.0	0.05	7.73	0.237	18.0	0.106	14.0	0.431
2000	99	348	Inlet	61.5	0.301	29.9	1.22	127.0	1.02	101.0	4.14
			Outlet	21.0	0.104	10.3	0.421	18.0	0.147	14.7	0.594
2000	66	280	Inlet	48.5	0.326	21.6	1.12	28.5	0.318	21.1	1.09
			Outlet	21.0	0.142	9.45	0.488	5.5	0.062	4.11	0.212
2000	33	195	Inlet	41.5	0.573	18.8	1.42	26.0	0.605	19.8	1.50
			Outlet	29.0	0.411	13.5	1.02	11.0	0.263	8.62	0.650
1600	112	447	Inlet	57.5	0.181	20.2	0.808	126.0	0.636	71.2	2.84
			Outlet	17.0	0.054	6.14	0.245	14.0	0.073	8.14	0.325
1600	84	335	Inlet	50.5	0.214	18.0	0.924	92.0	0.640	53.9	2.76
			Outlet	20.5	0.089	7.49	0.383	13.0	0.092	7.78	0.398
1600	56	234	Inlet	59.5	0.384	21.5	1.52	96.0	1.04	57.8	4.10
			Outlet	28.5	0.187	10.5	0.743	15.5	0.170	9.50	0.674
1600	28	148	Inlet	101.0	1.32	37.4	4.18	205.0	4.53	128.0	14.4
			Outlet	96.0	1.29	36.7	4.10	194.0	4.44	126.0	14.1

TABLE 5.4

Engelhard PTX-623D Catalytic Purifier NO_x Gaseous Emissions (F8L 413 F/W)

Speed (rpm)	Load (kW)	Catalyst Temp. (°C)	Sample Point	Nitric Oxide				Nitrogen Dioxide				Total Oxides of Nitrogen ($NO + NO_2$)			
				ppm	g/kW-hr	g/hr	g/kg Fuel	ppm	g/kW-hr	g/hr	g/kg Fuel	ppm	g/kW-hr	g/hr	g/kg Fuel
2300	139	536	Inlet	675	3.88	539	15.2	5	0.05	6	0.2	680	3.93	545	15.4
			Outlet	648	3.76	522	14.8	15	0.14	19	0.5	663	3.90	541	15.3
2300	103	432	Inlet	598	4.57	470	16.7	15	0.17	18	0.7	613	4.74	488	17.4
			Outlet	495	3.84	395	14.1	90	1.07	110	3.9	585	4.91	505	18.0
2300	69	333	Inlet	430	5.23	363	16.0	15	0.28	19	0.8	445	5.51	382	16.8
			Outlet	388	4.75	329	14.5	55	1.03	72	3.1	443	5.78	401	17.6
2300	35	242	Inlet	243	5.76	202	12.4	20	0.73	25	1.6	263	6.49	227	14.0
			Outlet	258	6.23	218	13.4	2	0.09	3	0.2	260	6.32	221	13.6
2000	132	480	Inlet	720	4.44	586	18.0	15	0.14	18	0.5	735	4.58	604	18.5
			Outlet	645	4.08	538	16.5	53	0.51	68	2.1	698	4.59	606	18.6
2000	99	348	Inlet	585	5.05	501	20.4	10	0.14	13	0.6	595	5.19	514	21.0
			Outlet	473	4.13	410	16.7	102	1.37	136	5.5	575	5.50	546	22.2
2000	66	280	Inlet	463	5.53	367	18.9	16	0.29	19	1.1	479	5.82	386	20.0
			Outlet	450	5.43	360	18.6	23	0.41	28	1.4	473	5.84	388	20.0
2000	33	195	Inlet	263	6.54	215	16.2	22	0.86	28	2.1	285	7.40	243	18.3
			Outlet	270	6.91	227	17.1	5	0.19	6	0.5	275	7.10	233	17.6
1600	112	447	Inlet	630	3.41	381	15.2	3	0.02	3	0.1	633	3.43	384	15.3
			Outlet	555	3.09	346	13.8	48	0.41	45	1.8	603	3.50	391	15.6
1600	84	335	Inlet	565	4.21	355	18.1	18	0.20	17	0.9	583	4.41	372	19.0
			Outlet	460	3.50	295	15.1	98	0.14	96	4.9	558	4.64	391	20.0
1600	56	234	Inlet	400	4.62	258	18.3	23	0.39	22	1.6	423	5.01	280	19.9
			Outlet	390	4.58	256	18.2	8	0.13	8	0.5	398	4.71	264	18.7
1600	28	148	Inlet	185	4.38	124	13.9	45	1.64	47	5.2	230	6.02	171	19.1
			Outlet	193	4.72	134	15.0	30	1.12	31	3.5	223	5.84	165	18.5

TABLE 5.5

Engelhard PTX-623D Catalytic Purifier Emission Reductions

F8L 413 F/W

Speed (rpm)	Load (kW)	Catalyst Temp. (°C)	F/A Ratio	Catalyst Back Pressure (cm H_2O)	% Reduction (1)		% Conversion	
					THC as C_1	CO	NO to NO_2	SO_2 to $SO_4^=$
2300	139	536	0.0428	36	69	91	2	61
2300	103	432	0.0350	30	67	86	18	
2300	69	333	0.0267	25	62	85	14	28
2300	35	242	0.0192	20	43	78	1	
2000	132	480	0.0386	35	72	87	8	
2000	99	348	0.0278	27	66	86	21	48
2000	66	280	0.0240	22	57	81	5	
2000	33	195	0.0162	18	43	58	2	6
1600	112	447	0.0395	20	70	89	9	68
1600	84	335	0.0302	15	59	86	21	
1600	56	234	0.0212	11	52	84	2	8
1600	28	148	0.0132	10	5	5	16	

(1) Based on mass emissions

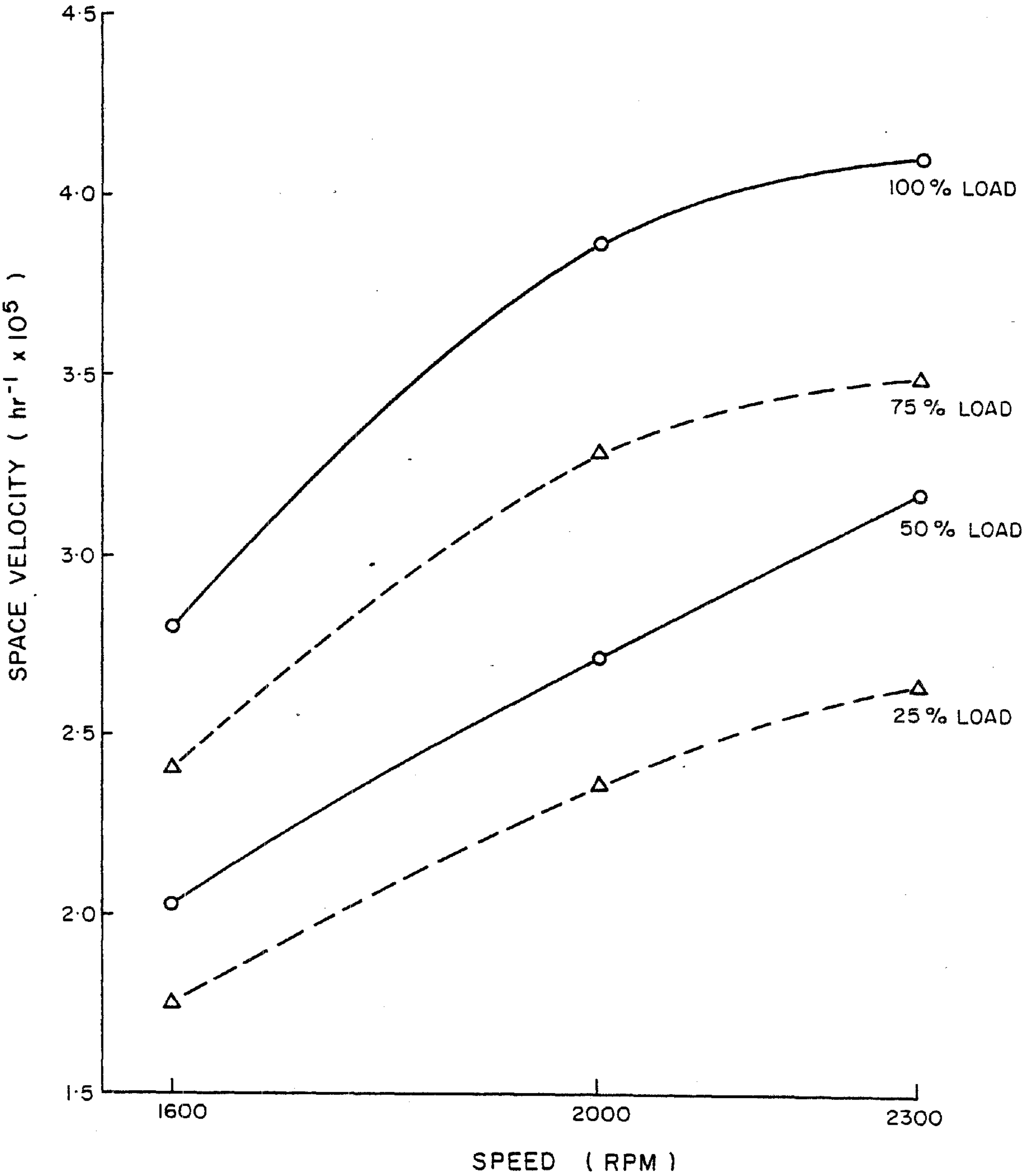


FIGURE 5.1 SPACE VELOCITY vs ENGINE SPEED and LOAD
ENGELHARD PTX-623D CATALYTIC PURIFIER.

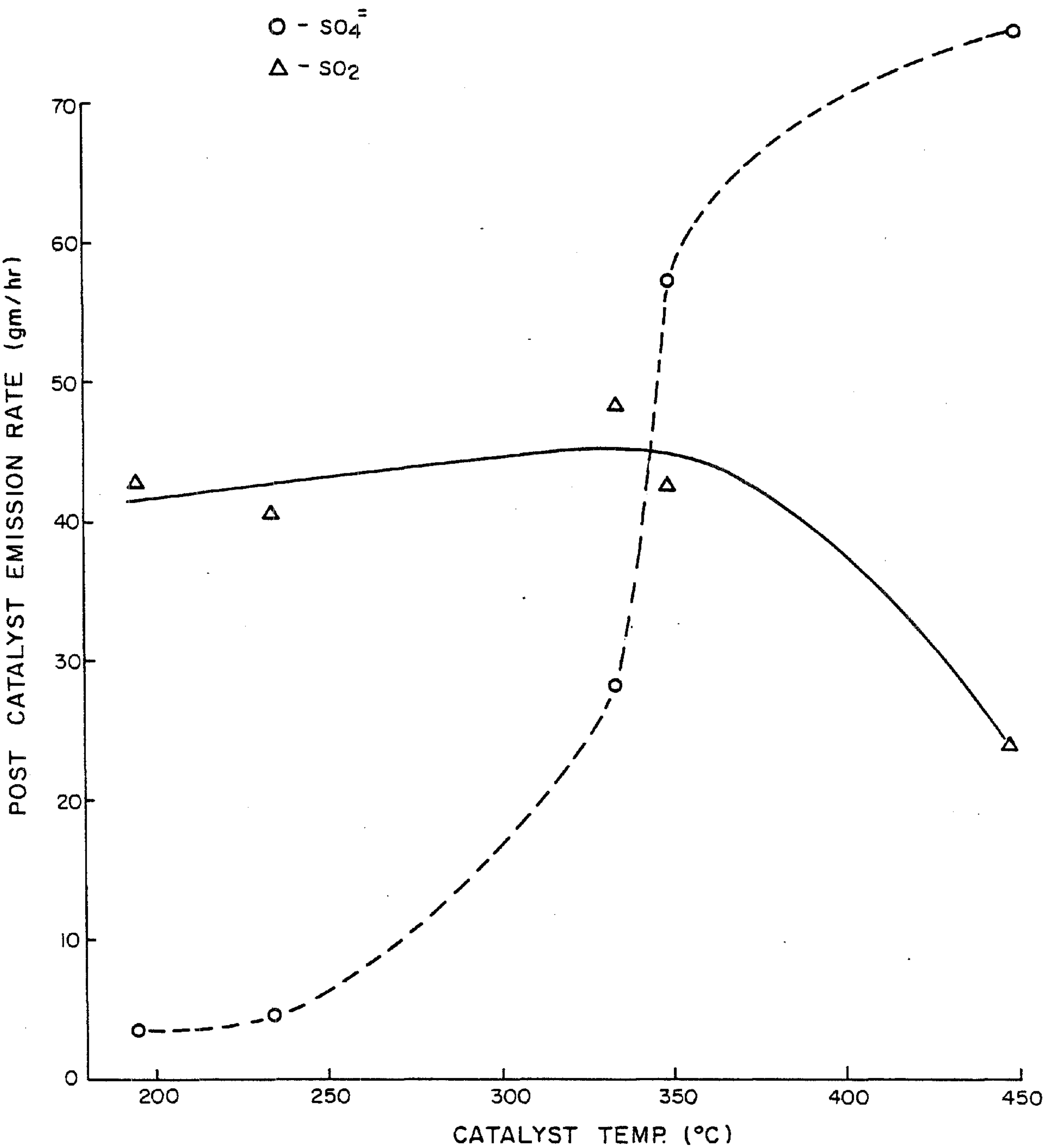


FIGURE 5.2 POST CATALYST SULPHATE & SULPHUR DIOXIDE EMISSION RATE (gm/hr) vs CATALYST TEMPERATURE. ENGELHARD PTX-623D CATALYTIC PURIFIER.

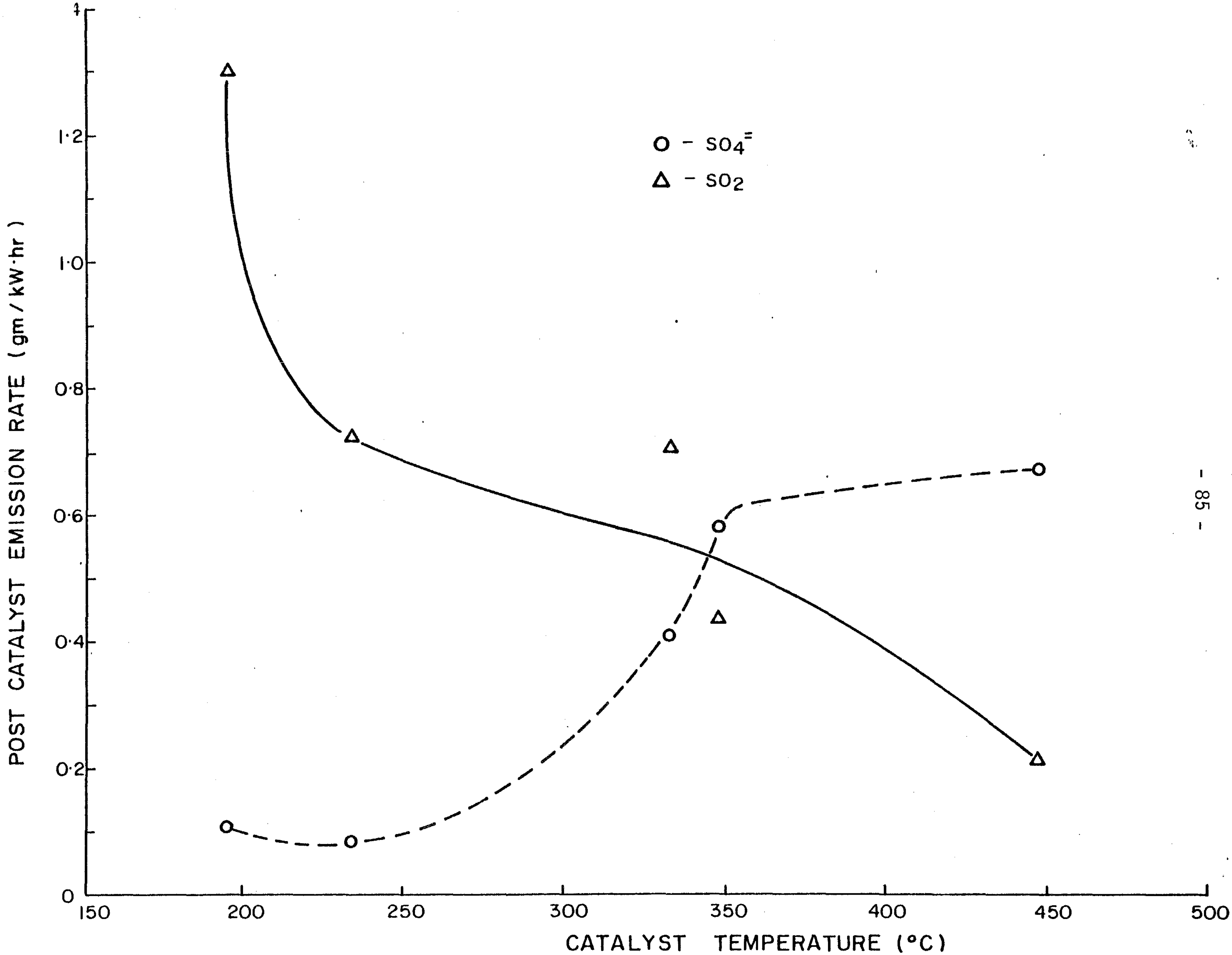


FIGURE 5.3 POST CATALYST SULPHATE & SULPHUR DIOXIDE EMISSION RATE (gm/kW·hr) vs CATALYST TEMP. ENGELHARD PTX-623D CATALYTIC PURIFIER.

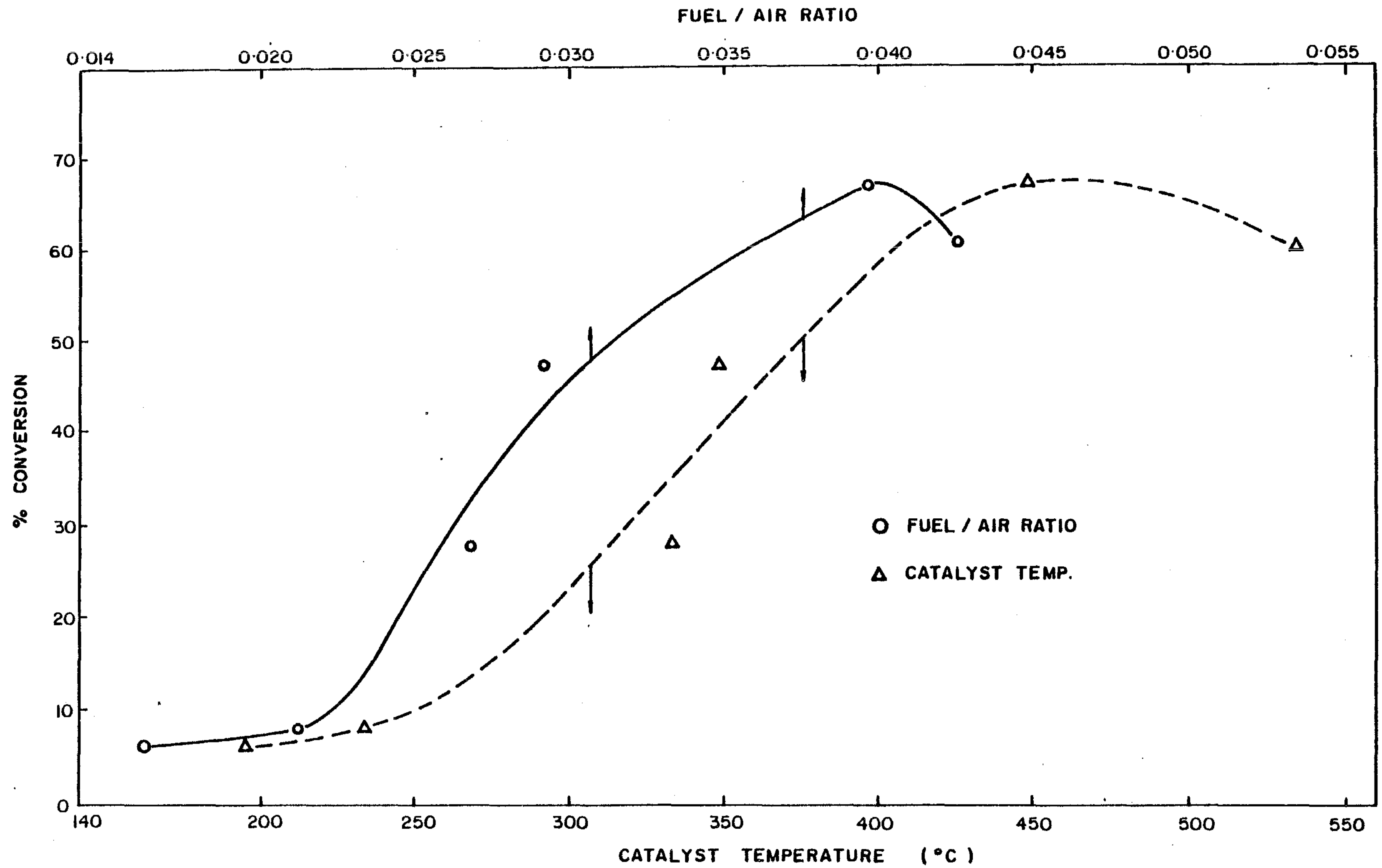


FIGURE 5.4 % CONVERSION SO_2 to $SO_4^{=}$ vs CATALYST TEMP. and FUEL / AIR RATIO ENGELHARD PTX-623D CATALYTIC PURIFIER. DEUTZ F8L 413 F/W

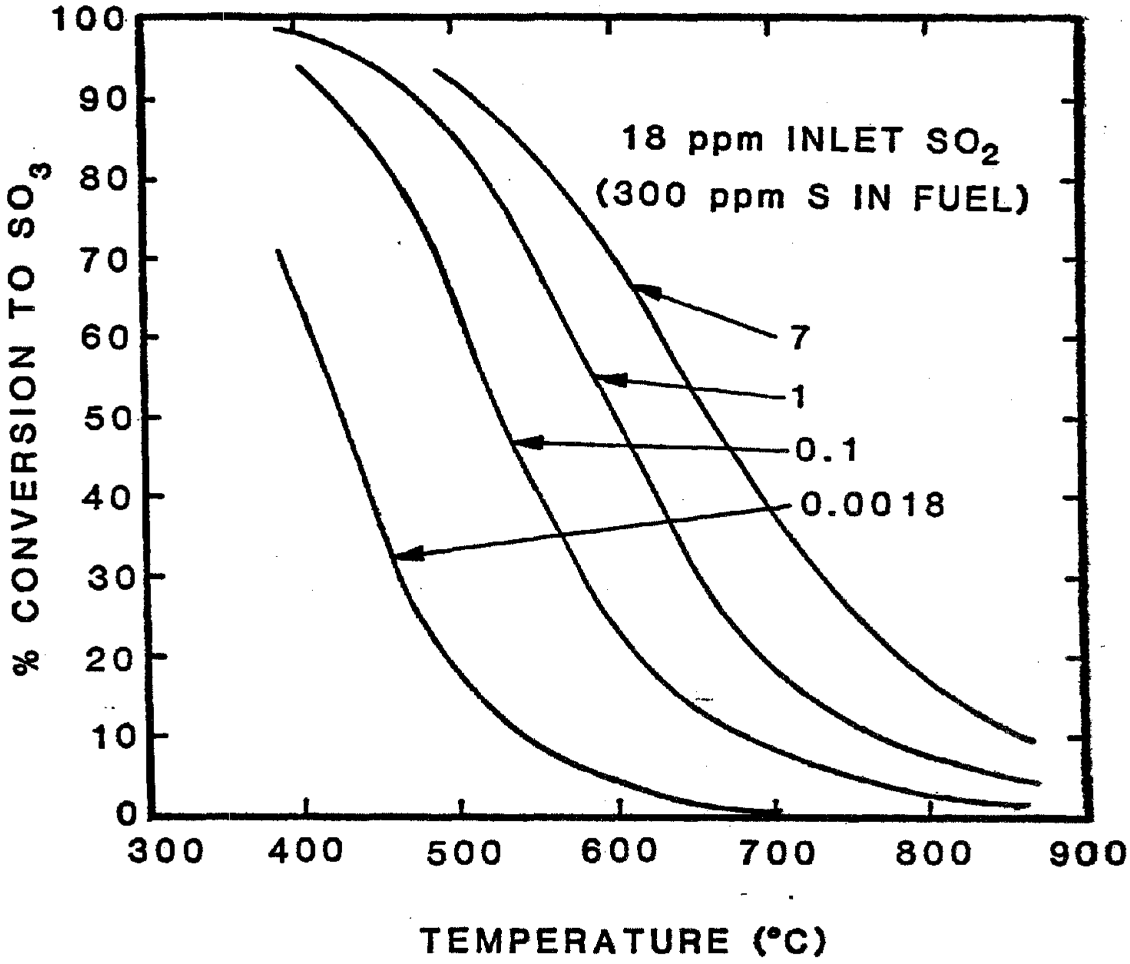


FIGURE 5.5

EQUILIBRIUM CONVERSION OF EIGHTEEN PPM INLET SO_2 TO SO_3 AT 1 ATM. PRESSURE AS A FUNCTION OF CATALYST TEMPERATURE FOR VARIOUS OXYGEN CONCENTRATIONS

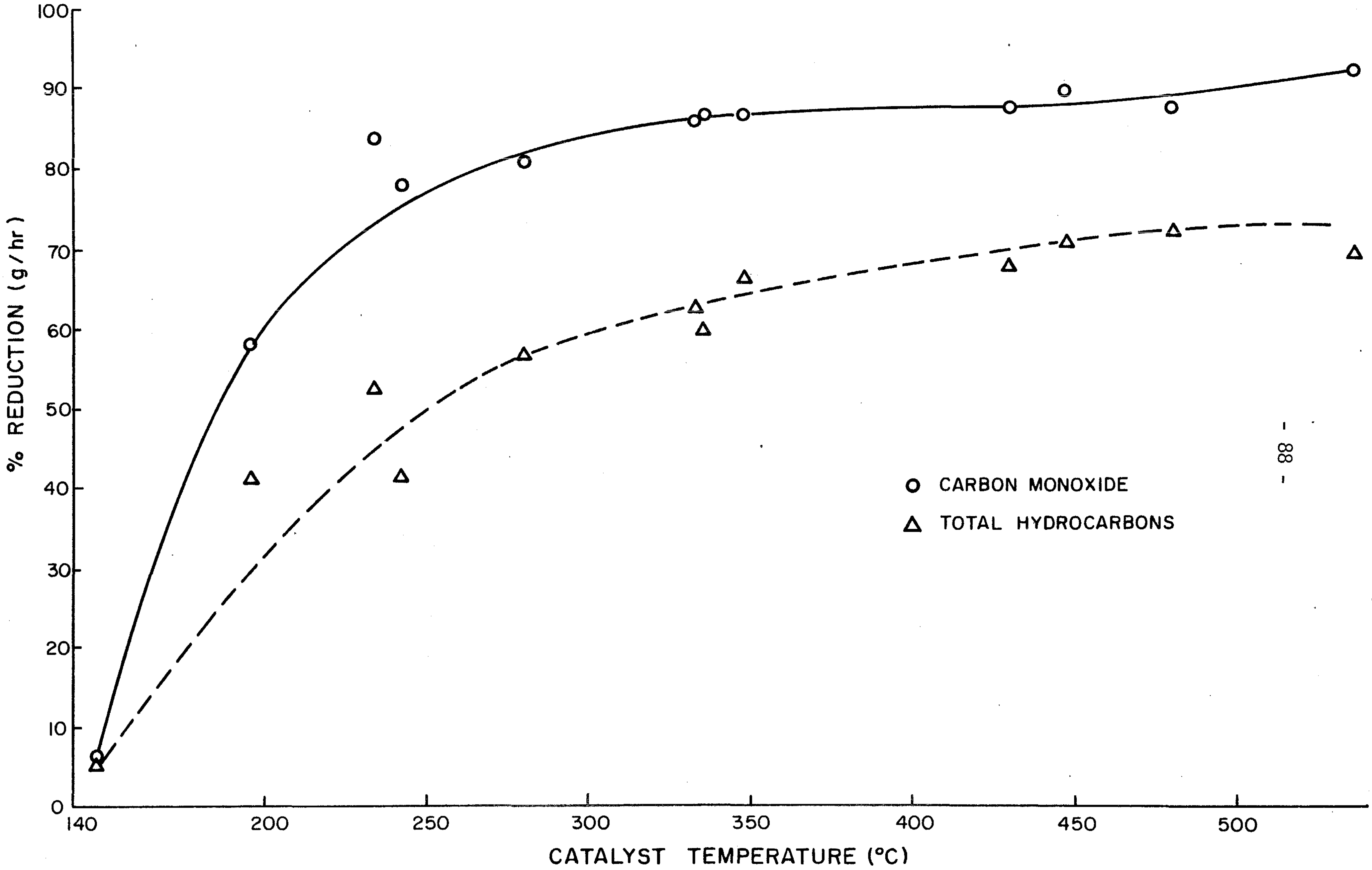


FIGURE 5.6 % REDUCTION vs CATALYST TEMPERATURE of CO and THC
ENGELHARD PTX -623D CATALYTIC PURIFIER.

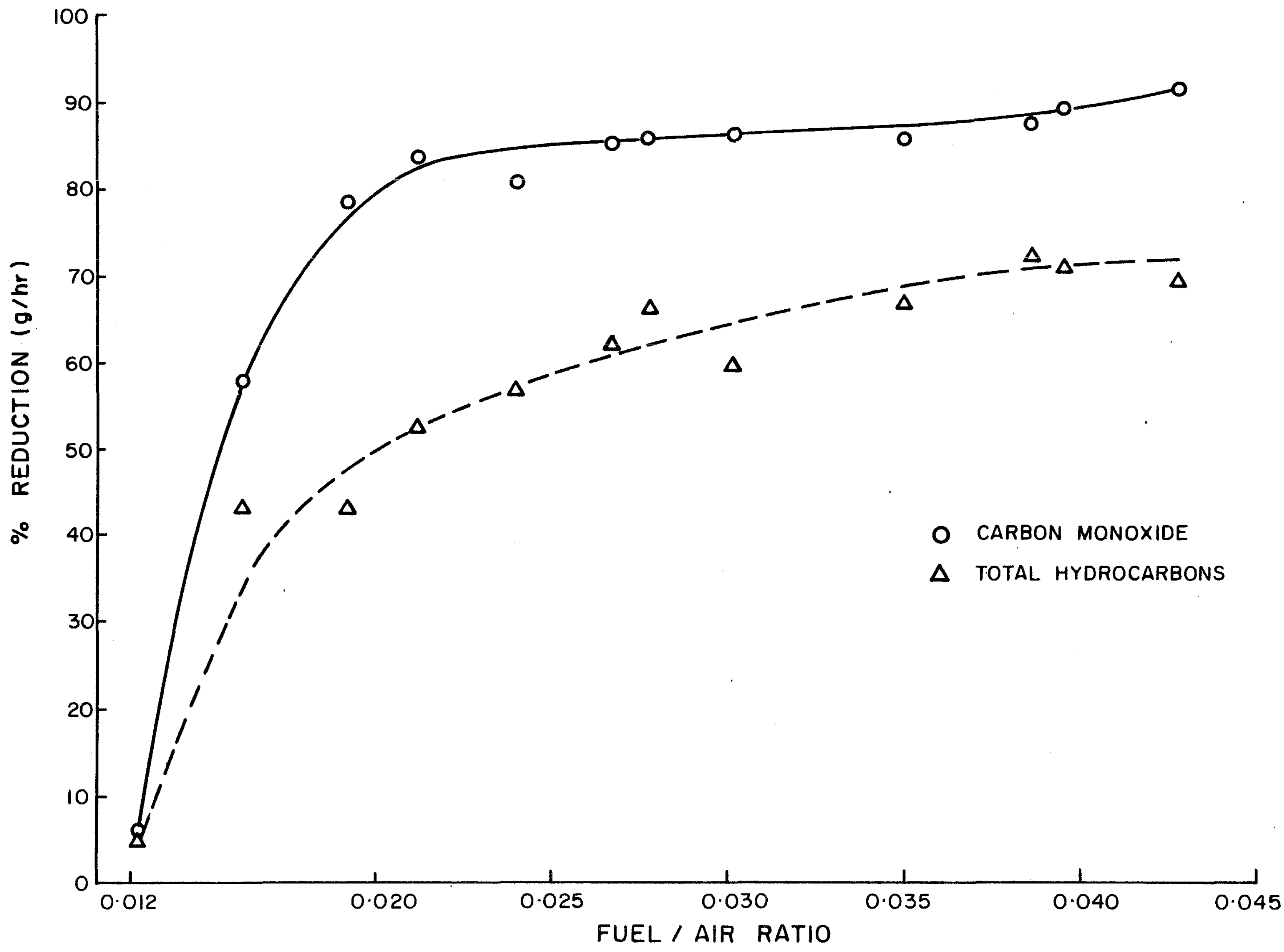


FIGURE 5·7 % REDUCTION vs FUEL / AIR RATIO of CO and THC ENGELHARD PTX-623D CATALYTIC PURIFIER.

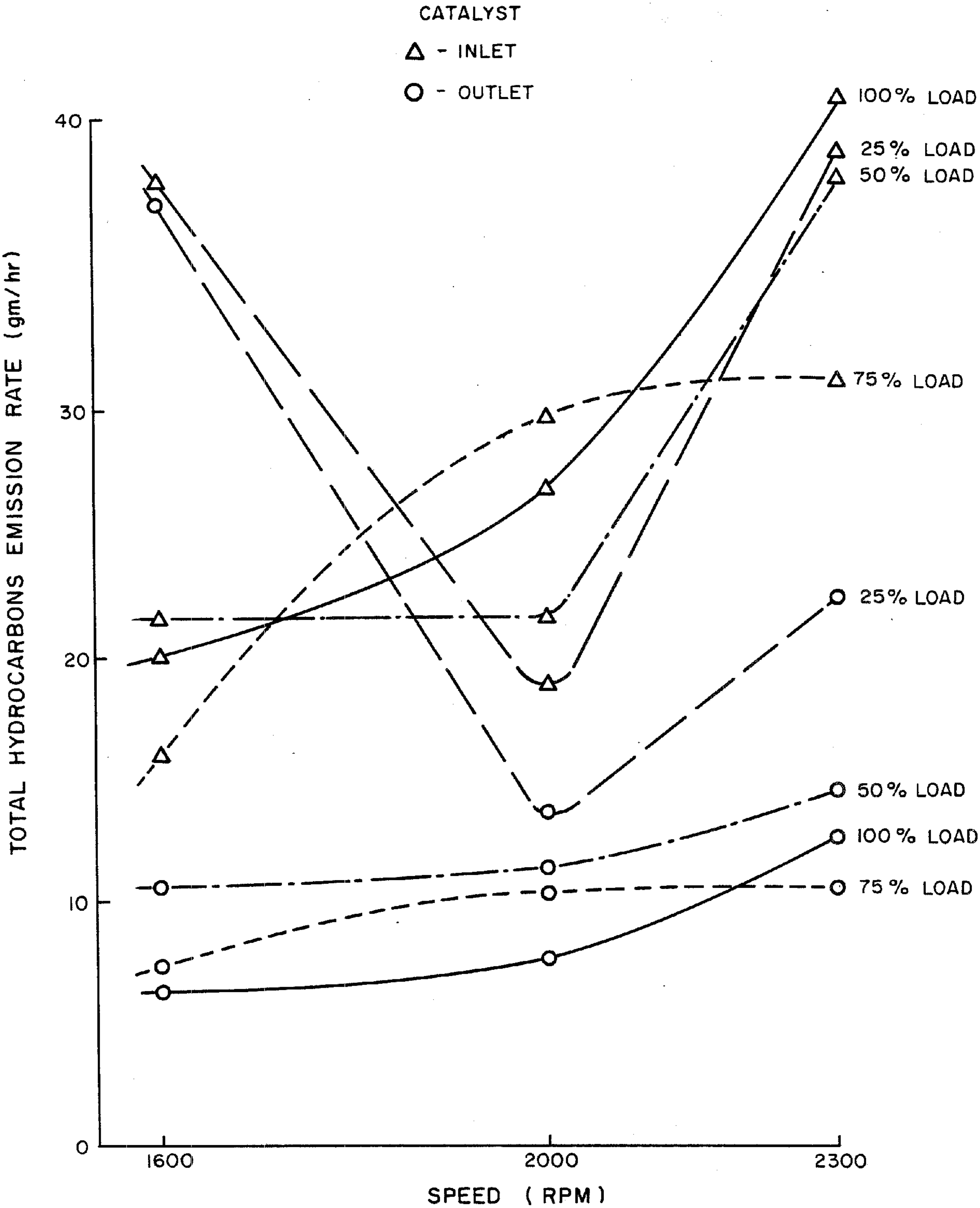


FIGURE 5·8 THC EMISSIONS vs ENGINE SPEED and LOAD (g/hr)
ENGELHARD PTX-623D CATALYTIC PURIFIER.

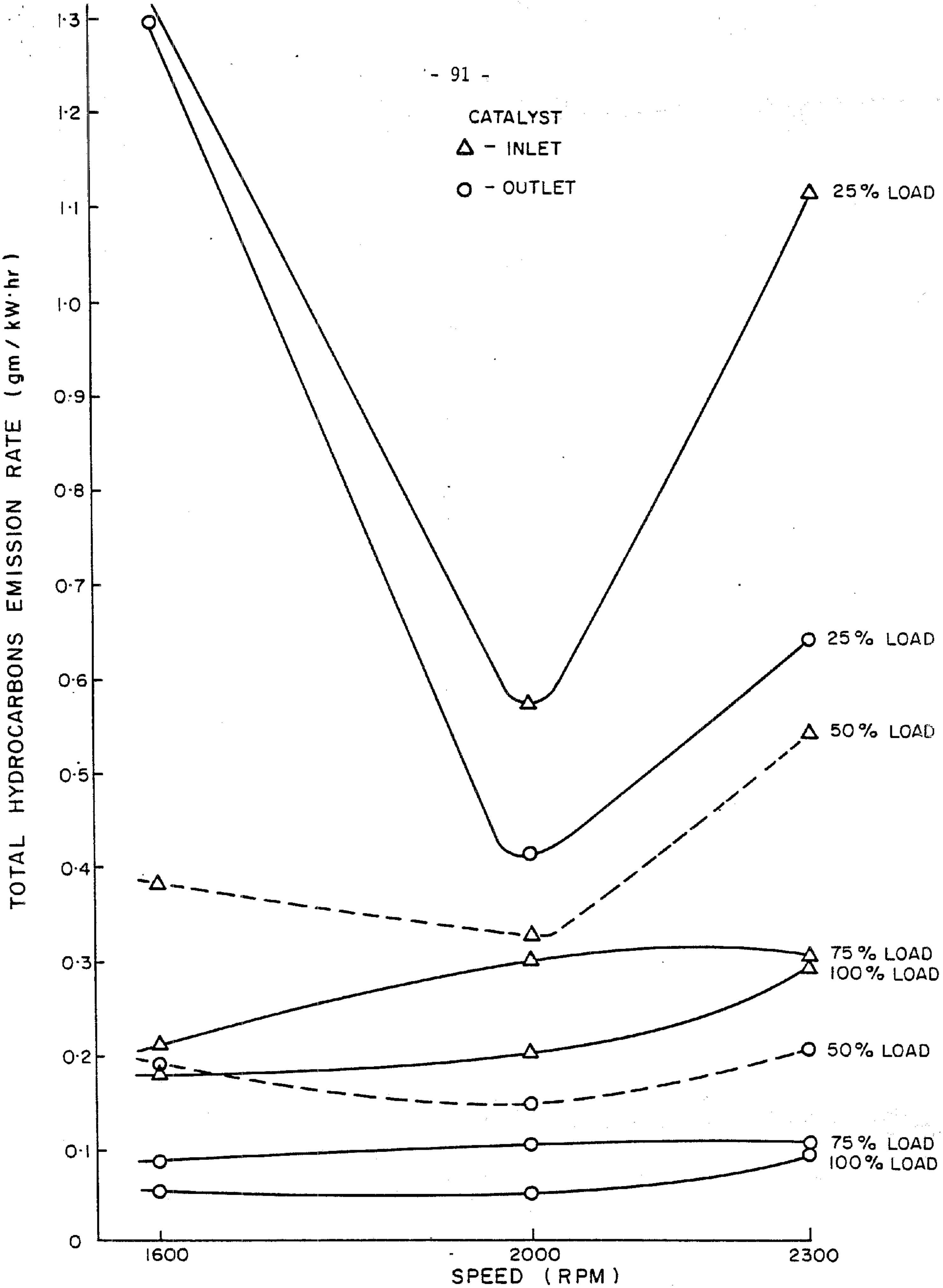


FIGURE 5.9 THC EMISSIONS vs ENGINE SPEED and LOAD ENGELHARD PTX-623D CATALYTIC PURIFIER.

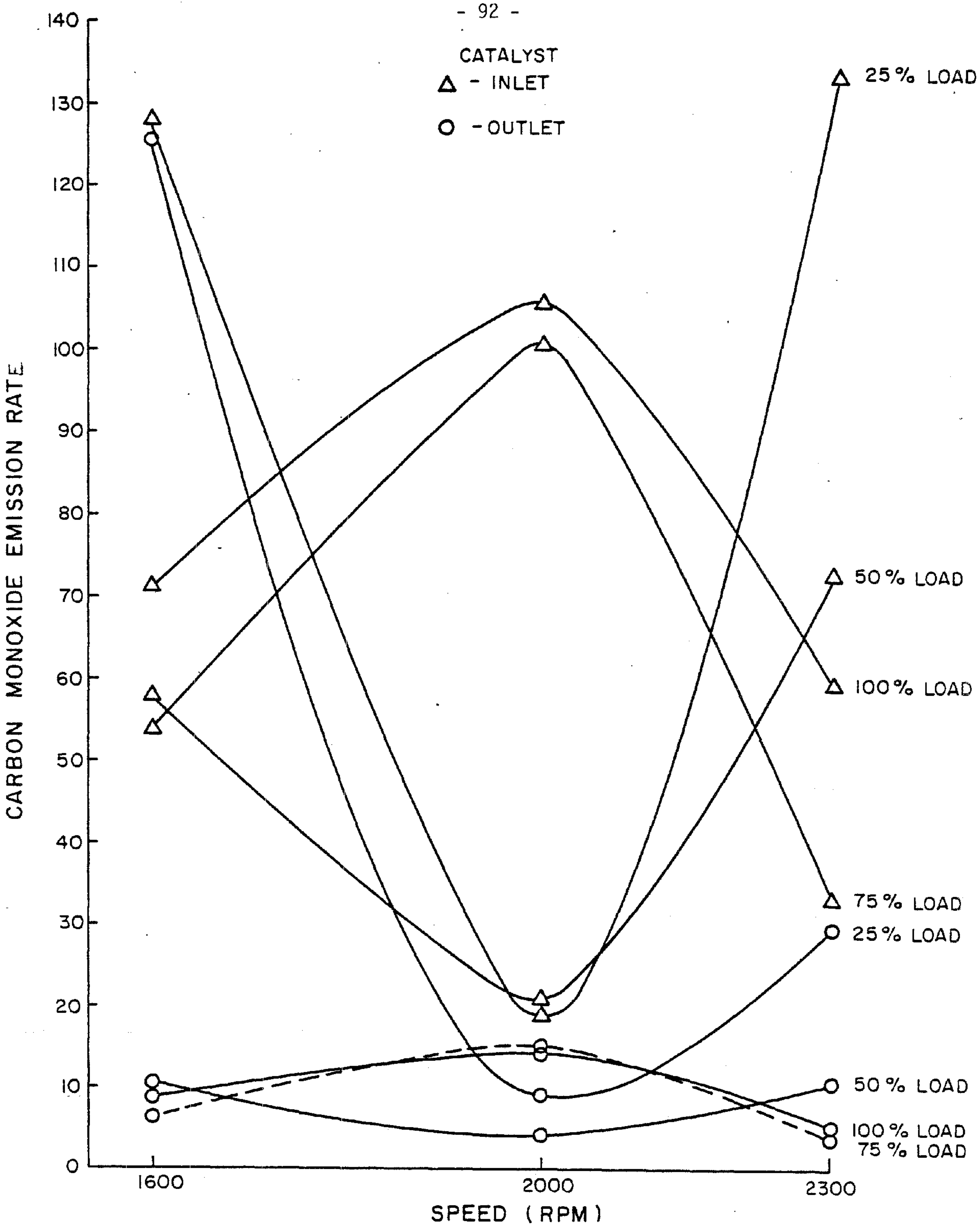


FIGURE 5.10 CO EMISSIONS vs ENGINE SPEED and LOAD
ENGELHARD PTX-623D CATALYTIC PURIFIER.

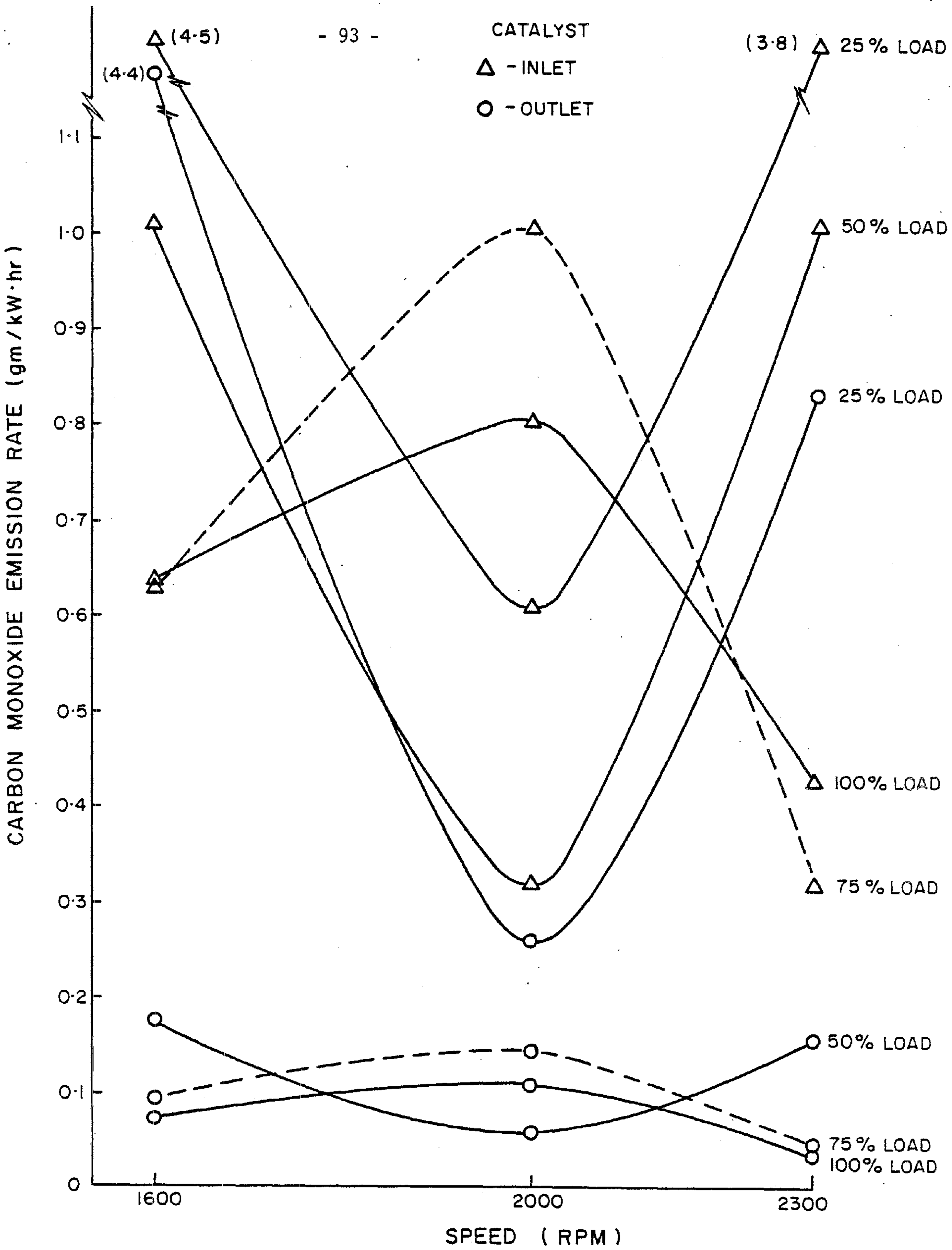


FIGURE 5.11 CO EMISSIONS vs ENGINE SPEED and LOAD
ENGELHARD PTX-623D CATALYTIC PURIFIER.

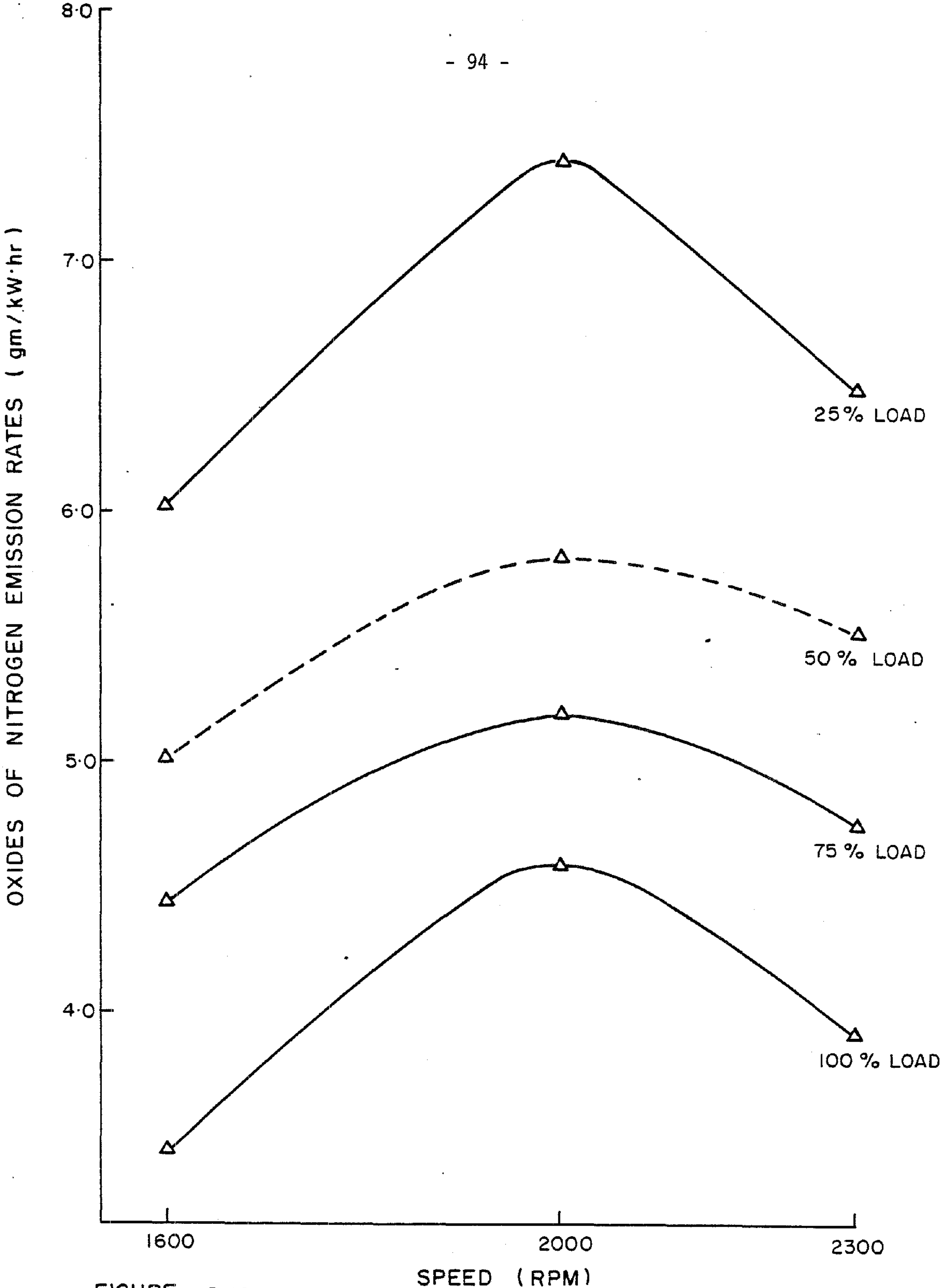


FIGURE 5.12

NO_x EMISSIONS (gm / kW·hr) vs ENGINE SPEED and LOAD
ENGELHARD PTX - 623D CATALYTIC PURIFIER (INLET)

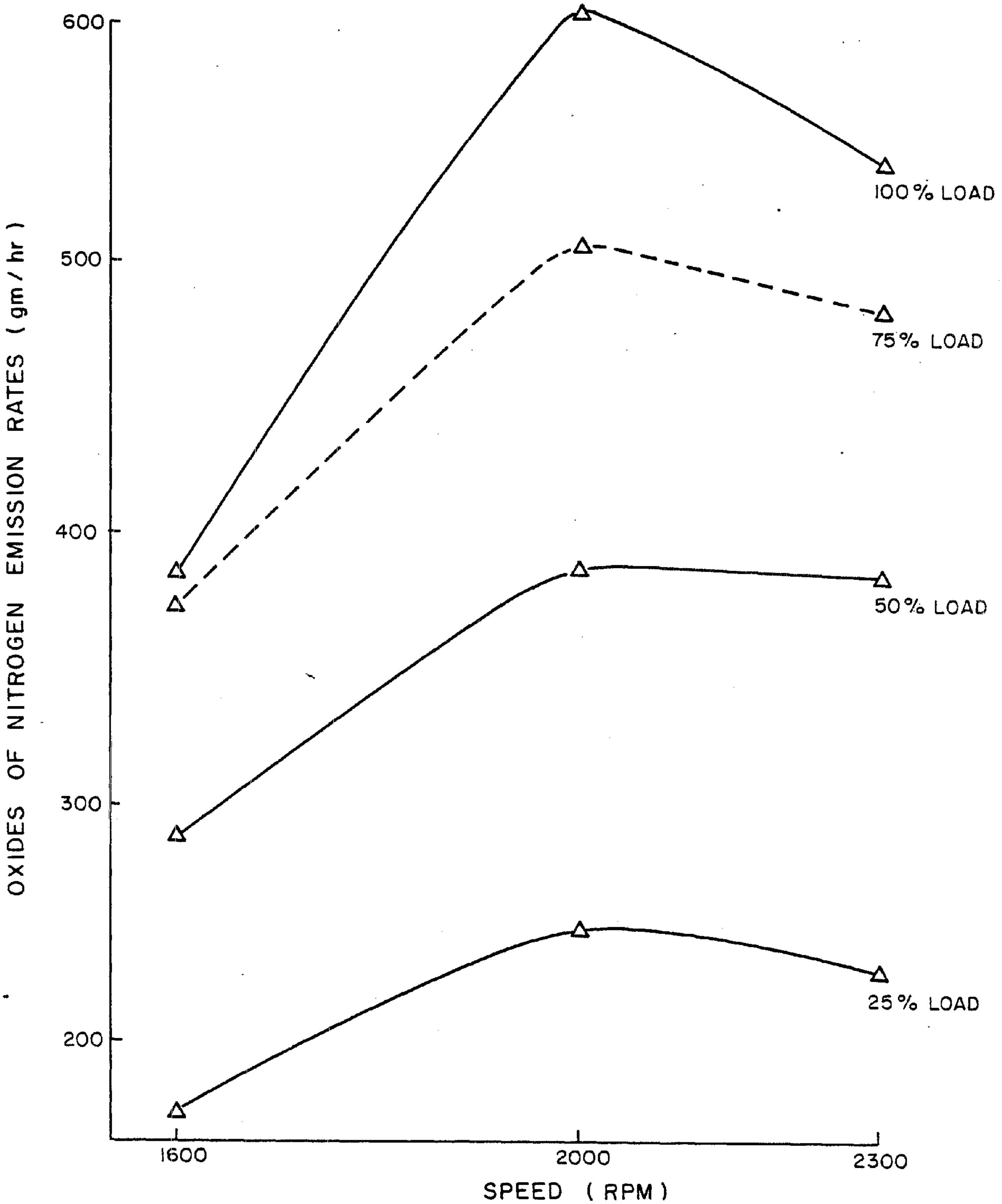


FIGURE 5.13

NOx EMISSIONS (gm / hr) vs ENGINE SPEED and LOAD
ENGELHARD PTX-623D CATALYTIC PURIFIER (INLET)

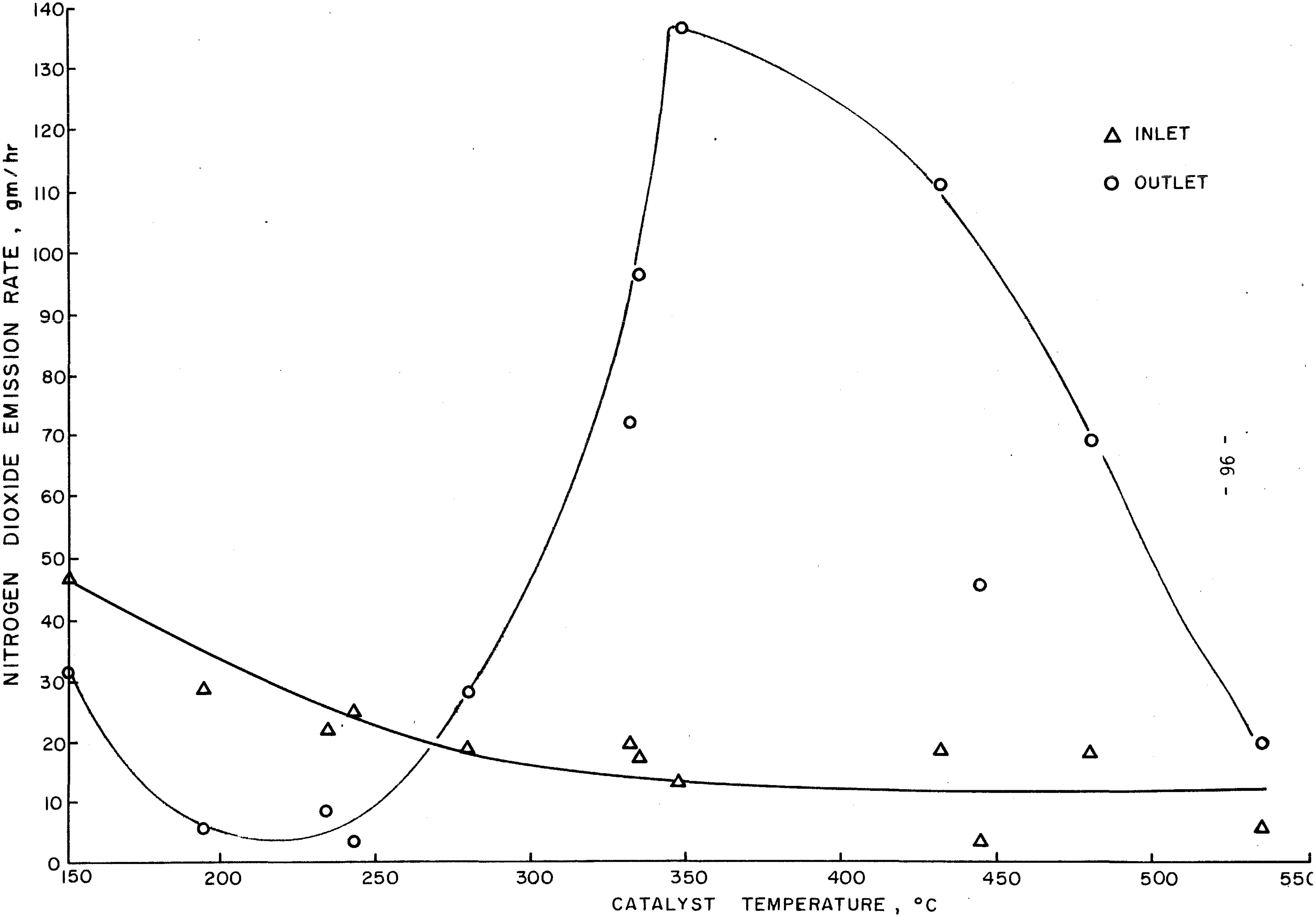


FIGURE 5·14 NO_2 EMISSIONS vs CATALYST TEMPERATURE (2 / hr)

6. WATER SCRUBBER AND WATER SCRUBBER SYSTEMS

6.1 Scope

Water scrubbers are used presently on some underground vehicles, principally as flame proofing devices. An evaluation was therefore made of the effect of such devices on exhaust emission characteristics. Two water scrubbers were tested:

- Domino combined catalyst/water scrubber system;
- Gaspe Mines water scrubber.

Both scrubbers were tested on an F6L 714 engine only. Since the Domino device was supplied as a combined catalyst/water scrubber system, tests of the Gaspe Mines scrubber were also conducted in a systems approach, employing catalytic and EGR techniques together with the water scrubber.

6.2 Domino Catalyst/Water Scrubber System

A diagram of the cross section of the Domino scrubber is shown in Figure 6.1. It comprises a monolithic catalyst located close to the exhaust manifold together with a multipass water scrubber through which the exhaust must pass before emission to the atmosphere. Figure 6.2 shows a photograph of the test set-up. Testing was carried out at two engine load speed conditions:

- 1850 rpm and 78 kW (3/4 load)
- 1625 rpm and 70 kW (3/4 load)

1850 rpm was the highest speed which could be achieved while maintaining an acceptable water level in the scrubber. Higher speeds blew most of the water out of the scrubber.

The scrubber was mounted on the left bank of the exhaust only, and an equivalent back pressure applied to the right bank by installation of a butterfly valve immediately downstream of its exhaust manifold. Emission testing was carried out with a water make-up delivery system installed to replace continuously lost water, through evaporation. Test results are therefore reported with the water maintained in the scrubber at an optimum level.

Table 6.1 shows the scrubber operating parameters of back pressure, inlet and outlet exhaust temperature, scrubber water temperature, inlet and outlet exhaust moisture content, and scrubber water evaporation rates, measured at the two load/speeds tested. Back pressures and water evaporarion rates are similar to those measured during operation of a Gaspé Copper Mines water scrubber tested in an earlier ORF study(8). However, the Domino water box contains only 23 litres of water in steady state operation at 1853 rpm, 3/4 load, in contrast to the Gaspé scrubber which had an operational capacity of 90 litres at 2200 rpm, full load, full exhaust treatment. Thus the outlet exhaust temperatures were higher with the Domino than the Gaspé being typically 180°C with the Domino, and 70°C with the Gaspe. As a result of the scrubber water capacity of the Domino scrubber, it would be evaporated to dryness in less than one hour at 1625 rpm, 70 kW load using the exhaust from one engine bank.

Gaseous emissions from the left bank of the exhaust, equipped with the Domino scrubber, are compared with the uncontrolled right bank exhaust in Table 6.2. CO and THC emissions are very effectively reduced by the catalyst. NO emissions are, however, reduced only at the expense of an increase in NO_2 emissions.

Particulate emission data are shown in Tables 6.3 and 6.4. Table 6.3 shows the particulate emissions from the left bank of the Deutz exhaust, with and without the Domino scrubber installed. Total particulate is increased with the Domino installed, in part due to the increased back pressure created by the device, and in part due to sulphate production by the catalyst. A breakdown of the particulate matter is shown in Table 6.3 for insoluble matter, and a combination of the soluble organic fraction with sulphuric acid. It is clear that the Domino is doing little for the removal of particulate matter from the Deutz exhaust.

The reason the comparison was made in Table 6.3 of the uncontrolled and controlled left exhaust bank was due to the finding (see Table 3.4) that the particulate emissions were different from the right and left banks of the engine. This made it unsatisfactory to compare the Domino equipped left bank with the uncontrolled right bank exhaust using simultaneous sampling, as had originally been intended. This makes it clear, that it is generally unsatisfactory to try to determine the control efficiency of a device when it can be used to treat only half of the exhaust flow. Table 6.4 shows the effect of increased back pressure on the right bank exhaust particulate emissions. Total particulate emissions are increased about 10% with 50 - 60 cm H_2O increase in back pressure. This explains, in part, the increased particulate emissions observed when the Domino exhaust at 60 - 80 cm H_2O back pressure are compared with the normal uncontrolled exhaust at a back pressure of 13 - 17 cm H_2O.

It is to be concluded that the present design of the Domino scrubber allows catalytic control of CO and THC emissions, and acts as an exhaust cooler and flame trap, but acts adversely in terms of increase in total particulate emissions (due to back pressure effects and sulphate production), and in terms of increased NO_2 emissions.

6.3 Gaspé Water Scrubber Systems

Because the Domino scrubber was undersized and difficult to test, it was decided to continue testing of water scrubber systems using a water scrubber which had been obtained from Gaspé Copper Mines, and was sized to accommodate the exhaust from both banks of the F6L 714 engine. Figure 6.3 shows a layout of the scrubber which is a simple single pass unit, while Figure 6.4 shows a photograph of the installation on the test bed. Tests were carried out with a combination of the PTX catalyst and

Gaspe scrubber, and further scrubber systems were examined by combining EGR with the catalyst/scrubber device.

Table 6.5 shows the difference in gaseous emissions measured upstream of the scrubber (but downstream of the catalyst)and downstream of the scrubber. CO and THC emissions are low as a result of catalytic oxidation, and the effect of the scrubber is therefore difficult to assess. However, it is apparent that about 5 to 20% of the NO was converted to NO_2 by the scrubber, possibly as a result of increased residence time of the gas in the scrubber exhaust system.

The effect of EGR on the catalyst/scrubber system is shown in Table 6.6. All measurements were taken at the outlet from the catalyst scrubber while 0, 10.8 and 21.6% EGR was applied to the system. 21.6% EGR decreases the NO emission rate by 64% to 75%, and 10.8% EGR decreases it by 39 to 50% at the four engine conditions tested. NO_2 formation in this system is seen to be a complex phenomenum, but clearly, the EGR reduces the amount of NO_2 produced by the catalyst/scrubber combination. CO and THC emissions are not greatly increased when EGR is applied to the catalyst/scrubber system, which suggests that the catalyst is capable of controlling the increased CO, THC emissions produced by EGR (see Section 4).

The effect of the EGR/catalyst/scrubber system on particulate emissions is shown in Table 6.7.

Without EGR application, the scrubber reduces the particulate emissions by only 25-30%. At both high load conditions of 2200 rpm/93 kW and 1625 rpm/70 kW, application of 21.6% EGR created very large increases in particulate emissions (mostly insoluble matter), and the scrubber did little to reduce these unacceptably high emission rates. Application of 21.6% EGR at the lower fuel/air ratio conditions of 2200 rpm, 71 kW produced a more acceptable solution, since EGR increased particulates by only 30% which the scrubber was able to control. Similarly, 10.8% EGR at the higher load conditions again produced more acceptable emissions almost back to the baseline condition of an uncontrolled engine.

6.4 Conclusions

Water scrubber technology will at best reduce particulate emissions by about 30%, and have little effect on gaseous emissions other than SO_2 which can be removed with 90% efficiency. The back pressure created by the scrubber also tends to increase baseline particulate emissions, and water consumption rates are high enough to create considerable maintenance problems in order to ensure that the scrubbers contain sufficient water at all times.

In combination with a catalyst, however, there was a sound improvement in particulate collection efficiency, and when used in combination with small quantities of exhaust gas recirculation, the scrubber was able to control the increased levels of particulate emissions to values no greater than the uncontrolled baseline engine emissions. This demonstrates the value of using combined devices for diesel emissions control, and much more powerful approaches will be demonstrated later in this report through the combination of more effective devices.

TABLE 6.1

Control Device Parameters

Domino Combined Water Scrubber/Catalyst

Speed (rpm)	Load (kW)	Torque (Nm)	Description	Back Pressure cm of H_2O	Domino Inlet Temp. °C	Domino Outlet Temp. °C	Scrubber Water Temp. °C	Domino Inlet Moisture %	Domino Outlet Moisture %	Water Evaporation Rate kg/hr
1850	78	407	- continuous water feed to scrubber, and, catalyst-manifold cooling, asbestos gasket.	80	515	180-200	75-76	9	25	30
1625	70	407		63	505	165-185	74-76	9	22	30
1625	70	407	- none of the above, dropping scrubber water level, rubber gaskets.	68	510	280-330	79-84	9	23	30

TABLE 6.2 - A Comparison of the Uncontrolled and Domino Scrubber Controlled Gaseous Emissions from a Deutz F6L 714 Diesel Engine

Speed rpm	Load kW	Torque Nm	Domino Scrubber Installed	Engine Bank - Back Pressure cm of H_2O	Concentrations and Emission Rates									
					NO		NO_2		THC			CO		
					ppm	g/hr	ppm	g/hr	ppm	g/hr	% Reduc.	ppm	g/hr	% Reduc.
			No	R - 40	500	260	>1	>1	25	8		92	45	
1850	78	407	Yes	L - 80	450	234	50	40	5	2	75	18	9	80
1625	70	407	No	R - 63	415	185	15	10	18	5		108	45	
			Yes	L - 63	360	161	70	48	2	1	80	14	6	87

TABLE 6.3

A Comparison of the Uncontrolled and Domino Scrubber Controlled Emissions From the Left Bank of a Deutz F6L 714 Diesel Engine

Speed rpm	Load kW	Torque Nm	Domino Scrubber Installed	Engine Bank Back Pressure Cm of H_2O	Particle Emission Rates: Total Particulate mg/m^3	Total Particulate g/hr	Insoluble Matter mg/m^3	Insoluble Matter g/hr	Insoluble Matter % of Total	$SOF + H_2SO_4$ mg/m^3	$SOF + H_2SO_4$ g/hr	$SOF + H_2SO_4$ % of Total
1850	78	407	No	L - 17	49.53	20.58	48.17	20.02	97	1.37	0.57	3
			No	L - 17	53.42	22.20	47.72	19.83	89	5.68	2.36	11
			Yes	L - 80	82.33	34.21	41.55	17.27	50	39.76	16.93	50
			Yes	L - 80	49.21	20.45	29.27	12.16	60	19.94	8.29	40
			No	L - 13	50.22	17.96	46.47	16.61	93	3.75	1.34	7
			No	L - 13	48.37	17.27	45.03	16.10	93	3.35	1.20	7
1625	70	407	Yes	L - 63	80.84	28.90	68.06	24.33	84	12.78	4.57	16
			Yes	L - 63	75.46	26.98	52.66	18.83	70	22.80	8.15	78

TABLE 6.4

A Comparison of the Particulate Emissions from the Right Bank of the Deutz F6L 714 Diesel Engine at Normal and High Back Pressures

Speed rpm	Load kW	Torque Nm	Engine Bank Back Pressure cm of H_2O	Total Particulate			Particulate Emission Rates: Insoluble Matter			Particulate Emission Rates: Condensible Organic		
				mg/m^3	g/hr	% Increase	mg/m^3	g/hr	% of Total	mg/m^3	g/hr	% of Total
1850	78	407	R - 17	45.06	18.72		40.95	17.02	91	4.11	7.71	9
			R - 80	48.44	20.12		41.87	17.40	86	6.57	2.73	14
			R - 80	53.54	22.25	13	40.82	16.96	76	12.72	5.29	24
1625	70	407	R - 13	66.76	23.87		56.51	20.20	85	10.25	3.66	15
			R - 13	72.20	25.81		57.87	20.69	80	14.33	5.12	20
			R - 63	75.28	26.91		68.07	24.34	90	7.21	2.58	10
			R - 63	74.72	26.71		66.13	23.64	89	8.59	3.07	11
			R - 68	76.93	27.50	10	73.75	26.37	96	3.18	1.14	4
			R - 68	79.28	28.34		73.10	26.14	92	6.17	2.21	8

TABLE 6.5

The Effect of the Gaspé Scrubber on the PTX Catalyst Controlled Gaseous Emission of a Deutz F6L 714 Diesel Engine

Speed rpm	Load kW	Torque N.m	Location	Concentratons and Emission Rates (PTX Catalyst Controlled)							
				NO		NO_2		THC		CO	
				ppm	g/hr	ppm	g/hr	ppm	g/hr	ppm	g/hr
2200	93	407	Inlet	450	259	<1	<1	3	1.0	14	7.5
			Outlet	410	235	20	17	6	2.4	10	5.4
1625	10	407	Inlet	420	185	<1	<1	<1	<0.5	8	3.3
			Outlet	380	165	60	41	<1	<0.5	8	3.3
2200	71	305	Outlet	480	287	80	73	12	4.7	20	11.2
1500	48	305	Outlet	330	144	90	60	8	2.2	6	2.4

TABLE 6.6

The Effect of EGR on the Gaseous Emissions of a Deutz F6L 714 Diesel Engine

Controlled by the PTX Catalyst/Gaspé Scrubber Combination

Speed rpm	Load kW	Torque N.m	EGR %	Concentrations and Emission Rates (PTX Catalyst Controlled)								
				NO			NO_2		THC		CO	
				ppm	g/hr	% Reduc.	ppm	g/hr	ppm	g/hr	ppm	g/hr
2200	93	407	0	460	264.0		< 1	< 1	8	3.2	6	3.2
			11.0	260	132.0	50	20	16	8	2.9	18	5.4
			21.8	150	67.3	75	< 1	< 1	25	8.0	52	21.9
1625	70	407	0	400	177.0		30	20	4	1.2	10	4.1
			10.9	245	96.5	45	10	6.1	6	1.6	10	3.7
			21.7	145	50.2	72	< 1	< 1	20	4.7	16	5.2
2200	71	305	0	480	287.0		80	73	12	4.7	20	11.2
			10.7	330	176.0	38	50	41	16	5.7	18	9.0
			21.4	220	103.0	64	20	15	20	6.4	22	9.6
1500	48	305	0	330	144.0		90	60	8	2.2	6	2.4
			10.7	210	81.8	43	50	30	4	1.0	6	2.2
			21.3	150	51.5	64	30	16	10	2.2	6	1.9

TABLE 6.7

The Efficiency of the Gaspé Scrubber on the PTX Catalyst Controlled Particulate Emissions with Various Percentages of EGR, Deutz F6L 714 Diesel Engine

Speed rpm	Load kW	Torque N.m	EGR %	Location	Average Particulate Concentrations and Emission Rates						
					Total Particulate			Insoluble Matter		Condensible Organic	
					mg/m^3	g/hr	% Reduc.	mg/m^3	g/hr	mg/m^3	g/hr
2200	93	407	0	Inlet	72.1	33.3		52.5	24.2	7.4	3.4
				Outlet	54.9	25.2	25	37.0	17.0	4.3	2.9
			21.6	Inlet	461.4	164.4		431.2	186.6	7.3	3.0
				Outlet	339.2	122.4	26	315.9	113.9	5.4	2.0
1625	70	407	0	Inlet	118.6	42.0		86.0	30.4	16.6	5.9
				Outlet	82.1	29.0	31	58.6	20.7	6.2	2.2
			10.8	Inlet	198.7	63.7		178.4	56.3	5.9	1.8
				Outlet	153.0	48.3	24	129.6	40.9	6.3	2.0
			21.6	Inlet	459.5	127.5		431.4	119.7	10.3	2.9
				Outlet	358.4	99.4	22	326.5	90.6	8.3	2.3
2200	71	305	0	Inlet	42.3	20.2		26.1	12.5	6.8	3.3
				Outlet	32.4	15.5	23	18.7	8.9	5.2	2.5
			21.6	Inlet	71.9	26.9		53.0	19.9	8.4	3.2
				Outlet	53.7	20.3	25	36.7	13.8	6.8	2.5

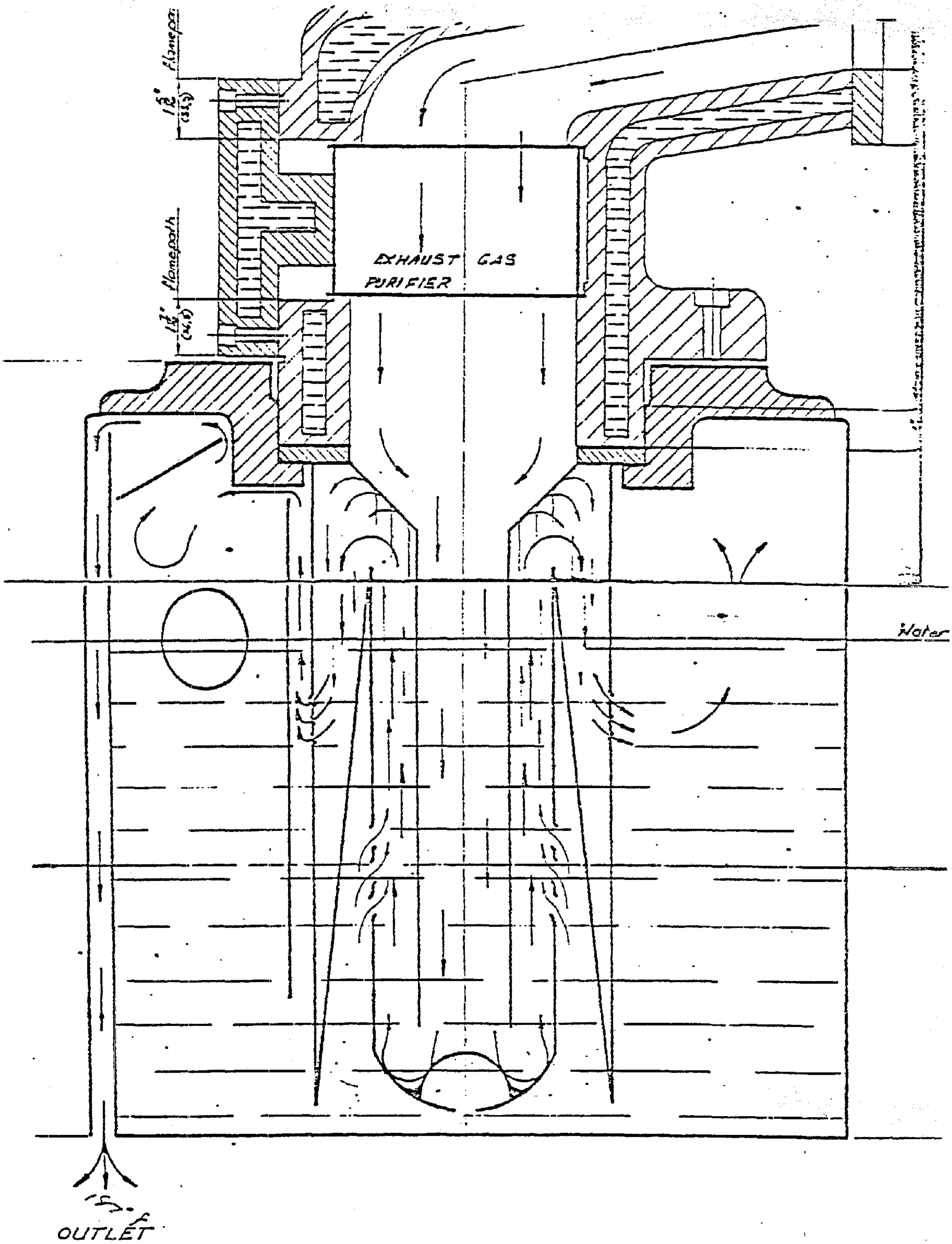
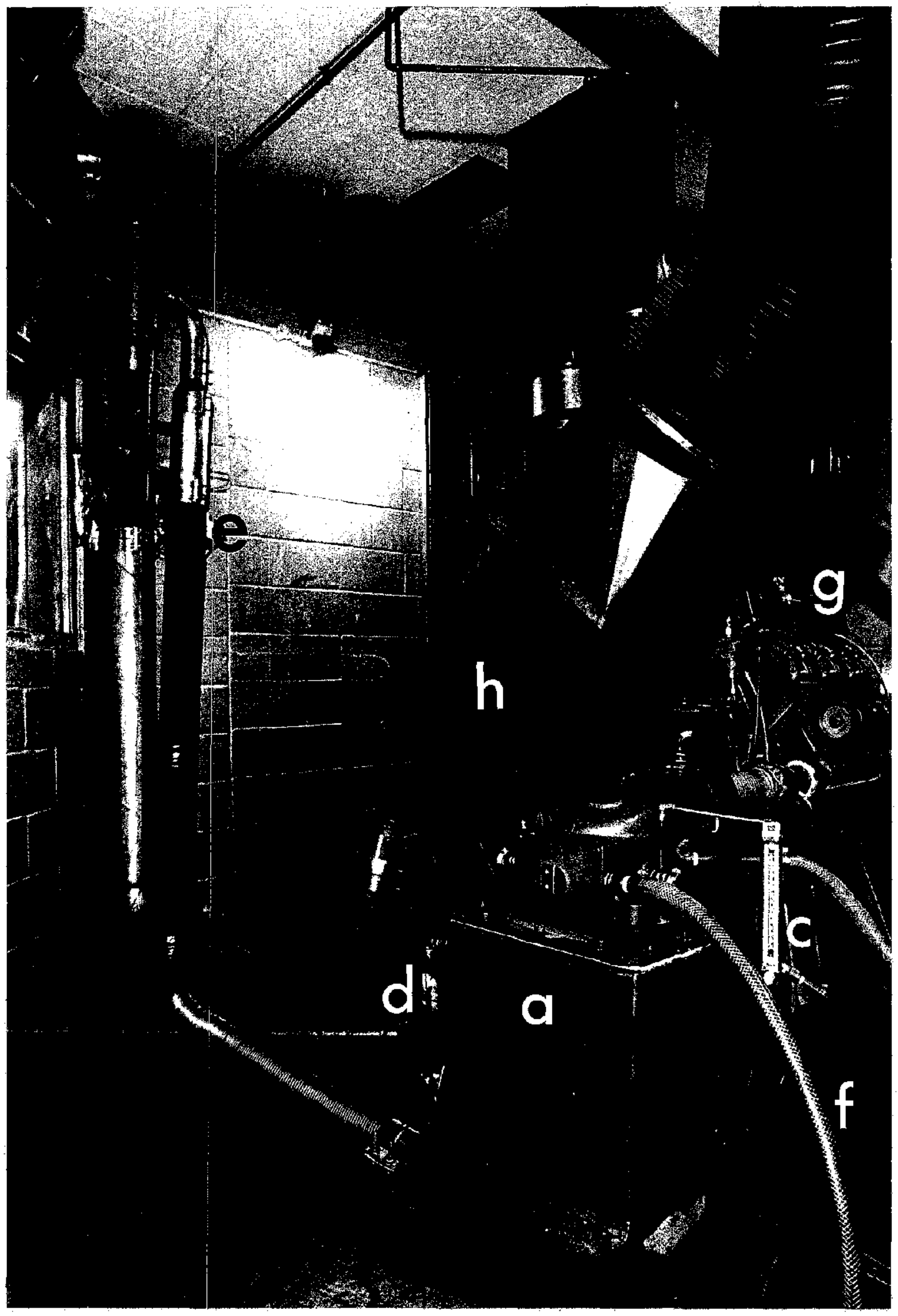


FIGURE 6.1 Domino Catalyst Scrubber

FLOW.



a - Domino Scrubber
b - Butterfly Valve
c - Make-up Water Delivery System
d - Water Level Sight Glass
e - Particulate Sampling Ports (through wall)
f - Manifold Cooling Water Drain
g - Fuel Emulsification Control Panel
h - Engine Cooling Air Supply

FIGURE 6.2: Domino Scrubber Test Set-Up.

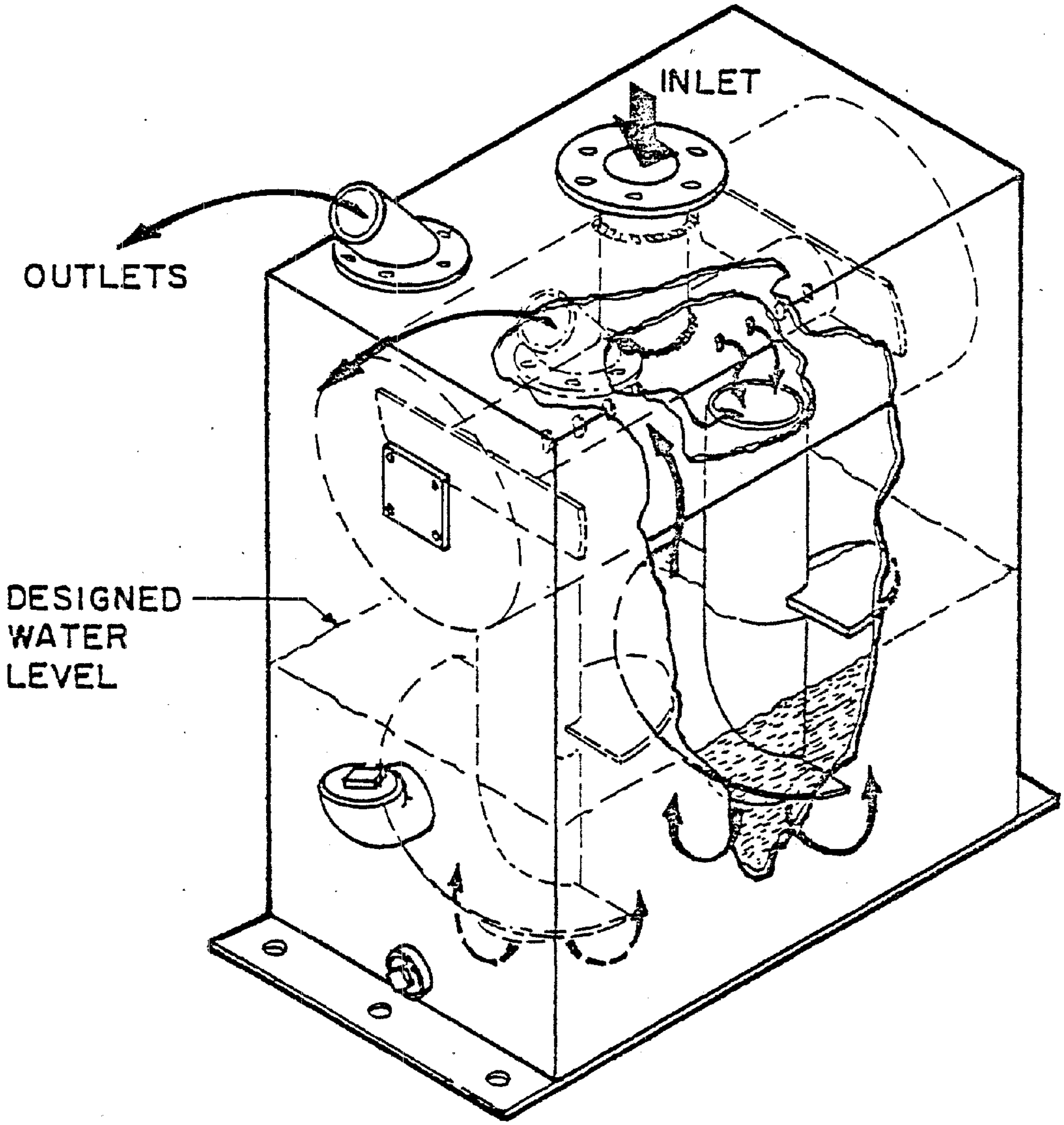
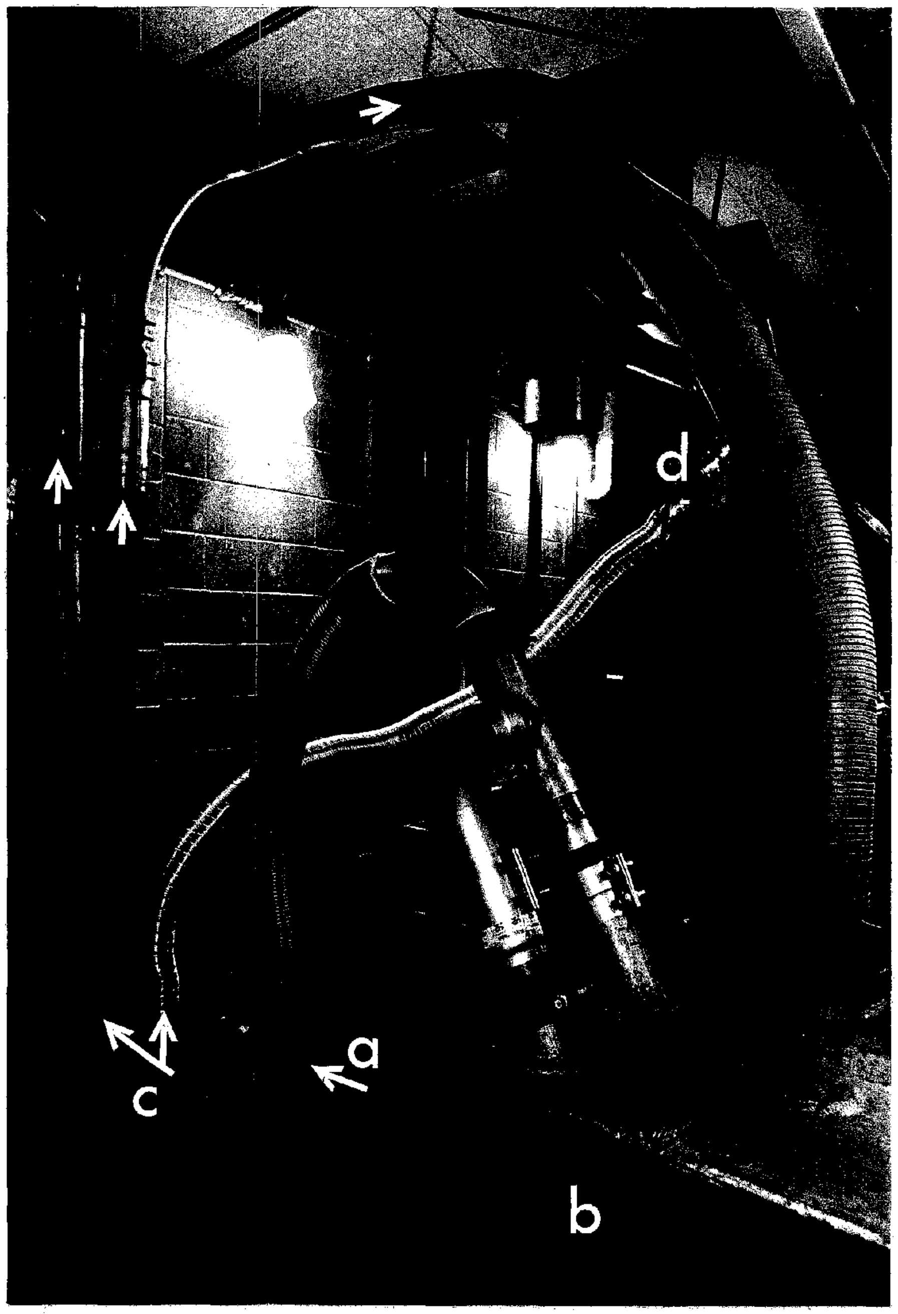


FIGURE 6.3 Gaspé Copper Mines - Scrubber



a - PTX Catalyst
b - Gaspé Scrubber
c - EGR Take-Off Point
d - EGR Control Valve

FIGURE 6.4: Gaspé Scrubber/EGR Test Set-Up.

7. FILTERS AND TRAP OXIDIZERS

7.1 USBM Mesh Filter

7.1.1 Cooled Filter

Basic studies of the filtration of sub-micron particlate from gas streams carried out at the University of Waterloo, Canada, resulted in the development of a number of filter media which were considered suitable candidates for the filtration of diesel exhaust particulate. The basic studies were developed further at the U.S. Bureau of Mines (USBM) Bruceton Research facility, and a full scale filter was constructed suitable for testing in a mine diesel engine. After preliminary tests had been carried out at Bruceton[22], the USBM filter was shipped to the Ontario Research Foundation (ORF) for testing under the current program. The filter was initially tested on the Deutz F6L-714 engine, using exhaust which had been cooled by water injection upstream of the filter.

Installation of the filter in the exhaust system of the Deutz engine is shown in Figures 7.1 and 7.2. Figure 7.1 shows the general layout relative to the engine, with sampling ports located at the inlet and outlet from the filter at points close to the vertical white arrows indicating direction of flow.

The filter material used for the tests was Mister Mesh Type X102, a fibreglass material knitted in a stainless steel mesh for support. Each filter bale, as received from ACS Industries in Rhode Island, measured 38 cm square by 81 cm long. The number of single filter sheets varied from one bale to another (160-170). The first configuration employed in testing made it necessary to cut the bale in half and place one half behind the other. The filter was compressed and inserted into a cage to prevent movement of the sheets. Dimensions of the bale were then 38 cm square by 50 cm long, with the bale positioned in the holder so that exhaust gas flow was perpendicular to the filter sheets. The bulk density of the bale was 185 kg/m^3.

Figure 7.2 shows a close-up of the filter, indicating the point at which a water atomizing spray was used to cool the exhaust gas. Because the exhaust gas temperature varied with load/speed condition employed, there was some variation in water flow rate, added to the exhaust, in order to cool the exhaust gas entering the filter to approximately the same temperature of 75^{o}C. In general, a slight excess of water was employed over that required to produce maximum decrease in exhaust gas temperature by evaporation, that is, the gas entering the filter was saturated with water vapour at 75^{o}C, and contained condensed water. The water flow rate required to achieve the condition was about 2.2 kg/min. A drain, located at the lowest point of the filter allowed the water collected in the filter to be removed.

A critical aspect of filter operation on diesel exhaust, relates to the ease and effectiveness of cleaning the filter when it becomes loaded with particulate matter to the extent that the pressure drop across the filter becomes unacceptable. The procedure developed to clean the filter was as follows. The filter bundle was removed from the container and immersed in the solvent Diverfos 207 for about 15 minutes. It was then removed, and hosed down with water for about 30 minutes. It was then replaced in its container in the exhaust system, and evaluation of its effectiveness for particulate matter continued.

Data showing the effectiveness of the filter in reducing particulate matter is shown in Table 7.1 and Figure 7.3. Figure 7.3 shows a histogram plot of the insoluble particulate matter removal from the water cooled exhaust over operating periods of up to 12 hours.

Excellent collection efficiencies of 75% to 85% are evident, with the filter efficiency improving as it loads up. After 12 hours of operation, the filter was cleaned as described earlier, and the cleaned filter efficiency is shown, at time zero, to remain satisfactory at 66%.

Table 7.1 shows details of the test series. Three load/speeds were employed during the tests at elapsed times, from commencement of the test, indicated in the table. Initial pressure drop across the filter was found to be only 16 cm H_2O, increasing to 20 cm H_2O after 12 hours of operation. This pressure drop is still within acceptable limits for operation of the Deutz engine. Manufacturer's specifications allow for 100 cm H_2O backpressure. After cleaning the filter, the pressure drop reverted to a value, a little lower than that of the clean filter, and the efficiency of removal followed a similar trend. A plot of the variation in removal efficiency with pressure drop across the filter, as it loads up with particulate, is shown in Figure 7.4 for a load/speed condition of 1625 rpm, 70 kW. Good correlation is evident.

7.1.2 Uncooled Filter

As part of the optimization of size and configuration for the USBM filter, the same size of filter with the same bale configuration was installed on the exhaust system of the Deutz F8L-413 engine. Being a larger engine than the F6L-714 tested previously, and having a higher exhaust flow rate, some impact on the size of the filter was expected. In effect, since this filter size worked well on the smaller 714 engine, using the same filter on the 413 engine would show whether downsizing of the filter was possible while still remaining effective. In addition, since the use of cooling water in the earlier experiments, was considered a complication feature for future practice, it was decided to investigate the feasibility of operating the filter in a dry, uncooled, condition. Stability of the material was therefore investigated using thermal analysis.

The glass fibre material was separated from the wire mesh and cut into shorter lengths of about 3 mm. A sample (3.4 mg) was heated at 20°C/min to 760°C in air flowing at 15 ml/min, and examined by differential thermal analysis. An exothermic reaction occurred from 200-400°C with a major peak at 304-315°C and two smaller ones at 231°C and 354°C. No melting endotherm was observed at 760°C, and visual inspection of the sample after cooling, showed that the filter material had not fused. The sample was also examined by thermogravimetry, and observed to lose 0.74% of its weight from ambient to 200°C, with an additional weight loss of 2.4% from 260-700°C for a total eight loss of 3.1%. The major weight loss was in the temperature region where the exothermic reaction was observed. Reheating to 700°C caused only a very small weight loss of 0.3%. Based on the results it appears that the Mister Mesh material should be capable of withstanding diesel exhaust temperatures without cooling.

Table 7.2 shows the results of testing this filter on the 413 engine at full load/speed condition. The spread of the data is greater than normally observed, particularly with respect to the SOF, and is indicative of the mechanical problems which were experienced with this engine, which resulted in abnormally high oil consumption. The uncooled filter showed insoluble particulate collection efficiencies ranging from 50% on a cleaned filter to 80% on a loaded filter, that is, not greatly different from the cooled filter. Total particulate collection efficiency was lower due to the impact of the SOF and ranged from 50% on a cleaned filter to 70% on a loaded filter with an average of 62%. Figure 7.5 shows plots of the collection efficiency and pressure drop across the filter with operating time. The engine was stopped and restarted once during the test series. The pressure drops across the filter using the larger 413 engine were considerably greater than that observed with the 714 engine. After 5 hours operation, the pressure drop reached 80 cm H_2O compared with only 30 cm H_2O on the 714 engine. After 10 hours operating, the pressure drop reached the maximum permissible backpressure for the engine. Figure 7.6 shows a profile of the particulate loading on the filter as measured by pressure taps located at different distances from the inlet bale face. The profile shows a reasonably uniform distribution, with no evidence of caking or plugging on the face of the filter.

A further observation of the performance of this filter was the finding of glass fibre particles on the particulate collection filters. Photomicrographs of samples were prepared and analyzed using a digitiser to measure the fibre lengths. Details of the analysis are contained in Appendix III. Thirty three percent of the fibres measured less than 0.3 mm and 77% less than 0.7 mm. The lowest detection limit of this method, using the digitiser, is 0.1 mm, assuming all fibres to be greater than 0.1 mm, it was calculated that the filter concentration was 240 fibres/m^3 gas. Further examination with different methodology revealed fibres ranging from 2 - 20 micron diameter and 40 - 1000 microns in length. These fibres are not respirable, but are considered a nuisance dust.

In the present bale configuration, a larger filter would be required for the 413 engine. However, further optimization was considered possible through changes in bale configuration which might allow the present filter size to be maintained. Accordingly, a new configuration was devised, where a new ACS filter bale was placed in the filter holder such that the layers of material were vertical in the holder, and parallel to the exhaust flow. This has been designated as a parallel flow configuration. The bulk density was also lowered to about 130 kg/m^3. Tests with this configuration showed that more acceptable engine backpressures were created during engine operating and, further, the filter bale was easier to clean after loading up with particulate. Table 7.3 shows that at full load/speed condition, engine backpressure increased from 60 - 80 cm H_2O in 12 hours which is a significant gain in bale life over the previous configuration, and higher filter bulk density. (A catalyst was installed during the collection of these data, which added about 15 cm H_2O backpressure to that of the filter alone). It was clear that, even with a catalyst present, the present parallel flow configuration, 130 kg/m^3 bulk density, would allow the filter to operate for 24 hours at full load/speed condition before reaching the maximum permissible 100 cm H_2O backpressure limit. Table 7.4 shows particulate collection efficiencies of this filter configuration over a range of load/speed conditions. Disregarding the first test as a spurious result, the total particulate collection efficiency ranged from 34-67% with insoluble particulate removal ranging from 48-66%. Comparison of the relative efficiencies of the 185 kg/m^3 and 130 kg/m^3 filter bales, at full load/speed condition can be made as follows:

Configuration	Bulk Density	Average Insoluble Collection Efficiency	Average Total Particulate Collection Efficiency
Perpendicular Flow	185 kg/m^3	71%	62%
Parallel Flow	130 kg/m^3	48%	45%

Degradation of efficiency is significant, and there is clearly a trade-off between collection efficiency and load-up time.

It was considered that shorter load-up times than that observed with the 130 kg/m^3 filter would be practical. Therefore in the next step towards optimization, the bulk density was increased to 150 kg/m^3 while maintaining the parallel flow configuration. Table 7.5 shows the variation of insoluble particulate collection efficiency with pressure drop across the filter at full load/speed condition. High collection efficiencies are evident, and it was estimated that

30 hours of operation would be possible before the engine backpressure reached the maximum permissible level of 100 cm H_2O. Table 7.6 shows a similar set of data for total particulate matter. Correlation of the data is not so good due to possible bleed-off from the filter of soluble organic material. A plot of the ΔP/efficiency characteristics for both the insoluble and total particulate is provided in Figure 7.7.

7.1.3 Conclusions on USBM Filter

Table 7.7 summarizes the bale endurance under different conditions of configuration and density. For the 413 engine, it is clear that the 150 kg/m^3 density, parallel flow filter represents the best design of the USBM filter. This design allows operation with good efficiency for periods of about 30 hours between cleaning. The filter can be operated dry in order to reduce the complexity of operation, and cleaning of the filter is facilitated by the parallel flow sheets allowing it to be opened up easily for cleaning. Some concern remains, however, for long term durability, as fraying of the material was observed during cleaning, and fibreglass emissions were found during operation.

7.2 Corning Filter

During the course of this project, it became apparent that technological advances were being made in the development of particulate trap oxidizers for light duty diesel vehicles. One example of this technology is the development of a trap oxidizer, or filter, by Corning Products Division of Corning Glass Works. It was possible to incorporate testing of these filters through the co-operation of Corning Products Division who supplied filter units suitable for testing on the Deutz F8L 413 engine. The two ceramic filter units supplied by Corning were installed in metal containers by Walker Manufacturing. The filter elements are 28.6 cm diameter by 30.5 cm in length, and are sealed within each container to prevent leakage. The sealant also serves to reduce vibration of the element within the container.

Figure 7.8 shows a photograph of a typical Corning filter element together with a schematic of the porous wall filtering effect. Details of the design and mode of filtering the exhaust are described by Howitt and Montierth of Corning Products Division[22]. Figure 7.9 shows a photograph of both units installed on the Deutz engine test bed, and Figure 7.10 provides a close up view of one of the units with a scale showing the size of the units.

The exhaust system of the Deutz engine was modified to accommodate the Corning units. Each of the two units was located 36 cm from the exhaust manifold flange. This arrangement prevents simultaneous testing of the upstream and downstream particulate loadings. Tests,therefore, were conducted on the downstream side of the filter only, and efficiencies were based on baseline testing without the Corning units. Placement of the filter units near the exhaust manifold where temperatures are high, provides a better opportunity for achieving trap regeneration by combustion of the particulate at the highest exhaust temperatures.

Table 7.8 shows the baseline particulate emissions from the bare engine at three load/speed conditions of 2300 rpm, 138 kW, 2300 rpm, 104 kW and 2000 rpm, 63 kW. Table 7.9 shows, at the same load/speed conditions, the particulate emissions from the engine when equipped with the Corning filters. The filters are clearly effective in reducing all particulate emissions including removal of some of the soluble organic matter. Table 7.10 averages the data and provides efficiencies for both insoluble and total particulate. Efficiencies of 84% and 90% are evident for insoluble particulate removal, and total particulate removal efficiency ranges from 69% to 83%. The efficiency of these units for reducing particulate emissions is very satisfactory.

The durability of the units in terms of load-up time and possible regenerative capability was examined by monitoring changes in engine back-pressure with time as the filter loaded up with particulate matter. Engine backpressure is, of course, a function of both the porosity of the filter and the filter space velocity, which in turn is related to the engine load/speed condition. Figure 7.11 shows the increase in backpressure over a period of 10 hours with the engine operating at 2000 rpm and 63 kW, that is, about half full load condition. Both left and right bank exhaust pressures are shown. These are different due to a difference in position of the pressure sensor in each exhaust bank. It is suspected that the pulsating nature of the exhaust creates a standing wave, so that the recorded pressure is sensitive to the position of the pressure tap in the exhaust. Also shown in Figure 7.11 is the maximum backpressure limit which the engine is capable of tolerating. It is clear that at this load/speed condition, the filter is not rapidly loading up, and after 10 hours had changed from a backpressure condition, (left bank) of 30% of the maximum, to 40% of the maximum tolerable backpressure. Figure 7.12 shows a similar plot at 2300 rpm and 104 kW. The rate of loading up of the filter has now increased, and after 7 hours of operation, the backpressure had increased from 35% to 50% of the maximum tolerable limit. This is considered quite a satisfactory performance. Figure 7.13 shows the results of operating the engine and filter at 2300 rpm, 138 kW, which is full load/speed condition. The characteristics of pressure change with time are now different, and it was observed that the engine backpressure decreased with time of operating at full load/speed condition. This suggested that regeneration of the filter was occurring by combustion of the particulate matter.

Finally, Figure 7.14 shows a composite record of the variation in engine backpressure which occurred at the different load/speed conditions over the indicated time intervals. Also shown, is the exhaust temperature at each load/speed condition. The vertical changes in backpressure which occur with each change in load/speed condition are due to changes in filter space velocity. Figure 7.14 shows that after loading up the filter at 2300 rpm, 104 kW, partial regeneration can be achieved by operating the engine at full load/speed condition and an exhaust temperature of 550°C. The partial regeneration can be observed by comparing the two pressure traces for 2300 rpm, 104 kW load/speed condition.

7.3 Filter Comparison Summary

Table 7.11 summarizes the essential data from the testing of both the mesh (USBM) filter, in two versions, and the Corning Filter. All three filters are satisfactory in reduction of particulate, reaching high reduction levels of insoluble matter (85-90%) and substantial reductions of soluble organics. The dry mesh filter, however, was very variable with respect to SOF, perhaps due to the operation of a storage effect.

The greatest concern in application of the filters is with operating time and overall durability. This is limited by rate of back-pressure increase which seems greatest for the high density, perpendicular flow, mesh filter and most promising for the Corning filter. The 150 kg/m^3 parallel flow mesh filter is also promising in terms of operating time.

The most serious consideration with the mesh filters is the potential attrition due to loss of fibreglass yarn and the need for frequent off vehicle cleaning. The Corning filter seems more durable and apparently has potential for extended on board operating periods. For this reason, the Corning filter seems favoured for further development and optimization.

TABLE 7.1

The Effect of the USBM Filter on the Particulate Emissions of a Deutz F6L 714 Diesel Engine

Speed rpm	Load kW	Torque N.m **	Pressure Drop Across Filter CM H_2O	Time Elapsed At Start hr	Location wrpt Filter	Particulate Concentrations and Emission Rates						
						Total Particulate			Insoluble Matter		S.O.F.	
						mg/m^3	g/hr	% Reduction	mg/m^3	g/hr	mg/m^3	g/hr
1625	70	407	16	1.25	Inlet	83.9	29.7	72	78.0	27.6	5.9	2.1
					Outlet	23.7	8.4		18.6	6.6	5.1	1.8
			19	2.50	Inlet	78.7	27.8	78	71.8	25.4	6.9	2.5
					Outlet	17.1	6.1		13.1	4.6	4.0	1.4
2200	93	407	28	3.75	Inlet	53.9	24.8	77	50.8	23.4	3.1	1.4
					Outlet	12.5	5.7		8.7	4.0	3.8	1.8
			32	5.00	Inlet	61.6	28.3	82	56.0	25.8	5.6	2.6
					Outlet	11.4	5.2		7.6	3.5	3.8	1.7
1625	70	407	28	11.75	Inlet	62.5	22.1	84	58.0	20.5	4.5	1.6
					Outlet	10.1	3.6		7.2	2.5	2.9	1.0
			*11	After Filter Cleaning	Inlet	54.1	19.1	66	50.1	17.7	4.0	1.4
					Outlet	17.6	6.2		15.3	5.4	2.3	0.8

*Filter was cleaned with Diverfos 207

** Newton-metres.

TABLE 7.2

Particulate Test Results Run No. 2.

For Bale 1 (Used Filter Bale) 2300 RPM 130 kW

Deutz F8L 413

Location	Insoluble Particulate (mg/m^3)	S.O.F. (mg/m^3)	Total Particulate (mg/m^3)	% Collection Efficiency Insoluble	% Collection Efficiency Total
Inlet	61.2	21.5	82.7	54	50
Outlet	28.1	13.1	41.2		
Inlet	64.3	44.8	109.1	73	72
Outlet	17.8	13.6	31.5		
Inlet	72.6	14.2	86.8	73	71
Outlet	19.7	5.41	25.1		
Inlet	58.4	12.0	70.4	75	47
Outlet	14.7	23.0	37.8		
Inlet	63.9	34.3	98.2	80	72
Outlet	13.3	14.4	27.7		
			Average =	71	62

TABLE 7.3

ΔP Characteristics (cm H_2O) for USBM Filter for Sulphate Tests

Test No.	Time (min.)	Location 1	Location 2	Location 3	Location Overall	Engine Back Pressure (Pre-Catalyst)
1	0					
	5	9	13	18	21	56.
	15	10	15	19	25	60
	25	10	16	20	26	61
	35	10	16	20	27	61
	45	11	16	21	28	62
	67	11	17	22	29	62
	92	11	17	23	30	64
2	117	11	18	23	31	65
	127	11	18	23	31	65
	137	12	18	23	32	66
			Engine Shut Down			
3	0	11	16	21	27	61
	10	12	19	24	33	69
	20	12	20	26	34	70
	30	12	20	26	35	70
	65	13	20	26	36	70
	85	13	20	27	37	70
	110	13	20	27	37	71
	130	13	20	27	37	71
	145	13	21	27	38	72
4	165	13	21	28	38	72
	180	13	21	28	38	72
	200	13	21	28	39	72
5	240	13	21	29	40	74
	260	13	21	29	40	75
	275	14	22	29	41	75
	290	14	22	30	41	75
			Engine Shut Down			
6	0	12	20	26	35	71
	10	14	22	30	42	77
	20	14	22	31	43	77
	30	14	22	31	43	79
	40	14	23	31	44	79
	63	14	23	32	44	78
	85	15	23	32	45	78
	100	15	23	32	45	79
7	115	15	23	32	45	79
	130	15	23	33	46	80
	145	15	23	33	46	80
	165	15	24	33	47	80

Note: All tests done at 2300 rpm, 139 kW

TABLE 7.4

PARTICULATE COLLECTION EFFICIENCY OF USBM FILTER

11 ℓ Flow Configuration, 130 kg/m^3 bulk density

Speed (rpm)	Load (kW)	Location wrt Filter	Fuel/Air Ratio	Insoluble mg/m^3	Insoluble g/kW.h	Insoluble g/h	Insoluble g/kg Fuel	Insoluble % Efficiency	Soluble mg/m^3	Soluble g/kW.h	Soluble g/h	Soluble g/kg Fuel	Soluble % Efficiency	Total mg/m^3	Total g/kW.h	Total g/h	Total g/kg Fuel	Total % Efficiency
2300	138	Inlet	0.042	88.8	0.429	59.8	1.65		24.7	0.119	16.6	0.458		114	0.547	76.3	2.11	
		Outlet		50.2	0.242	33.8	0.933	43.5	41.8	0.202	28.1	0.776	<0	92.1	0.444	61.9	1.71	19.2
2300	138	Inlet	0.042	75.9	0.361	50.4	1.41		18.6	0.088	12.3	0.344		94.4	0.450	62.7	1.75	
		Outlet		39.5	0.188	26.2	0.734	48.0	12.1	0.058	8.06	0.225	34.9	51.7	0.245	34.3	0.959	45.2
2300	103	Inlet	0.032	43.5	0.296	30.5	1.05		38.0	0.259	26.6	0.920		81.5	0.555	57.1	1.97	
		Outlet		15.7	0.107	11.0	0.380	63.9	11.4	0.078	8.01	0.277	70.0	27.2	0.185	19.0	0.657	66.7
2300	69	Inlet	0.023	21.1	0.229	15.9	0.725		25.7	0.280	19.4	0.884		46.8	0.510	35.3	1.61	
		Outlet		10.1	0.110	7.62	0.347	52.1	14.5	0.158	10.9	0.499	43.6	24.6	0.268	18.6	0.846	47.4
2000	132	Inlet	0.040	63.0	0.307	40.6	1.22		7.46	0.036	4.81	0.144		70.4	0.344	45.4	1.36	
		Outlet		24.7	0.120	15.9	0.477	61.0	15.8	0.077	10.2	0.305	<0	40.4	0.197	26.1	0.783	42.6
2000	98	Inlet	0.028	40.5	0.280	27.6	1.12		7.89	0.055	5.38	0.219		48.4	0.335	33.0	1.34	
		Outlet		13.6	0.094	9.29	0.378	66.4	18.1	0.126	12.4	0.503	<0	31.8	0.220	21.7	0.881	34.3
2000	65	Inlet	0.022	23.0	0.251	16.3	0.847		29.3	0.318	20.7	1.08		52.3	0.569	36.9	1.92	
		Outlet		8.89	0.097	6.28	0.327	61.3	15.0	0.163	10.6	0.551	48.8	23.9	0.260	16.9	0.878	54.3
1600	113	Inlet	0.043	109	0.475	53.9	1.98		17.0	0.075	8.45	0.311		126	0.550	62.3	2.29	
		Outlet		45.4	0.199	22.5	0.830	58.3	39.1	0.171	19.4	0.714	<0	84.5	0.370	42.0	1.54	32.9

TABLE 7.5

VARIATION OF INSOLUBLE PARTICULATE REMOVAL EFFICIENCIES WITH PRESSURE DROP ACROSS THE USBM FILTER

150 kg/m^3 bulk density, parallel flow, Deutz F8L 413 Engine

Test Condition (rpm/kW)	Location	ΔP Across Bale (cm H_2O)	Engine Back Pressure (cm H_2O)	Insoluble Particulate (mg/m^3) Filter Only	% E
2300/138	Inlet	32	41	106	81
	Outlet			20	
2300/138	Inlet	44	52	85	85
	Outlet			13	
2300/138	Inlet	62	70	102	90
	Outlet			10	
2300/138	Inlet	73	81	92	93
	Outlet			6	
2300/138	Inlet	79	86	103	90
	Outlet			10	

TABLE 7.6

VARIATION OF TOTAL PARTICULATE REMOVAL EFFICIENCY WITH PRESSURE DROP ACROSS USBM FILTER

150 kg/m^3 bulk density, parallel flow, Deutz F8L 413 Engine

Test Conditions (rpm/kW)	Location wrt Filter	ΔP Across Bale (cm H_2O)	Back Pressure on Engine (cm H_2O)	Total Particulate Emissions				% Efficiency
				mg/m^3	g/kW.h	g/h	g/kg Fuel	
2300/138	Inlet	32	41	151.0	0.691	95.3	2.57	73.6
	Outlet			39.8	0.182	25.2	0.680	
2300/138	Inlet	44	52	127.0	0.572	78.9	2.17	73.9
	Outlet			33.0	0.149	20.5	0.564	
2300/138	Inlet	62	70	147.0	0.660	91.1	2.51	77.7
	Outlet			32.7	0.147	20.3	0.559	
2300/138	Inlet	73	81	132.0*	0.589	81.3	2.25	61.8
	Outlet			50.3**	0.225	31.0	0.861	
2300/138	Inlet	79	86	142.0	0.645	89.0	2.43	79.4
	Outlet			29.3	0.133	18.3	0.501	

* This value is approximate due to a loss of some sample.

** Abnormally high probe rinse.

TABLE 7.7

Bale Endurance - USBM Filter

Bale Density and Configuration	Bale Condition	Testing Conditions	Engine Startups During Tests	Expected Lifetime* (hrs.)
185 kg/m^3 15" x 15" sheets, perpendicular to exhaust flow in a 15" x 15" x 20" frame	New bale	Full load/speed 2300 rpm, 185 HP	1	5.0**
185 kg/m^3 (as above)	- Washed once - Material Stained	Full load/speed 2300 rpm,185 HP	1	5.0**
185 kg/m^3 (as above)	- Washed twice - Fibreglass fraying - Material appears soiled	Various loads and speeds	1	5.0
185 kg/m^3 (as above)	- Washed three times - Frayed and soiled	Various loads and speeds	1	4.0
185 kg/m^3 (as above)	- Washed four times - Frayed, very soiled	Full load/speed 2300 rpm,185 HP	1	<1.0
149 kg/m^3 15" x 30" sheets parallel to exhaust flow held together by 4 wires, plus additional loose sheets and 3/4" metal plate	- Washed twice, frayed and soiled but cleaned throughout as bale could be opened up for cleaning	Evenly distributed between 7 load/speeds	6	30
130 kg/m^3 15" x 30" sheets parallel to exhaust flow held together by 4 wires plus 3/4" metal plate to assist sealing	- Washed twice - Frayed and soiled but cleaned throughout as bale could be opened up	Evenly distributed between 7 load/speeds	2	61

* Lifetime of a bale is the time from when it was installed until the engine back pressure reached 100 cm of H_2O and the bale had to be washed.

** These tests were performed without catalysts. The lifetimes were adjusted to take into account the additional 14 cm of H_2O engine back pressure (at 2300 rpm and 185 HP) caused by the catalysts.

TABLE 7.8

Baseline Particulate Emissions from the Bare Engine

Deutz F8L 413

Speed (rpm)	Load (kW)	Insoluble				Soluble				Total			
		mg/m^3	g/kW.h	g/h	g/kg Fuel	mg/m^3	g/kW.h	g/h	g/kg Fuel	mg/m^3	g/kW.h	g/h	g/kg Fuel
2300	138	85.7	.407	56.1	1.55	25.4	.121	16.6	.460	111.0	.527	72.7	2.01
2300	138	70.8	.337	46.4	1.28	11.7	.056	7.67	.212	82.5	.392	54.1	1.49
2300	138	78.6	.374	51.5	1.42	15.3	.073	10.0	.277	93.9	.446	61.6	1.70
2300	104	33.9	.216	22.4	.782	20.7	.132	13.7	.478	54.6	.349	36.1	1.26
2300	104	40.9	.258	26.8	.944	6.9	.044	4.52	.159	47.8	.302	31.3	1.10
2300	104	35.9	.227	23.6	.828	15.6	.099	10.2	.360	51.5	.326	33.8	1.19
2000	63	21.0	.220	14.0	.758	24.9	.261	16.6	.900	45.9	.482	30.5	1.66
2000	63	20.9	.216	13.7	.755	31.1	.321	20.3	1.12	52.0	.537	34.0	1.88
2000	63	22.2	.230	14.6	.802	22.8	.236	15.0	.823	45.0	.466	29.5	1.62

TABLE 7.9

Particulate Emissions from the Engine Equipped with Corning Filters

Deutz F8L 413

Speed (rpm)	Load (kW)	Insoluble					Soluble					Total				
		mg/m^3	g/kW.h	g/h	g/kg Fuel	% Efficiency	mg/m^3	g/kW.h	g/h	g/kg Fuel	% Efficiency	mg/m^3	g/kW.h	g/h	g/kg Fuel	% Efficiency
2300	138	8.80	.041	5.70	.159	88.8	4.9	.023	3.18	.088	71.8	13.7	.064	8.88	.247	85.7
2300	138	4.70	.022	3.03	.085	94.0	2.8	.013	1.81	.050	83.9	7.5	.035	4.84	.135	92.2
2300	138	10.2	.048	6.61	.182	87.0	17.0	.080	11.0	.304	2.3	27.2	.128	17.6	.486	71.6
2300	104	5.6	.036	3.71	.136	84.8	9.9	.063	6.56	.240	31.3	15.5	.099	10.3	.375	69.8
2300	104	5.7	.037	3.80	.138	84.6	13.9	.089	9.26	.034	3.5	19.6	.126	13.1	.474	61.8
2300	104	5.8	.038	3.94	.140	84.3	6.6	.043	4.49	.160	54.2	12.4	.081	8.43	.300	75.8
2000	63	2.5	.027	1.70	.092	88.3	9.8	.105	6.65	.361	62.7	12.3	.132	8.34	.453	74.2
2000	63	3.6	.039	2.48	.133	83.2	10.9	.119	7.51	.401	58.6	14.5	.158	9.99	.534	69.6
2000	63	2.6	.027	1.73	.096	87.9	8.1	.085	5.39	.298	69.2	10.7	.011	7.11	.394	77.6

TABLE 7.10

Average Particulate Removal Efficiencies

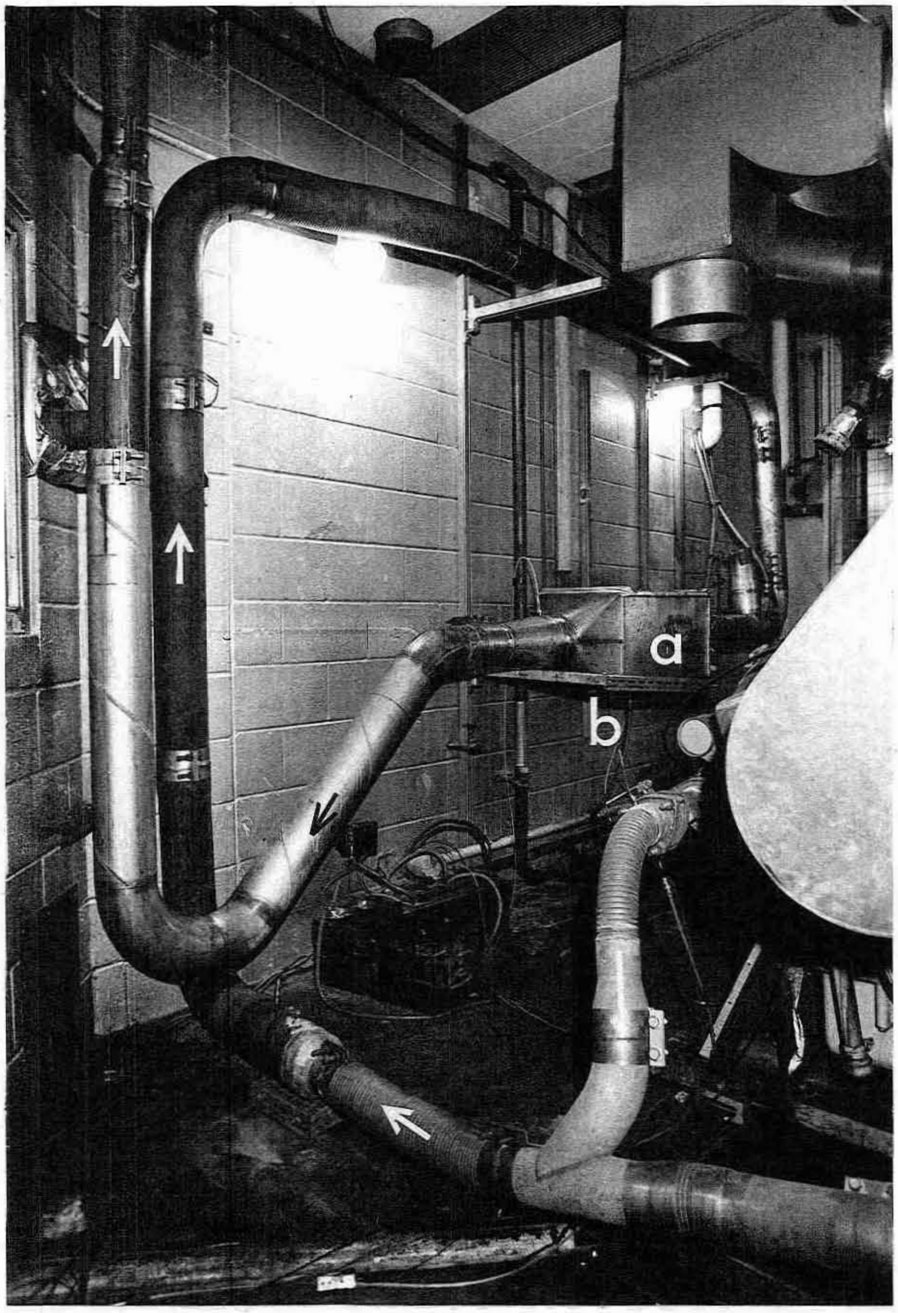
Corning Ceramic Filter

Speed (rpm)	Load (kW)	Insoluble Particulate			Total Particulate		
		Inlet (g/hr)	Outlet (g/hr)	% Efficiency	Inlet (g/hr)	Outlet (g/hr)	% Efficiency
2300	138	51.3	5.1	90.1	62.8	10.4	83.4
2300	104	24.3	3.8	84.0	33.7	10.6	68.5
2000	63	14.1	2.0	85.8	31.3	8.5	72.8

TABLE 7.11

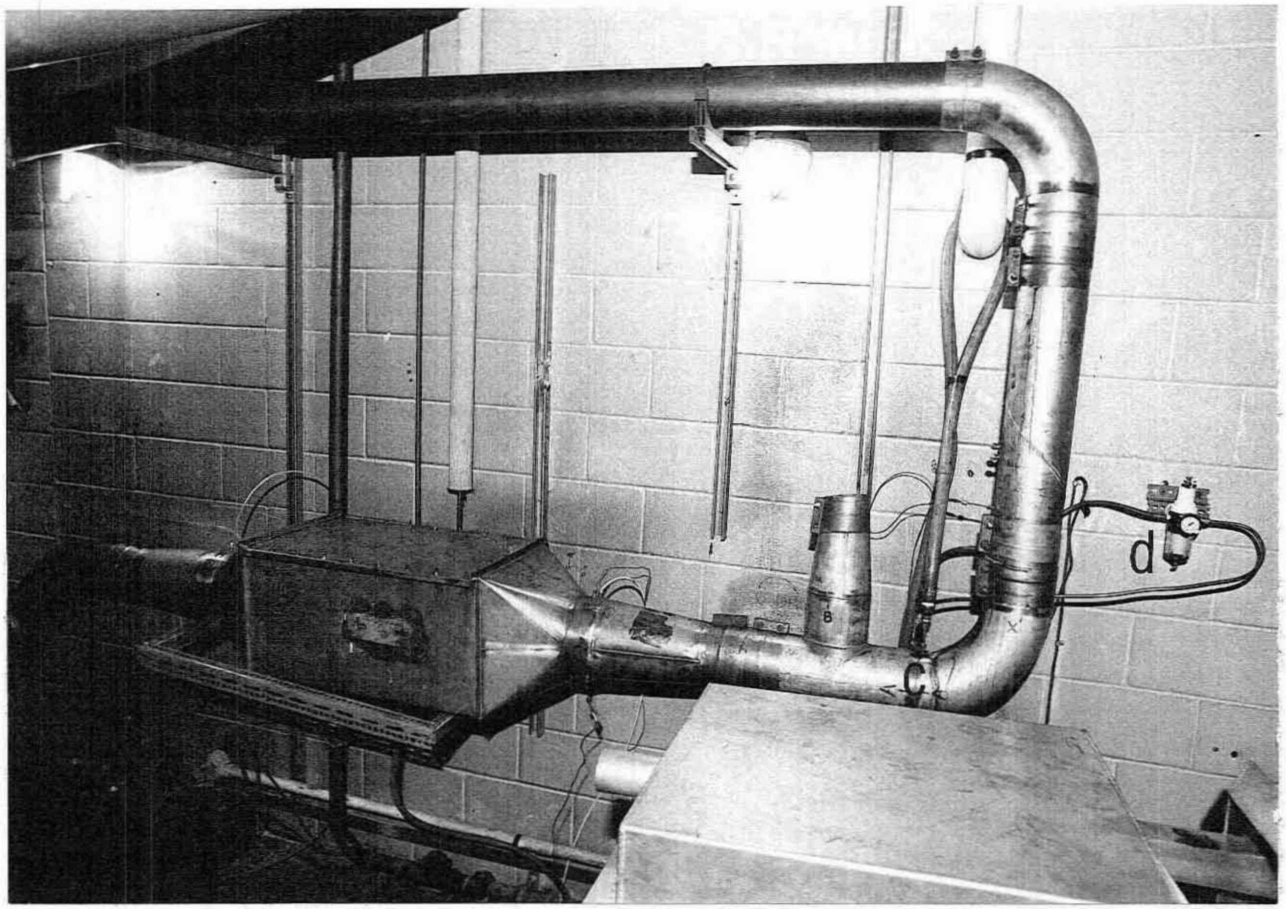
Filter Comparison Summary

	Mesh Filter		
	185 kg/m^3 with Water Spray, Perpendicular Flow (Deutz F6L-714)	150 kg/m^3 Dry Operation, Parallel Flow (Deutz F8L-413)	Corning Filter (Deutz F8L-413)
Average Particulate Reduction Efficiency %			
Total Particulate	77	73	75
Insolubles	84	88	87
S.O.F.	58	(variable)	49
Test P, initial (cm, H_2O	16	32	25 (approx)
Test P, final (cm, H_2O)	28	79	Not reached
"Continuous" Operating Time (Hrs)	12	30 (est)	26 hours tested (maximum not determined)



a - Mesh Filter b - Filter Drain Location

FIGURE 7.1 Mesh Filter Installation.



c - Water Atomizing Spray Location
d - Spray Air Pressure Filter and Regulator

FIGURE 7.2 Close-up of Mesh Filter Installation
and Water Spray Location

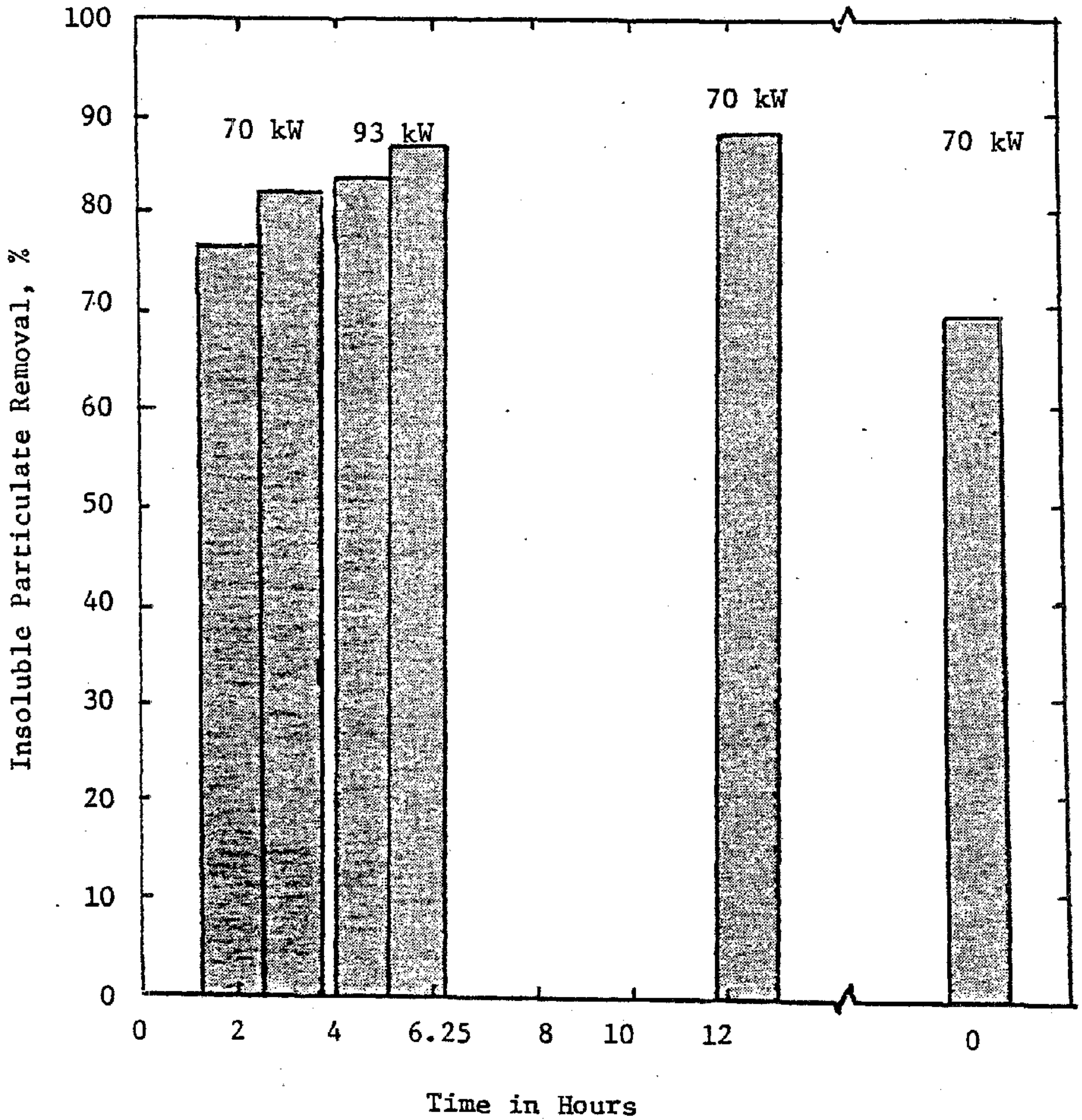


FIGURE 7.3 Histogram of Insoluble Particulate Matter Removal from Water Cooled Exhaust Using USBM Filter, Preliminary Results

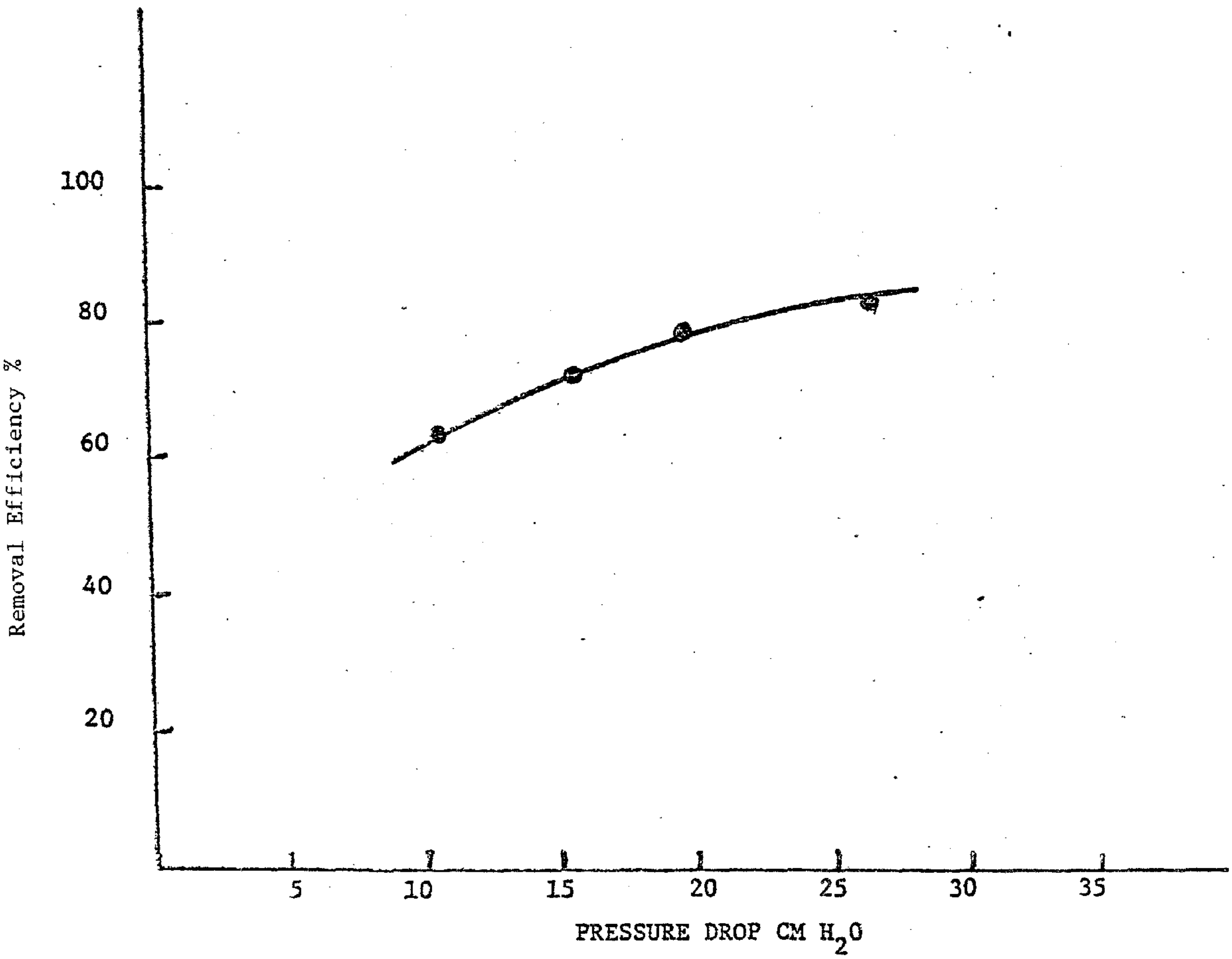


Figure 7.4 Variation in Removal Efficiency with Increase in Pressure Drop due to Loading of Filter with Particulate 1625 rpm 70 kW.

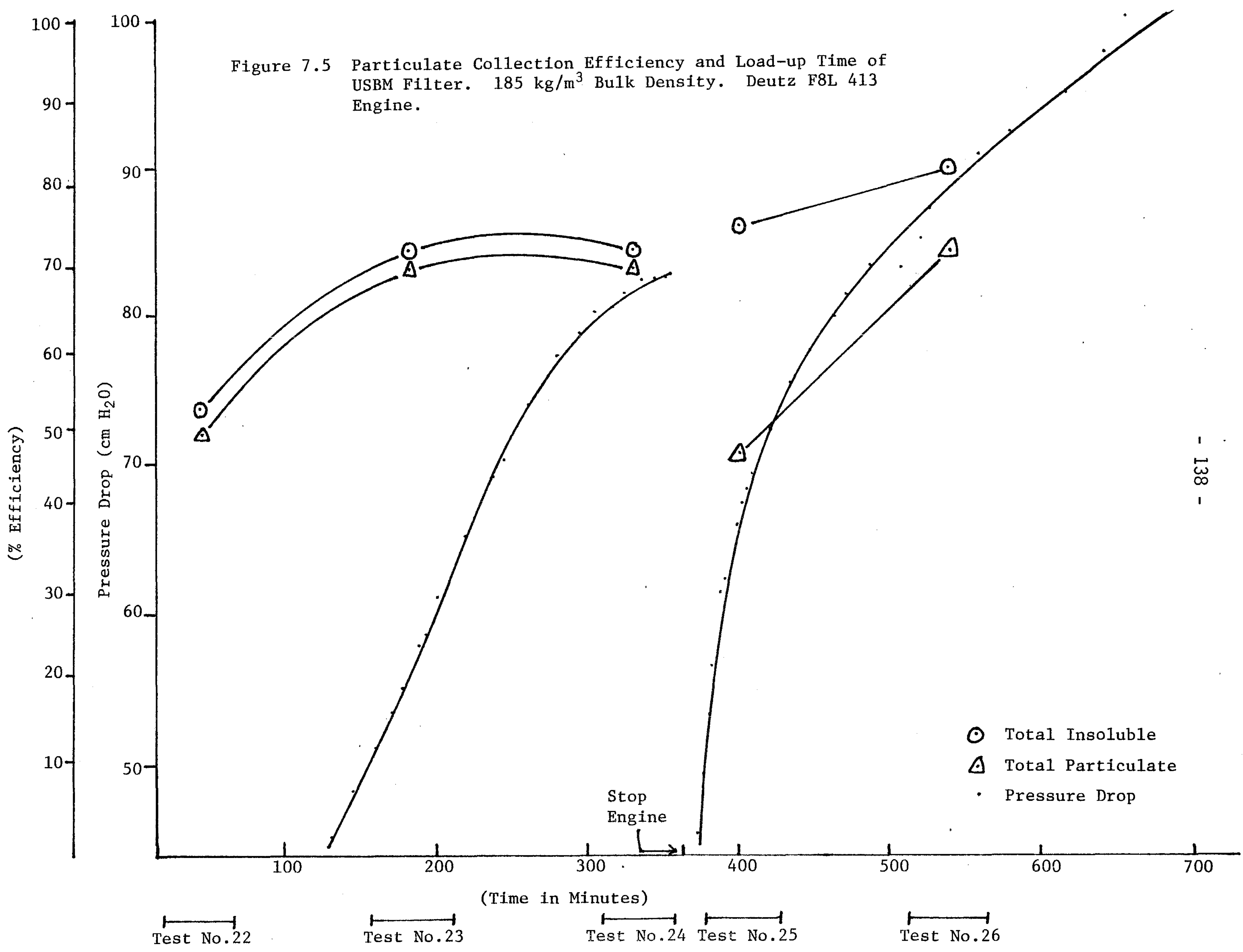


Figure 7.5 Particulate Collection Efficiency and Load-up Time of USBM Filter. 185 kg/m^3 Bulk Density. Deutz F8L 413 Engine.

FIGURE 7.6 Relationship of Pressure Drop vs Distance from Inlet of Bale

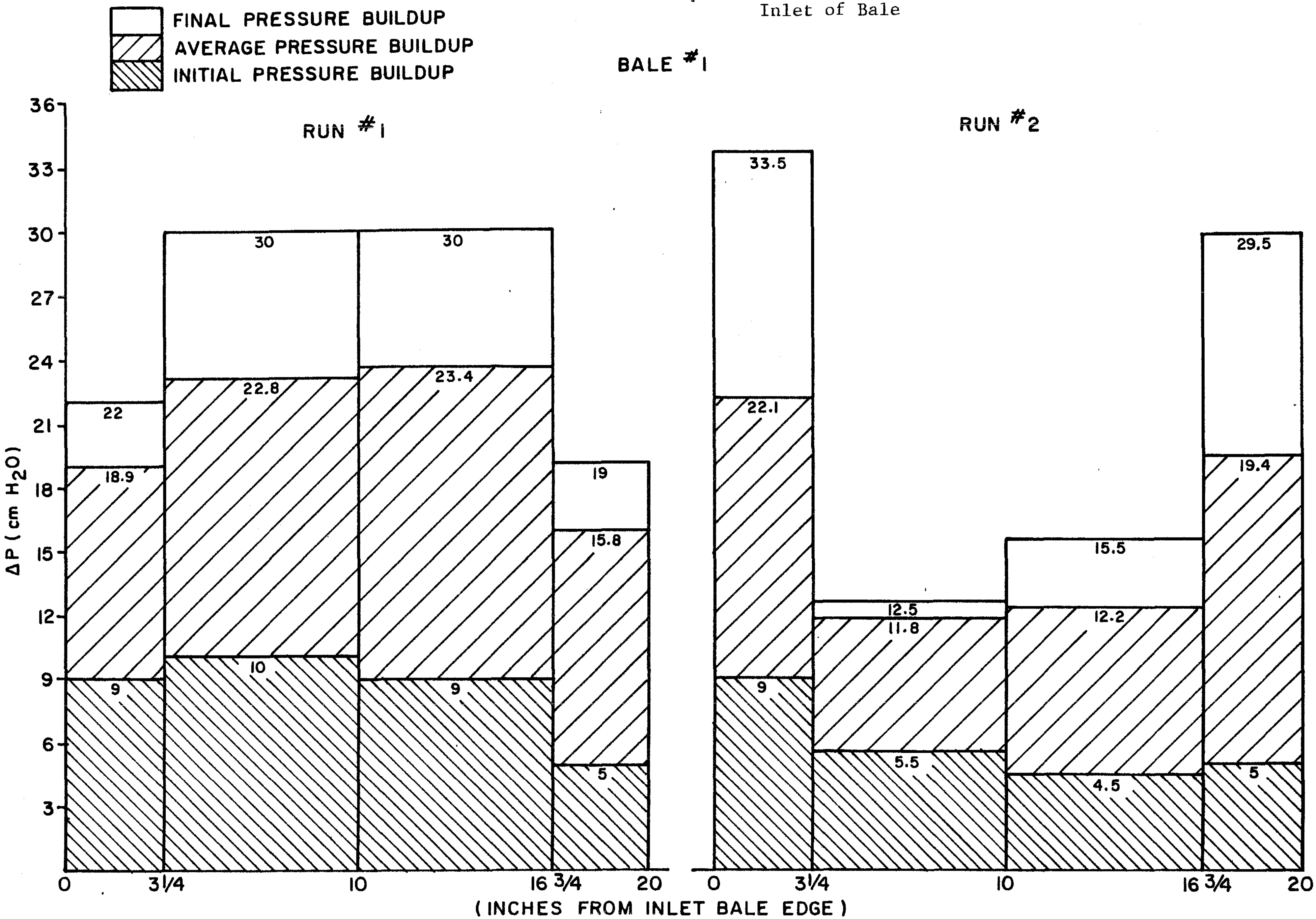
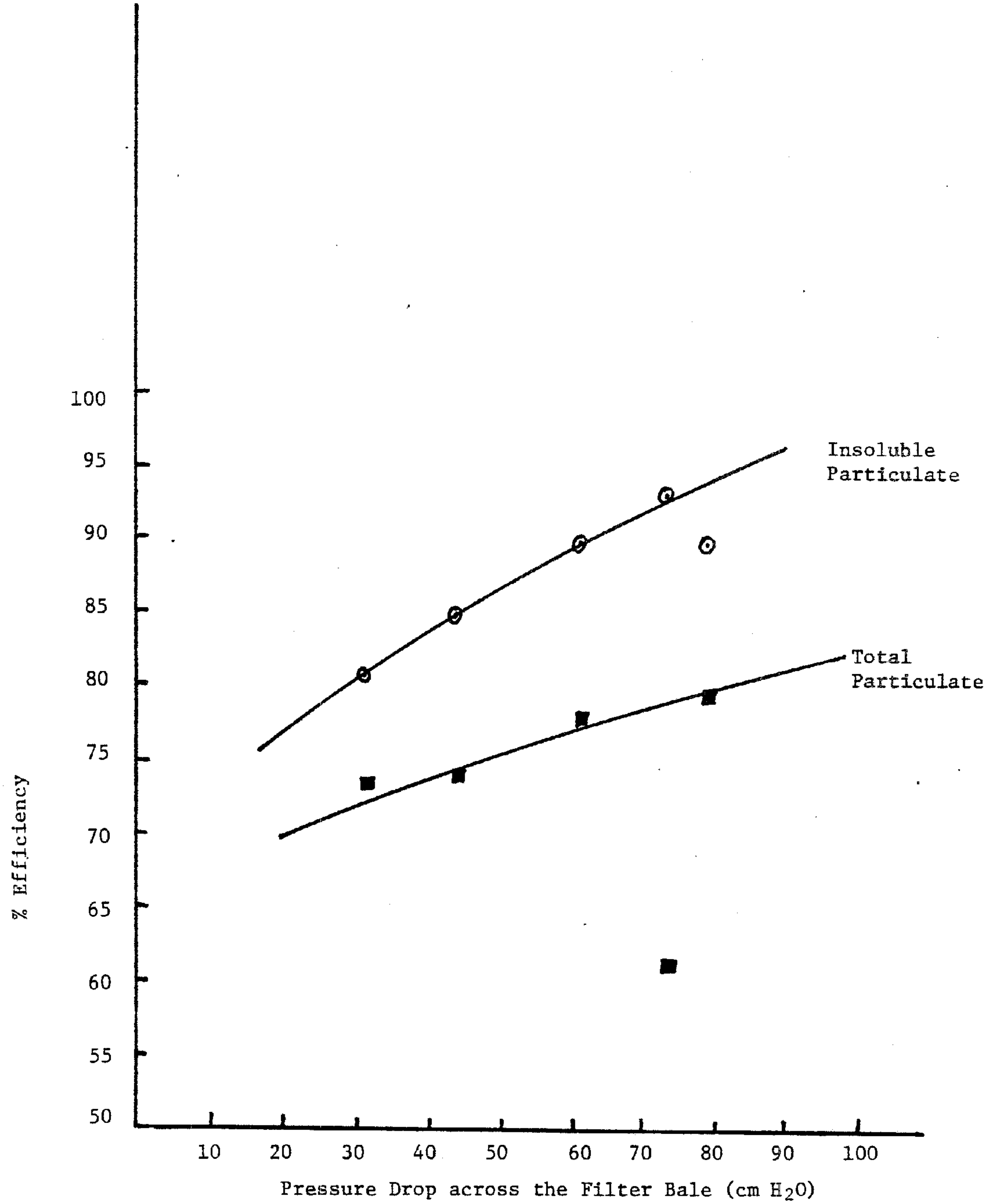
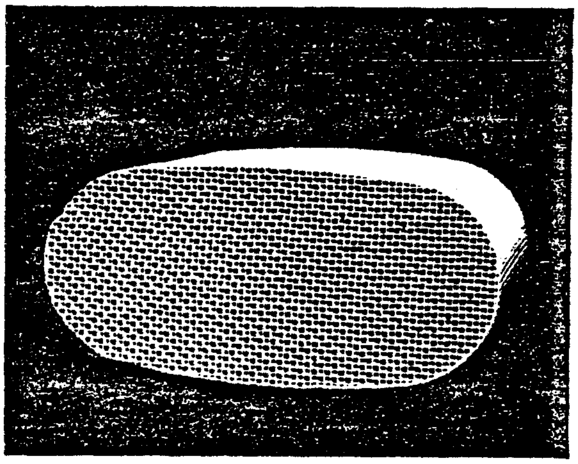


Figure 7.7

Variation of Particulate Removal Efficiency with Pressure Drop across the Filter - 2300 rpm/138 kW

USBM Filter: 150 kg/m^3, Parallel Flow, Deutz F8L 413 Engine





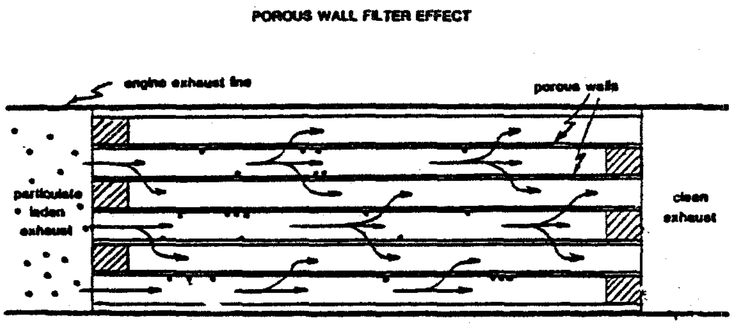


FIGURE 7.8 Corning Filter Element

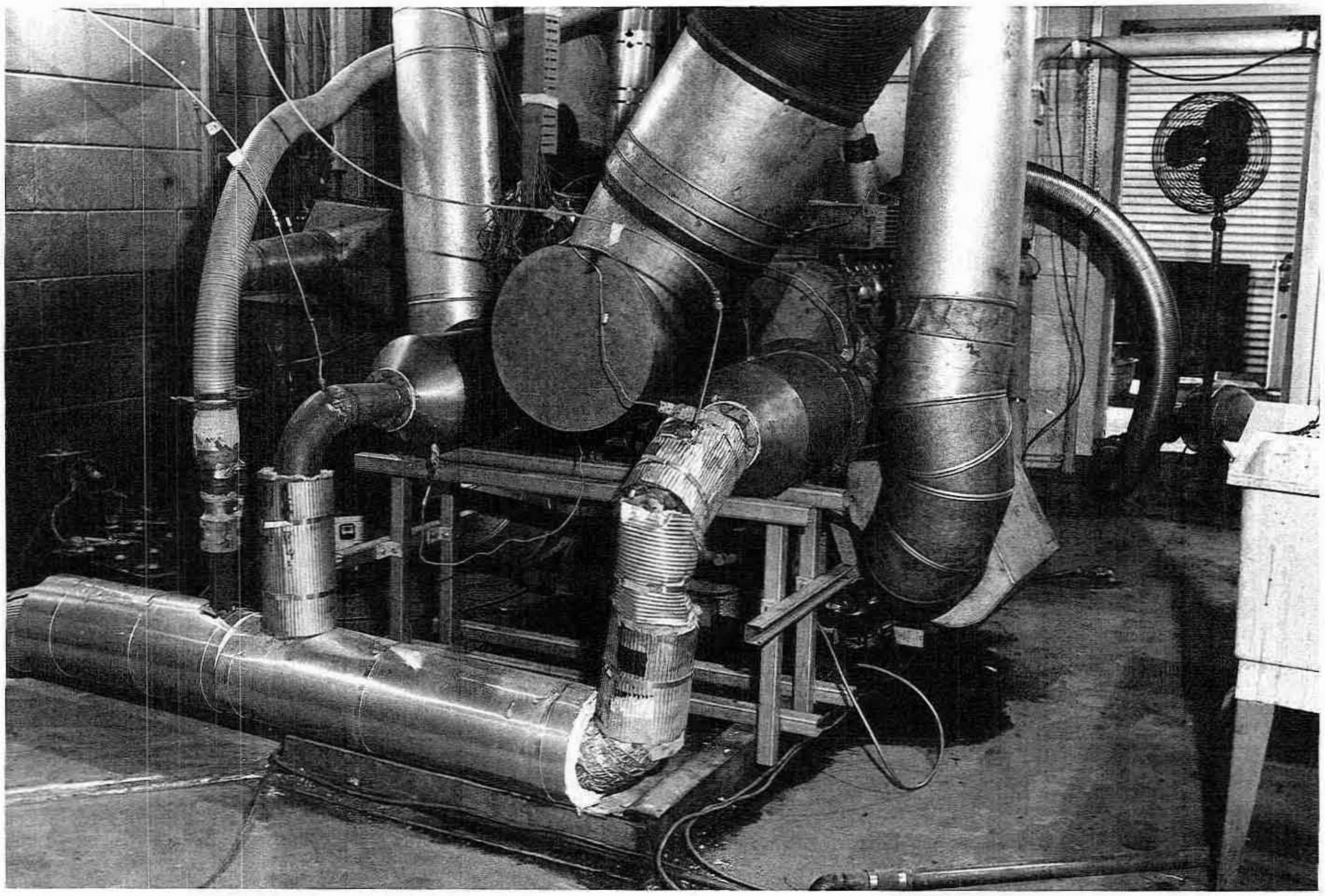


FIGURE 7.9 Corning Filter Installed on Deutz Engine.

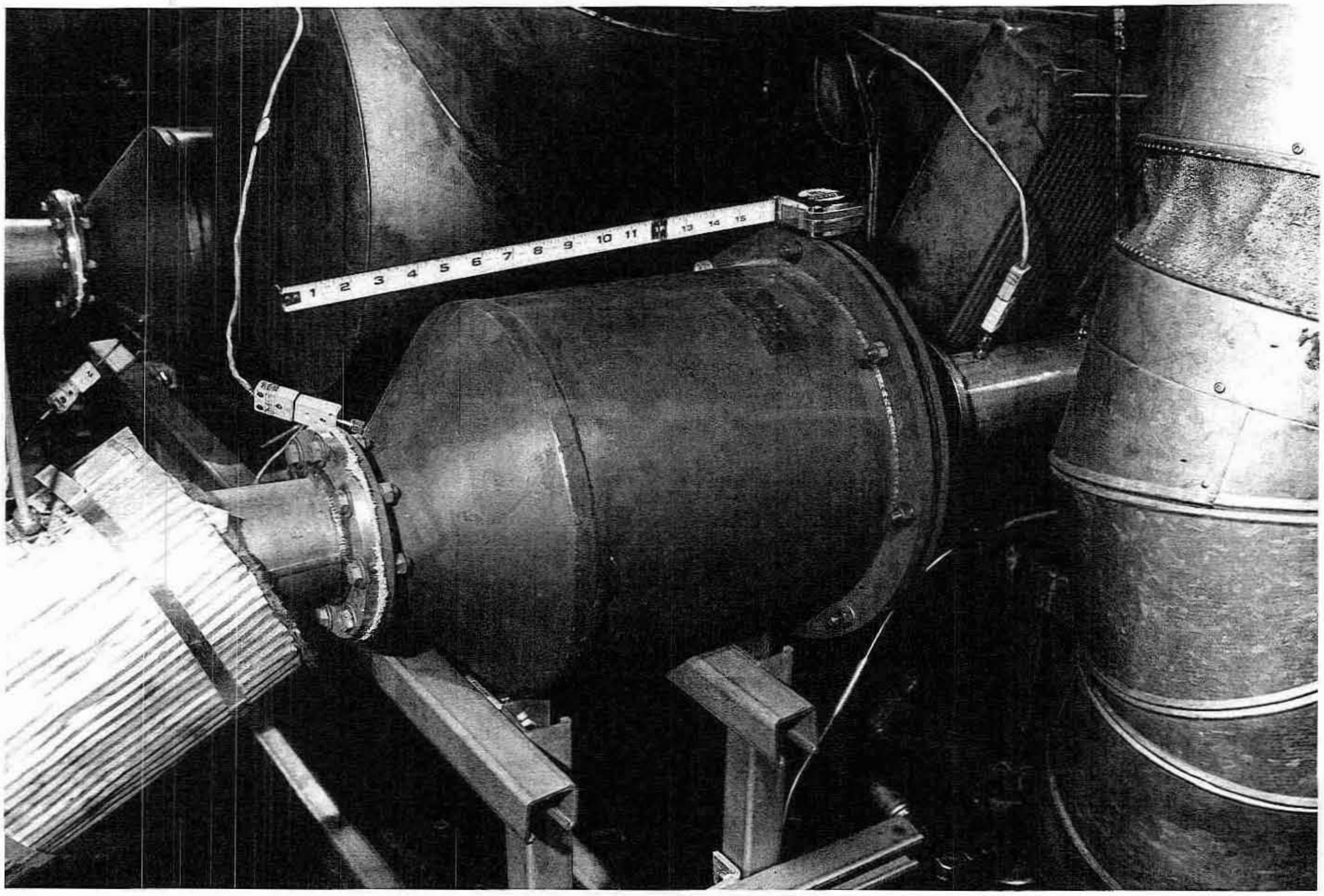


FIGURE 7.10 Close-up View of Corning Filter.

Figure 7.11

Corning Ceramic Filter

Variation in Engine Back Pressure
During Operation at 2000 rpm/63 kW

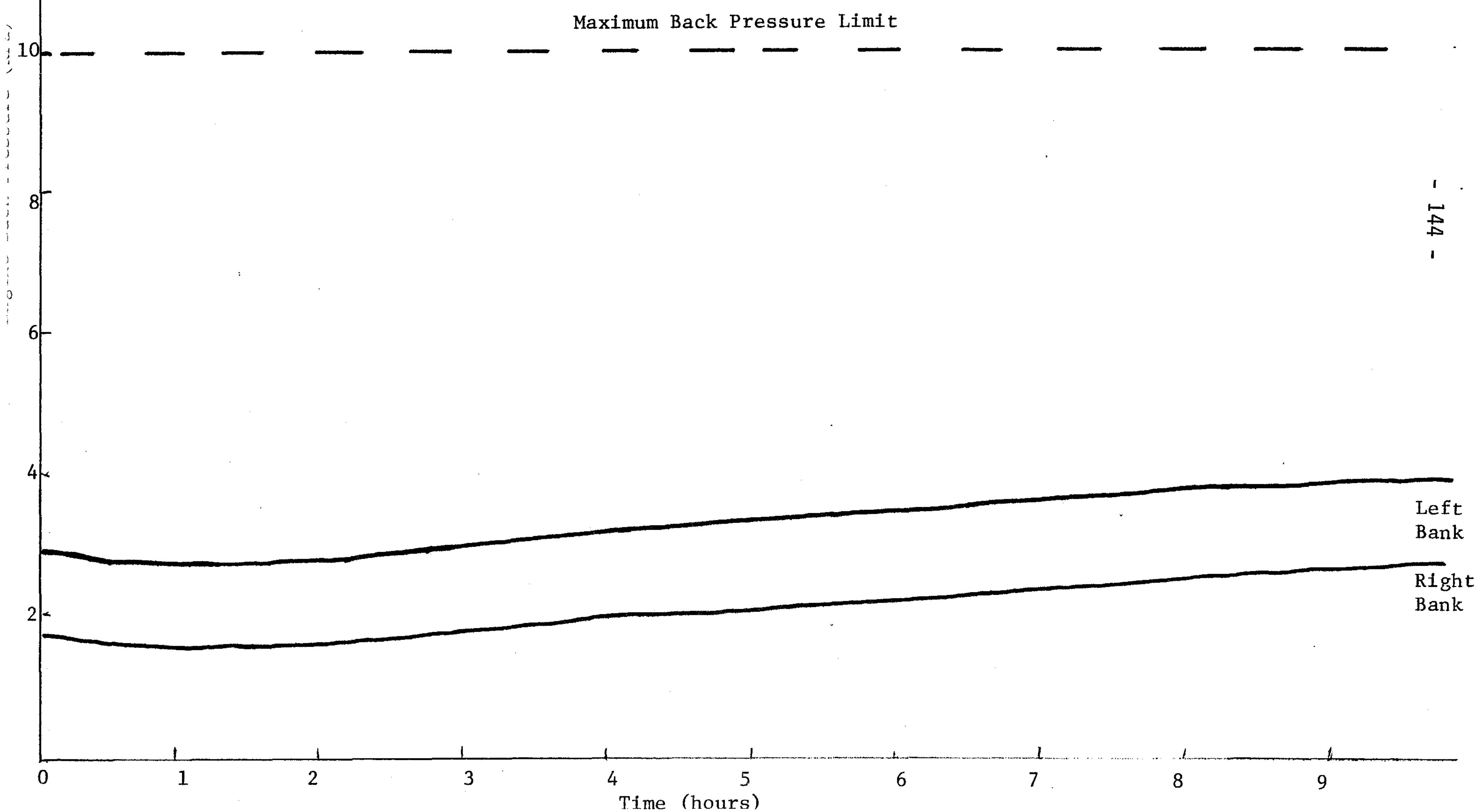


Figure 7.12

Corning Ceramic Filter

Variation in Engine Back Pressure During Operation at 2300 rpm/104 kW

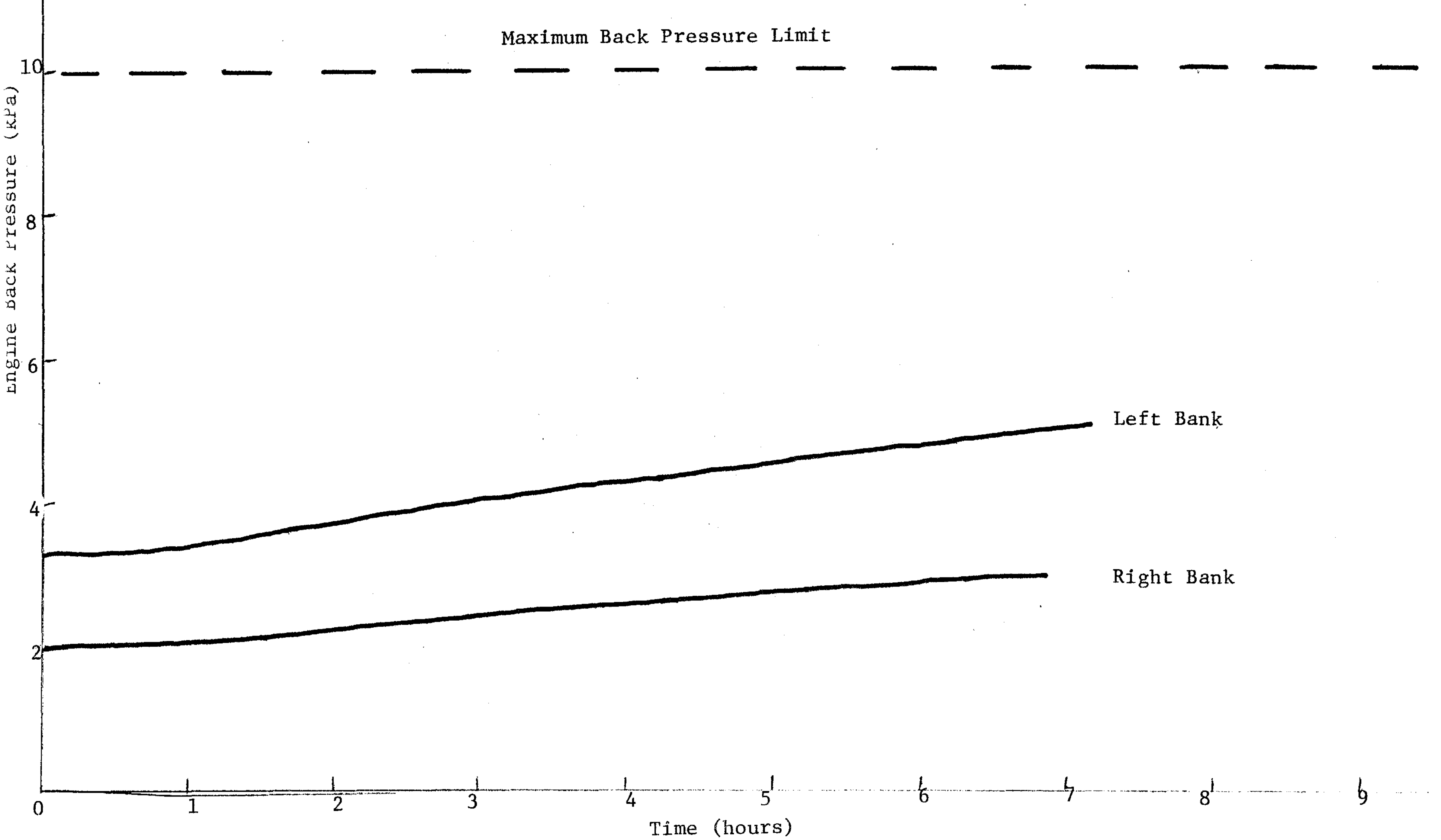


Figure 7.13

Corning Ceramic Filter

Variation in Engine Back Pressure During
Operation at 2300 rpm/138 kW

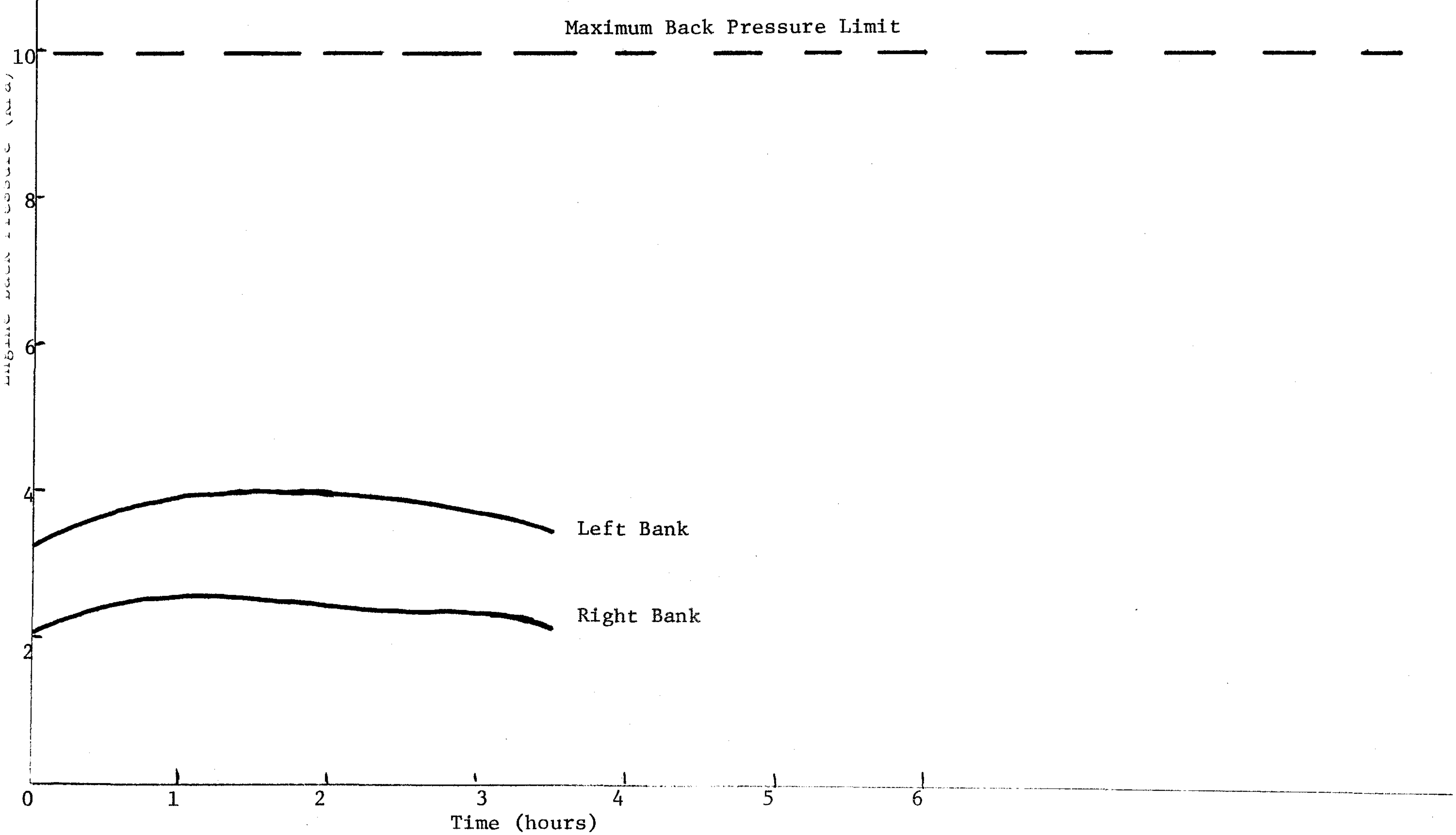
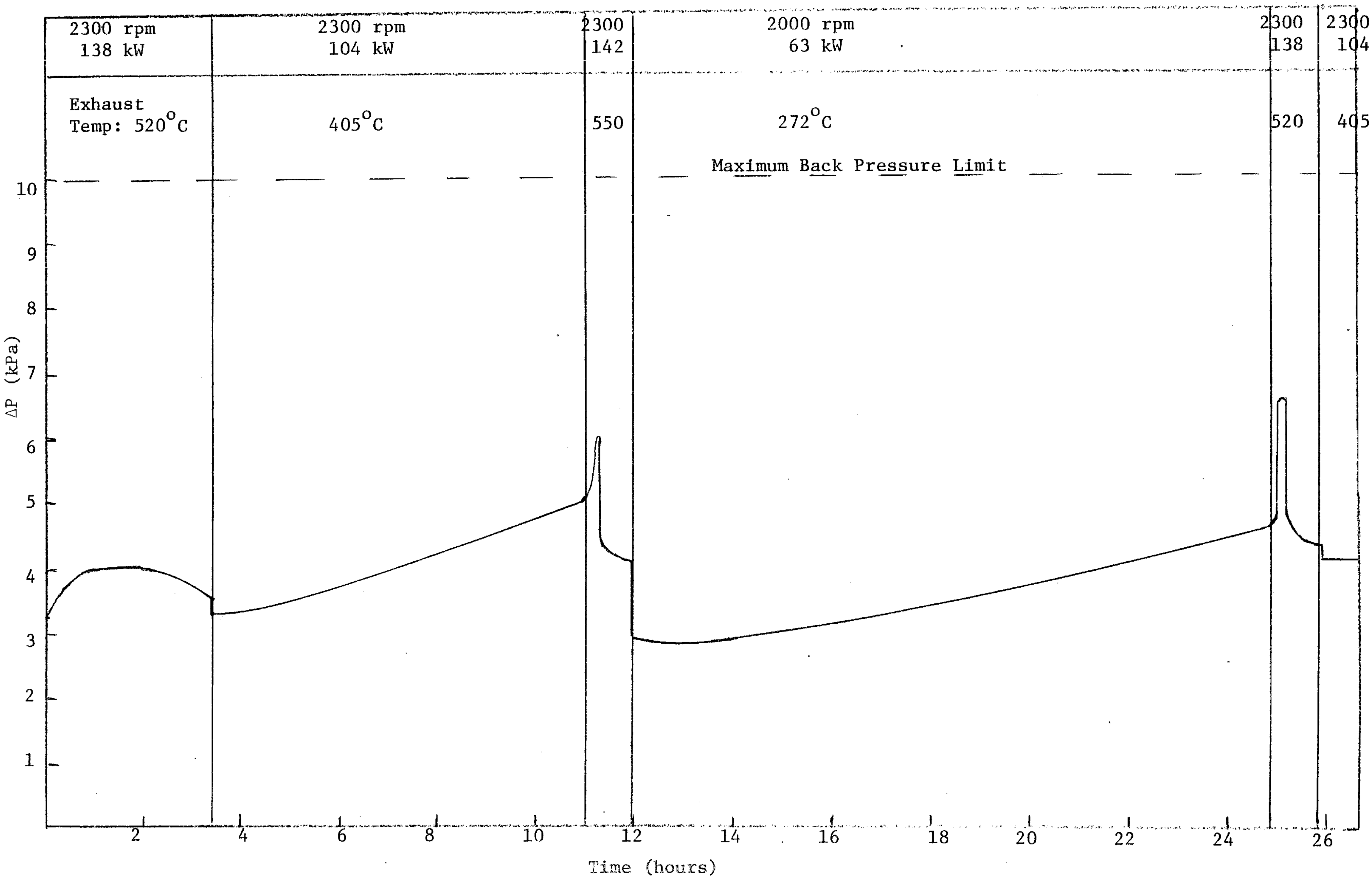


Figure 7.14

Load-up and Regeneration of Corning Ceramic Filter



8. WATER-FUEL EMULSIONS

8.1 Deutz 714 Engine

In an earlier study of the effect of unstabilized water/diesel oil emulsions on the Deutz F6L 714 diesel engine,[10, 13] it was shown that application of a 15% w/w unstabilized water/oil emulsion to the engine could reduce both NO_x and particulate emissions by about 40%. In the present study, this work was confirmed, and extended to combined device testing. This section deals with the configuration of the earlier results on the Deutz 714 engine, and extends the technique to the Deutz 413 engine.

Details of the technology for the creation and supply of an unstabilized water/oil emulsion to a diesel engine is described elsewhere [10, 13]. Figure 8.1 shows a schematic of the modified fuel system used to supply emulsions to the test engine. Water and diesel oil are proportioned and supplied under pressure to a mechanical emulsifier, the ORF HydroShear. The emulsion exiting from the HydroShear is fed with a fuel loop from which some of the emulsion is consumed in the engine. The remainder returns to the HydroShear for re-emulsification via a fuel cooler. Figure 8.2 shows a diagram of the HydroShear whose operation is described in detail elsewhere[10, 13]. The HydroShear used in the present studies was a double ended unit, designed to supply emulsion to both banks of the V-6 or V-8 engines. The effect of a 14% w/w water/fuel emulsion on the gaseous emissions of the Deutz 714 engine is shown in Table 8.1. At the load/speed conditions tested, NO emissions were reduced 28-33%, while CO emissions showed small increases and THC emissions moderate increases. The increases shown could easily be controlled with a catalyst.

The effect of the 14% water/oil emulsion on particulate emissions is shown in Table 8.2. Significant reductions in particulate emissions are evident at the load/speed conditions tested.

It is to be concluded that the effect of water/oil emulsions on the Deutz 714 engine is beneficial in terms of both reduced NO_x and particulate emissions.

8.2 Deutz F8L 413 Engine

The emulsion fuel system schematic used in tests on the larger 413 engine is shown in Figure 8.3. This is similar to that used with the 714 engine, but perhaps a little simpler in design. A larger capacity HydroShear was employed to satisfy the higher fuel consumption rate of the 413. The effect of 15% w/w water/oil emulsion on the gaseous emissions from the 413 engine is shown in Tables 8.3 and 8.4 The reduction in NO_x emissions was modest, ranging from 21% to 33%, but NO_2 emissions were reduced by 50% to 100% although only in the 10 ppm range. The emulsion had detrimental effects on the CO and THC emissions. Table 8.4 shows THC increased by 1-7 to 25 times baseline value, and CO increased by 36% to 236%. Table 8.5 shows the effect of the emulsion on particulate emissions. Total particulate increased, particularly at the intermediate load condition, due to the large increase in soluble organic fraction.

The results found in the 413 engine studies contrast those found with the 714 engine. The reasons for this difference could be due either to the difference in engines used, or to a difference in emulsion quality supplied to this larger engine. Poor combustion characteristics of the emulsified fuels is supported by the increased fuel consumption shown in Table 8.4., in addition to the unfavourable CO and hydrocarbon emissions. Some problems were also experienced with the injection pump when it was found that the delivery valve seats were eroded due to the water/diesel emulsion. This again contrasts with earlier data which showed that many hundreds of hours could be run on the pump for the 714 engine without effect from water emulsions. It is conceivable that water emulsion quality may have affected this larger engine.

An in-depth study is required to resolve the difference between this and earlier work. It may be possible to obtain insight on this problem by carrying out a few tests with emulsion stabilizers in order to reduce the settling out time of the emulsion, and examine the effects on emission characteristics.

It is to be concluded that water emulsions require further study to resolve the contrasting results from the 413 and 714 engines. The effect of combining water emulsion technology with other emission control approaches is described in the following section.

TABLE 8.1

The Effect of ∿ 14% w/w Water/Fuel Emulsion on the Gaseous Emissions of a Deutz F6L 714 Diesel Engine

Speed (rpm)	Load (kW)	Torque N.m.	Water % w/w	Concentrations and Emission Rates										
				NO			NO_2		THC			CO		
				ppm	g/hr	% Reduction	ppm	g/hr	ppm	g/hr	% Increase	ppm	g/hr	% Increase
2200	90	385	0	530	305	35%	<1	<1	22	7.6	36%	176	94.4	2%
			15	345	198		<1	<1	30	10.3		180	96.6	
1625	70	407	0	430	190	28%	<1	<1	20	5.2	90%	168	69.3	-20%
			13	310	137		<1	<1	38	9.9		133	54.9	
2200	71	305	0	600	359	32%	20	18	30	10.4	-16%	112	62.5	0
			15	410	245		<1	<1	25	8.7		112	62.5	
1500	48	305	0	480	210	33%	30	20	15	3.8	130%	73	29.7	26%
			13	320	140		20	13	35	8.8		92	37.5	

TABLE 8.2

The Effect of 14% w/w Water/Fuel Emulsion on the Particulate Emissions from a Deutz F6L 714 Engine

Speed (rpm)	Load (kW)	Torque N.m.	Water % w/w	Avg. Particulate Concentrations and Emission Rates								
				Total Particulate			Insolubles			S.O.F.		
				mg/m^3	g/hr	% Reduction	mg/m^3	g/hr	% Reduction	mg/m^3	g/hr	% Reduction
2200	93	407	0	72.1	33.2	40	52.5	24.2	41	7.4	3.4	3
			14	43.1	19.8		31.1	14.3		7.1	3.3	
1625	70	407	0	118.6	42.0	62	86	30.4	58	16.6	5.9	75
			14	44.7	15.8		361	12.8		4.4	1.5	

TABLE 8.3

Water Emulsion Gaseous Emissions for a Deutz F8L 413

Speed (rpm)	Load kW	% H_2O (w/w)	BSFC (kg/hr/kW)	Nitric Oxide					Nitrogen Dioxide					Total Oxides of Nitrogen (NO & NO_x)				
				ppm	g/kg-hr	g/hr	g/kg Fuel	% ** Decrease	ppm	g/kg-hr	g/hr	g/kg Fuel	% ** Decrease	ppm	g/kg-hr	g/hr	g/kg Fuel	% ** Decrease
2300	138		.280	590	3.68	507	13.1		10	.10	13.2	.341		600	3.77	520	13.5	
2300	138	14	.287	450	2.81	387	9.78	23.7	0	.00	0.0	.000	100	450	2.81	387	9.78	25.6
2300	104		.307	550	4.50	467	14.7		10	.226	13.0	.409		560	4.63	480	15.1	
2300	104	15	.331	405	3.57	370	10.8	20.8	5	.0675	7.0	.204	50	410	3.63	377	11.0	21.5
2000	63		.313	430	5.99	380	19.1		10	.214	13.5	.682		440	6.20	393	19.8	
2000	63	15	.336	270	4.14	263	12.3	30.8	0	.00	0.0	.000	100	270	4.14	263	12.3	33.1

** wrpt g/hr

TABLE 8.4

Water Emulsion Gaseous Emissions for a Deutz F8L 413

Speed (rpm)	Load kW	% H_2O (m/m)	FC (kg/min)	BSFC (lb/hr/kW)	% Increase	Total Hydrocarbons					Carbon Monoxide				
						ppm	g/kg-hr	g/hr	g/kg Fuel	% Increase	ppm	g/kg-hr	g/hr	g/hr Fuel	% Increase
2300	138		.644	.280		75	.272	37.6	.972		350	2.04	281	7.27	
2300	138	≈14	.660	.287	2.5	130	.473	65.3	1.65	73.7	700	4.08	562	14.2	100.
2300	104		.531	.307		56	.264	27.3	.858		144	1.10	114	3.58	
2300	104	≈15	.571	.331	7.8	1400	7.08	734	21.4	2590.	450	3.70	383	11.2	236.
2000	63		.331	.331		*41	.304	19.2	1.06		78	1.01	64.3	3.24	
2000	63	≈15	.355	.336	7.3	100	.857	54.3	2.55	180.	96	1.37	87.2	4.09	35.6

* Estimate from previous baseline data

TABLE 8.5

Particulate Emissions from Bare Engine and Engine Run on Water Emulsion

Speed (rpm)	Load kW	% H_2O	FC (kg/min)	BSFC	Insoluble					Soluble					Total				
					mg/m^3	g/kg-hr	g/hr	g/kg Fuel	% * Decrease (Avg.)	mg/m^3	g/kg-hr	g/hr	g/kg Fuel	% * Increase (Avg.)	mg/m^3	g/kg-hr	g/hr	g/kg Fuel	% Increase (Avg.)
2300	138		.636	.277	91.3	.450	62.0	1.63		11	.054	7.47	.196		102	.504	69.5	1.82	
2300	138		.650	.283	82.6	.416	57.4	1.47		8.3	.042	5.76	.148		90.9	.458	63.1	1.62	
2300	138		.645	.281	70.2	.351	48.4	1.25		7.5	.037	5.17	.134		77.7	.388	53.5	1.38	
2300	138	13	.660	.287	69.2	.346	47.7	1.20		31.4	.157	21.6	.546		101	.502	69.3	1.75	
2300	138	14.4	.660	.287	87.0	.434	59.9	1.51											
2300	138	15.3	.659	.287	65.4	.326	45.0	1.14	9.1	17.1	.085	11.8	.298	172.	82.5	.411	56.8	1.44	1.6
2300	104		.553	.309	41.5	.273	28.3	.885		23.5	.155	16.0	.501		65.0	.428	44.3	1.39	
2300	104		.526	.304	47.5	.308	32.0	1.01		10.8	.070	7.27	.230		58.2	.378	39.2	1.24	
2300	104		.535	.310	35.4	.234	24.2	.755		16.3	.108	11.2	.348		51.7	.341	35.4	1.10	
2300	104	14.3	.565	.327	41.1	.286	29.7	.875		116	.807	83.7	.247		157	1.09	113	3.34	
2300	104	15.4	.573	.332	34.8	.246	25.5	.741		130	.919	95.2	2.77		164	1.16	120	3.50	
2300	104	14.8	.576	.333	36.0	.256	26.5	.767	3.3	157	1.11	115	3.33	744.	193	1.37	142	4.10	215.
2000	63		.336	.318	20.8	.235	14.9	.740		11.6	.131	8.32	.413		32.1	.363	23.0	1.14	
2000	63		.329	.311	23.4	.259	16.4	.833		26.6	.295	18.7	.947		50.0	.554	35.1	1.78	
2000	63		.327	.310	19.3	.213	13.5	.687		20.3	.224	14.2	.722		39.6	.436	27.7	1.41	
2000	63	14.1	.334	.316	16.1	.186	11.8	.588		37.9	.440	27.8	1.39		54.0	.624	39.6	1.97	
2000	63	15.2	.355	.336	13.9	.171	10.8	.508		28.9	.355	22.5	1.06		42.8	.526	33.3	1.56	
2000	63	16.7	.354	.335	12.8	.157	9.94	.468	27.3	26.5	.325	20.6	.969	72.0	39.3	.481	30.5	1.44	20.5

Note: % increase/decrease is calculated using g/h and determined with respect to baseline emissions.

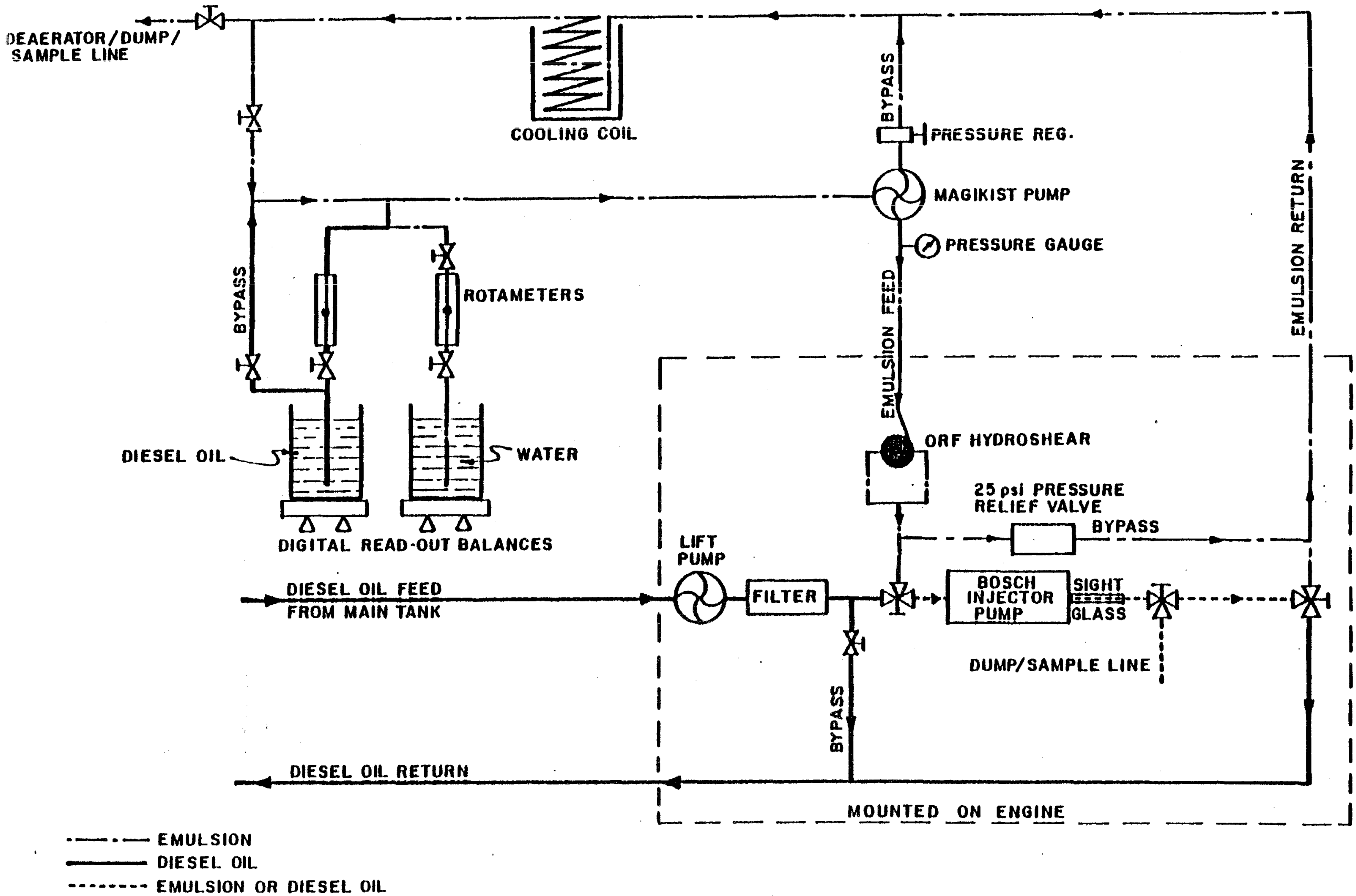


FIGURE 8.1

SCHEMATIC OF THE MODIFIED DEUTZ DIESEL ENGINE FUEL SYSTEM WHICH ALLOWS OPERATION ON WATER/FUEL EMULSION OR NEAT FUEL .

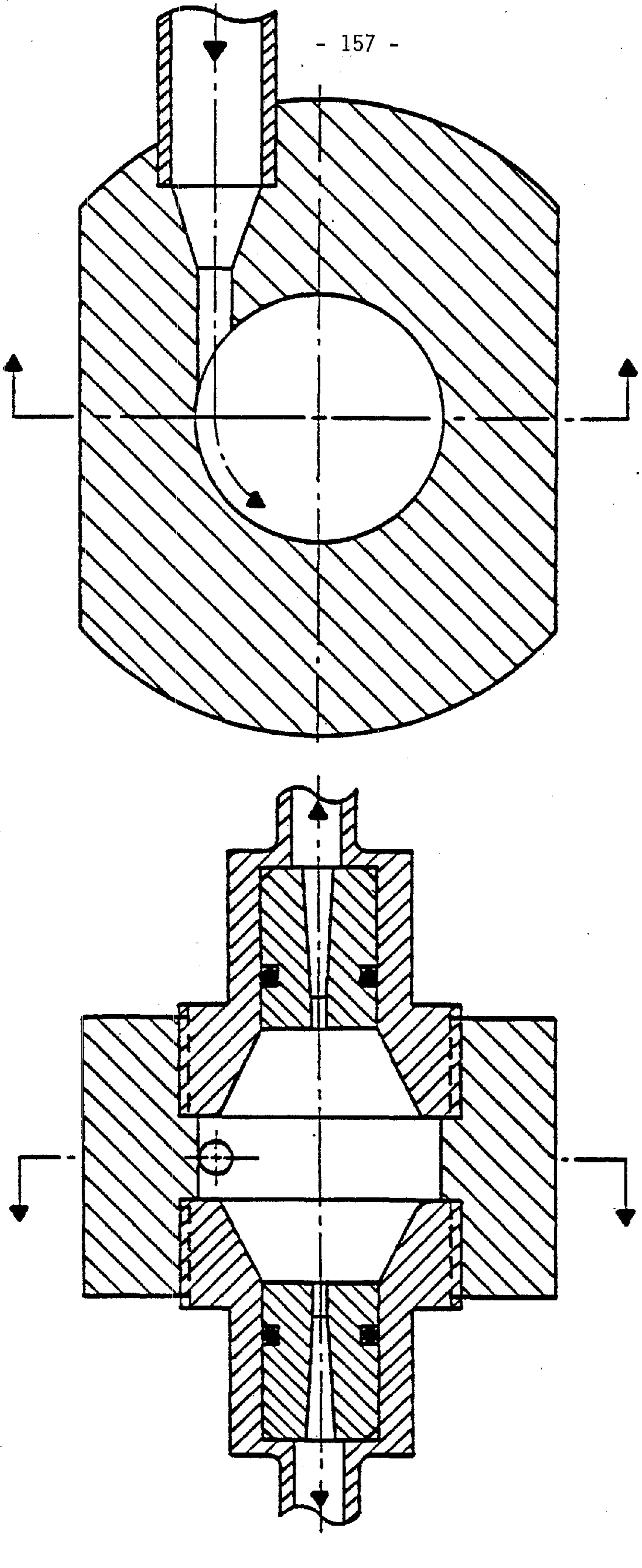


FIGURE 8.2 DUAL DISCHARGE HYDROSHEAR

(2 X FULL SCALE)

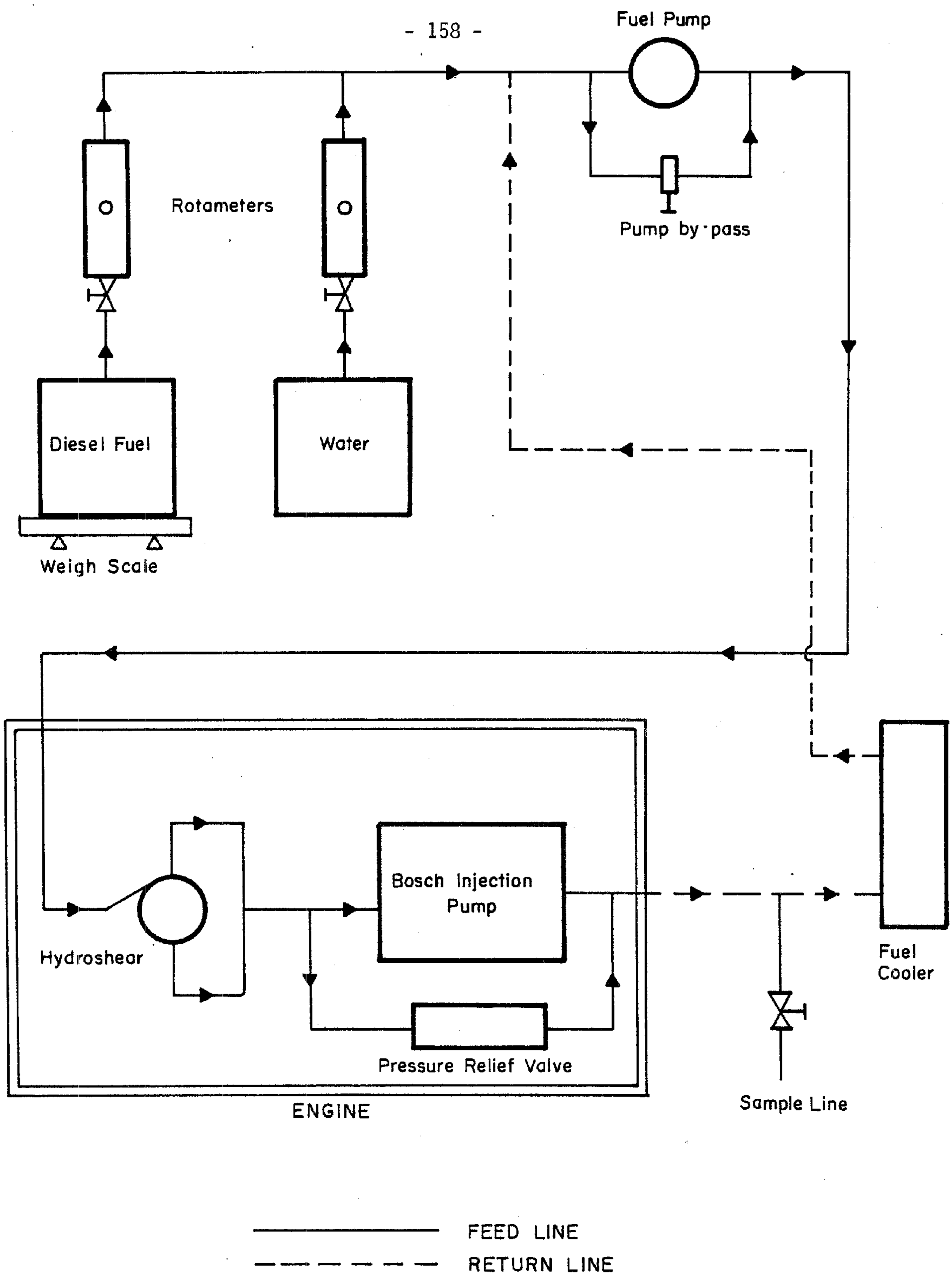


FIGURE 8.3: EMULSION FUEL SYSTEM SCHEMATIC FOR THE DEUTZ F8L 413

9. COMBINED SYSTEMS

9.1 Catalyst/Filter Combinations

The mesh filter has been shown to be effective in the removal of diesel particulate. Catalysts are effective in controlling CO and THC emissions, which is of special interest since these pollutants can be substantially increased when using EGR or water emulsion techniques. Catalysts, however, tend to produce undesirable sulphate and NO_2 emissions. It was of interest therefore to examine the filter's potential for reducing sulphate emissions by testing a catalyst/filter combined device.

Accordingly, a PTX catalyst was installed in the exhaust of a Deutz F6L-714 engine, upstream of the filter, and SO_2/H_2SO_4 analysis carried out at the inlet and outlet of the filter, while the engine was operated at 2200 rpm, 93 kW. Analytical tests did not commence until the filter had been loaded with particulate to the extent that the pressure drop was 36 cm H_2O. Test data were therefore collected over a period during which the pressure drop varied between 36-55 cm H_2O. In this test series, the mesh filter was operated on exhaust cooled by water injection upstream of the filter and downstream of the catalyst. Two cooling water flowrates were employed during the test series; 2.2 kg/min, similar to that used in particulate testing, and 1.5 kg/min, a lesser water flow rate designed to maintain the filter temperature at $100^{o}C$, but not create particulate water in the gas stream.

The results are shown in Table 9.1. Several important conclusions can be drawn:

1. The accountability of the total sulphur measured by the controlled condensation method is excellent.

2. The filter is highly efficient in removing H_2SO_4 showing an average removal efficiency of 95%.

3. The filter also reduces SO_2 concentrations by an average of 33%, presumably because of solution in the cooling water.

4. Little difference in removal efficiency is apparent when the cooling water flow rate is reduced from 2.2 kg/min to 1.5 kg/min.

These results clearly render the catalyst much more viable as a component of a combined emission control device.

Further testing of catalyst/filter combinations were carried out using the Deutz F8L-413 engine, and operating the mesh filter in an uncooled mode. Table 9.2 shows the effect of the uncooled catalyst/filter combination on the SO_2 and $SO_4^{=}$ emissions. In contrast the SO_2 emissions are largely unaffected by the dry uncooled filter. However, sulphates are still removed significantly by the hot filter, with collection efficiencies ranging from 24-75%. The mesh filter in this series of tests was the high bulk density filter of 185 kg/m^3. Testing was also carried out on the low bulk density filter (130 kg/m^3) in combination with a catalyst. The results (Table 9.3) still show good $SO_4^{=}$ trapping efficiency, ranging from 46-79%.

Testing of the catalyst/mesh filter combination for insoluble and total particulate (excluding $SO_4^{=}$) removal was also carried out, and the results compared with that of operating the filter alone. Table 9.4 shows that there is little difference between catalyst/filter and filter alone, with perhaps a trend towards improved efficiency with the filter acting alone at these load/speeds.

The major benefit of the catalyst/filter combination is that it allows the catalyst to act in controlling CO and THC emissions (such as might be increased by EGR application) while minimizing the sulphate emissions produced by the catalyst. Catalyst/Corning filter combinations will likely produce similar results although this system has not been tested in the present program. Furthermore, it is possible that the catalyst may act beneficially to improve the potential of in-situ filter regeneration using engine exhaust heat, by accelerating the rate of carbon combustion. This subject will be addressed in detail in a follow on Phase III project to the present program.

9.2 EGR Combined System

9.2.1 EGR/Catalyst/Mesh Filter Combination

This system was considered of interest because it offered the following advantages:

- EGR will reduce NO_x emissions, but increase CO, THC and particulate emissions.

- The catalyst will reduce the increased CO and THC emissions created by the EGR.

- The filter will reduce particulate emissions, including those generated by EGR, and sulphates generated by the catalyst.

Testing was therefore carried out on the Deutz F6L-714 engine to determine the magnitude of these effects. The test rig schematic for this set of tests is shown in Figure 9.1. The exhaust from both banks was combined and passed through an Engelhard PTX 623 DF catalyst (A), followed by an 'inlet' sampling point (B). The exhaust was then cooled by the atomized water spray (C). The EGR take-off point (D) followed the water spray, so that cooled, moist exhaust was directed to the engine air intake (E) before the air cleaner (F), by a flexible stainless steel pipe. The amount of EGR was controlled by a self-clamping butterfly valve (G). Immediately after the EGR take-off point was the USBM particulate filter (H), followed by the 'outlet' sampling point (J). The conditions tested were 2200 rpm and 1500 rpm at 75% load with 21% EGR.

The USBM filter material was washed once (with Diverfos 207) and rinsed, then 5.25 hours of running time was accumulated before this set of particulate tests was started.

Table 9.5 shows that the capability of the USBM filter to remove particulate remained excellent. 87% to 93% of the insoluble particulate matter was removed after the filter had remained in the exhaust 5.25 to 8.0 hours respectively. The pressure drop across the filter at 8 hours was 57 cm of water; correspondingly the engine backpressure is 90 cm of water. The soluble organic fraction was reduced almost to half the original value by the filter. The SOF was also reduced almost to half by the PTX catalyst, as seen when the first inlet test (without PTX) is compared to the second inlet test, which was controlled by the PTX. However, the outlet emissions for the two tests were 1.2 - 1.0 g/hr. This suggests the catalyst has little effect on net SOF emissions at the filter outlet, and that the filter is an effective trap for SOF.

All three particulate tests were done with 21% EGR, which caused relatively high particulate emissions. It is encouraging to note the very low particulate emission rates (4-6 g/hr) at the outlet of the filter, even after the filter had been in use for 8 hours.

A check was made to determine the effect of the mesh filter on the PTX, EGR treated gaseous emissions. As seen in Table 9.6 the filter has no effect on the emission rates of the gases measured.

The effect of EGR on gaseous emissions is shown in Table 9.7. Nitric oxide (NO) was decreased by 62-71% by application of 21% EGR. Nitrogen dioxide (NO_2) cannot be detected in the exhaust after the catalyst when the EGR is applied, presumably because of the decreased amount of oxygen present. Total hydrocarbon emissions (as measured by the FID) doubled at 2200 rpm and remained unchanged at 1500 rpm. Carbon monoxide also did not increase with application of 21% EGR as measured at the outlet of the catalyst. These results are consistent with the results described in Section 6, which showed that the catalyst successfully controlled the increased THC and CO which were produced when EGR was employed.

It can be concluded that the EGR/PTX catalyst/USBM filter emission control package has been shown to be an effective combination as tested at 2200 rpm and 1500 rpm at 75% load. The addition of EGR to the package succeeded in decreasing nitric oxide by 65% and nitrogen dioxide was below the detection limit. Carbon dioxide and total hydrocarbons were also greatly reduced by the PTX catalyst and the filter was very effective in reducing particulate including sulphates. In subsequent tests of EGR systems, described below, the amount of EGR was limited to 10-15%, which reduced the impact of increased CO and THC emissions, while maintaining respectable NO_x reductions.

9.2.2 EGR/Corning Filter Combination

This system employs the Ceramic Corning filter unit, described earlier, together with EGR. No catalyst was present in this series of tests which were run on the Deutz F8L-413 engine, due largely to concern of the added pressure drop burden this would place on the operating life of the filter between regenerations, and also in part to practical reasons, since the Corning filter became available late in the program. As a result of filter regeneration capability shown earlier, the primary interest, during this phase, was to determine the impact of increased particulate emissions due to EGR on the regeneration activity, efficiency and load up times of the filter. In this series of tests, a comparison was therefore made of the effectiveness of the following three systems:

- EGR alone
- EGR/Corning Filter
- Corning Filter alone

Figure 9.2 shows schematics of the various engine test configurations. The location of the emission sampling points are indicated, together with the EGR control valve in appropriate schematics. In the case of the EGR/Filter system, EGR was taken downstream of both filter units, so that "clean" EGR was applied to the intake combustion air, minimizing recycling of particulate matter. Figure 9.3(a) shows a photograph of the EGR intake system to the engine, and Figure 9.3(b) shows the EGR control valve located downstream of both filter units. This configuration was used for the 10% EGR tests. However, with 15% EGR, it was found necessary to locate EGR input further downstream in the air intake, in order to maintain the intake air temperature below 40°C. The amount of EGR applied to the engine was calculated from the CO_2 values measured in the intake combustion air.

The percentage of EGR employed in this test series varied between 10% and 15%. EGR was limited to 10% at full load/speed condition (2300 rpm, 138 kW) for two reasons; one, to limit the increase in particulate emissions, and the second, so that 2300 rpm, 138 kW could be maintained with and without EGR for comparative purposes. Greater than 10% EGR would result in inability to achieve rated speed, full load conditions. At off full load condition it was possible to apply higher and varying percentages of EGR while maintaining the same load/speed condition.

Gaseous Emission Characterisics

Table 9.8 shows the gaseous emission characteristics emitted from the engine with and without the application of the EGR/Filter combination. This data is represented in bar graph form in Figure 9.4 for No_x emissions and in Figure 9.5 for CO and THC emissions. Reduction in NO_x emissions of 40% occur with 10% EGR at full load/speed condition. At off full load condition, 10% EGR produces a 30% reduction in NO_x and 15% EGR at 50% NO_x reduction. Increases in CO emissions, and the absolute values of the emission rates, become of significant concern only at full load/speed condition with 10% EGR, where the emission rate doubles. If required, it should be possible to control this with catalyst application. THC emission increases are relatively small at off full load condition, with 10% EGR, becoming of greater concern with 15% EGR. At full load/speed condition, no change in THC emission was detected with 10% EGR application.

It can be concluded that it appears feasible to employ 10% EGR at full load conditions in order to reduce NO_x emissions without serious penalty to THC emissions. At off full load condition greater than 10% EGR may be applied. The need for catalyst control of CO and THC emissions resulting from EGR application, may be evaluated by applying appropriate information based on steady state engine test stand data to an Exhaust Quality Index (CANMET Formula). The validity of this exercise is discussed in Section 10 of this report.

Particulate Emission Characteristics

Table 9.9 shows the particulate emissions obtained from the bare engine. Table 9.10 shows the particulate emission characteristics from the engine equipped with the Corning filter units. Simultaneous sampling of particulate matter upstream and downstream of the filter was not possible in this case due to the location of the filter close to the exhaust manifold. Table 9.11 shows the new data from the engine with EGR application, and Table 9.12 shows the particulate emission characterisitcs from the engine equipped with the EGR/filter combination.

These data are reduced to a form convenient for interpretation in the bar graphs shown in Figures 9.6-9.9. Figure 9.6 shows a comparison of the three emission control strategies, EGR, EGR/Filter and Filter, on particulate emission rates, together with the bare engine particulate emission characteristics. Insoluble, soluble organic fraction (SOF) and total particulate emission rates are shown at full load/speed condition of 2300 rpm, 138 kW. It should be noted that the data is plotted on long-linear axes to make the lower emission rates, after the filter, more sensitive to interpretation. The data shows that the effect of 10% EGR is to increase insoluble particulate and decrease SOF. The filter is more effective in reducing the insolubles, so that the net effect on the EGR/Filter combination is that its performance for total particulate removal is quite similar to the filter alone.

Figure 9.7 shows a similar set of data at off full load condition, 2300 rpm, 104 kW. At this load/speed condition, the SOF is a greater percentage of the total particulate than occurred at full load/speed condition. The impact of 10% EGR is again to reduce the SOF and increase the insolubles, with the net result that total particulate with EGR is increased only 5% above the baseline value for the bare engine. The filter is more effective in removing insolubles than SOF, but, in addition, it appears that the EGR/Filter combination, at this load/speed is also more effective in reducing SOF than at a full load/speed condition. The sum total of these effects is that the EGR/Filter combination exhibits a superior performance for total particulate removal, at this load/speed condition, than does the filter alone. Figure 9.8 shows a similar effect at 2000 rpm, 63 kW.

Finally Figure 9.9 shows a comparison of the efficiencies of the EGR/Filter system, and filter alone, for particulate emission reduction. The benefits of the EGR/Filter combination over the filter alone, for both particulate and NO_x reduction suggests that this system merits further development.

Filter Load-Up Times and Regeneration Potential

Filter load-up times were monitored by following changes in engine backpressure upstream of the Corning filter units. Figure 9.10 shows a composite plot of engine backpressure measured during a series of filter load-ups and regeneration, with and without EGR application. The vertical lines indicate a change in load/speed condition which instantly affects the value of the engine backpressure. Arrows indicate where the engine had been stopped and restarted. At time zero, the engine was operated under full load, and the backpressure was observed to remain constant, indicating both loading-up and burning-off. At four hours, the load/speed condition was changed to three-quarter load, with a corresponding drop in backpressure. Backpressure was then observed to increase steadily as the filter loaded up. At nine hours from the reference point, a successful burn-off was achieved by moving the engine to full load/speed condition, and at about ten hours, the load/speed condition was again changed to a lower load/speed condition. The increase in backpressure reflected operation and filter load-up under these conditions. At eighteen hours, another filter burn-off was achieved at full load/speed condition. After the backpressure had reduced to about 4.5 kPa, 9% EGR was applied to the engine. The backpressure increased, suggesting filter load-up, and thus was continued at two other load speeds of 2300 rpm, 104 kW, and 2000 rpm, 64 kW. At twenty-eight and a half hours, the engine was moved into full load/speed condition, while maintaining 7.5% EGR, and on this occasion, a successful filter burn-off was achieved, as evidenced by the decreased backpressure. Particulate burn-off continued to be evident when the EGR was increased to 9.5% and, at thirty two and a half hours, the load/speed condition was decreased to 2300 rpm, 104 kW, while the EGR was increased to about 15%. The increase in backpressure reflects the loading up of the filter. Loading up was continued after thirty seven hours for a further three hours at the lower condition of 2300 rpm, 63 kW, which completed the composite test sequence.

It is evident that it is also possible to regenerate the filter when EGR is being applied, although the conflicting results require further study. It is also evident that EGR application does not create a large impact on filter load up times. Figure 9.11 shows a comparison of the increase in engine backpressure obtained from operating the engine with the Corning filter alone, and with 9% and 14.6% EGR application together with filters. The difference in slopes is not excessive. Figure 9.12 shows similar data, and results, at a lower load/speed condition. Figure 9.13 shows the constant backpressure achieved at full load/speed condition, with and without EGR. In this case, little difference was observed with and without EGR. Figure 9.14 shows the successful particulate burn offs with and without EGR, plotted on a more sensitive scale than Figure 9.10.

It appears that EGR application is not detrimental to filter load up times and may not affect filter regeneration potential. Table 9.13 shows the operating characteristics measured during the present series of tests. The latter was estimated at a given load/speed condition, assuming that the engine was operated steady state, and that there was an essentially linear increase in engine backpressure until the maximum tolerable backpressure value was reached. Projected lifetimes at steady state operation (i.e. without regeneration) range from twenty four to fifty two hours. Clearly the engine never operates in that mode on-board a vehicle, so that filter lifetimes are likely to be longer than those measured in Table 9.13 since intermittent particulate burn off is expected to occur at certain times during the mines vehicle duty cycle.

9.3 Emulsification Combined Systems

9.3.1 Emulsification/Catalyst/Mesh Filter Combination - 714 Engine

This system has similar emission reduction objectives to that of the EGR/catalyst/filter combination with the emulsification approach replacing the EGR approach to NO_x reduction. Additional benefits were experienced since the emulsification approach had the potential for reducing particulate emissions from the Deutz 714 engine, whereas the EGR approach increased particulates.

Tests were therefore carried out on the Deutz F6L 714 engine using the emulsification system described earlier, together with a PTX catalyst, and USBM filter operated in a cooled mode. At the time of collecting particulate samples, the USBM filter had been subjected to three cleaning cycles, and operated on the engine for an additional 11 hours. Table 9.14 shows that the combined effects of water emulsion and filter serve to reduce total particulate emission rates by 83-88%, and insoluble particulate matter by 92-94%. This results in very low total particulate emission rates from this combination of devices amounting to only 3-5 g/hr.

The effect of such a system on gaseous emissions is demonstrated by examining the catalyst impact on gaseous emissions produced from the combustion of 14% water/diesel fuel emulsion. Table 9.15 shows the results. At 2200 rpm, full load, there was no conversion to NO_2 by the catalyst, but as the speed and load decreased, increasing quantities of NO_2 were found in the exhaust. The catalyst was, however, capable of controlling the CO and THC emissions, even through they were increased by water emulsion application. The net effect was a significant reduction in all emission components except for NO_2 which increased at certain load/speed conditions. Sulphates produced by the catalyst were controlled by the filter as described earlier. The impact of this combination on emissions can be seen by comparison to the effects on emissions of using water emulsion alone as described in Figures 8.1 and 8.2. Here, although there are reductions in NO_x emissions, there are also increases in THC and CO and a smaller decrease in particulates.

9.3.2 EGR-Emulsification - Corning Filter - 413 Engine

It was shown earlier that the application of water emulsions to the 413 engine produced much less favourable results than on the 714 engine, for reasons yet unknown. It was of interest, however, to investigate the combined effect of water emulsion and EGR on the 413 engine. Since water emulsion increased the SOF dramatically in the 413 engine, which resulted in a net increase in total particulate emissions, and since EGR had been found to decrease SOF it was considered that the combined effect of both approaches would produce an interesting result. Tests were therefore carried out on the 413 engine at two load/speed conditions of 2300 rpm/104 kW and 2000 rpm/63 kW, using a combined water emulsion/EGR/Corning filter approach. The full load/speed condition could not be achieved in this series of tests due to derating from the combined effects of the water emulsion and EGR. 13-15% water emulsion was applied together with 14% EGR.

The effect of the combined approach on particulate emissions is shown in Table 9.16. The increased particulate emissions, created by the water emulsion, have now been controlled by the combined effect of EGR reducing the SOF and the filter removing the insoluble particulate. Total particulate reductions of 45-81% are evident. In addition to these benefits, Table 9.17 shows that NO_x emissions are reduced by 69-75%. However, significant increases in THC and CO emissions still remain as shown in Table 9.18. These emissions would likely require control with catalyst application.

It is of interest to compare the effect on particulate emissions of the various emission control strategies applied to the 413 engine. Figures 9.15 and 9.16 show this comparison in bar graph form at the two load/speed conditions of 2300 rpm, 104 kW, and 2000 rpm, 63 kW respectively. At 2300 rpm, 104 kW, the particulate reductions created by the H_2O emulsion/EGR/Filter combination are not as good as either the filter alone, or the EGR/Filter combination, probably because of the large SOF impact from the water emulsion. At 2000 rpm, 63 kW, however, the H_2O emulsion/EGR/Filter combination proves to perform better than all other devices. If the performance of the water emulsion system on the 714 engine could be duplicated on the 413 engine, extremely effective emission control should be achieved with the H_2O emulsion/EGR/Filter combination approach. Further work is in progress to resolve the issue of water emulsion application to the Deutz 413 engine.

9.4 Conclusions on Combined Systems

There is clearly a trade-off between the various emission control approaches in terms of their effectiveness in controlling different exhaust emission components, relative to the complexity of the device employed, and to the reduction of one pollutant at the expense of increase in other pollutants. This is apparent from Tables 9.19 and 9.20.

Table 9.19 summarizes the patterns of changes in emissions indicated by the application of some of the various control systems tested, both singly and in combination. The numbers assigned are based on average data at the indicated load/speed condition assembled from the various tests run during the program and rounded to the nearest 5%. Table 9.20 compares the effects of combined systems with the Corning Filter versus the individual devices operating alone on particulate, NO_x, CO and THC emissions as applied to the 413 engine at two specific load/speed conditions.

The Corning Filter, which exhibited excellent particulate reduction capability was teamed with EGR to provide NO_x reduction. The tendency of EGR to increase particulates is generally cancelled by the filter. Over the range of the two load/speed conditions shown (Table 9.20), the H_2O emulsion/EGR/Corning Filter system was able to reduce particulates by 45-90% and NO_x by 70-75%. The EGR/Corning Filter device showed higher particulate reductions of 90% but lower NO_x reduction of about 50%. The Corning Filter alone reduced particulate by 70-75% but there was no NO_x reduction. At the same time some EGR conditions showed relatively modest increases in THC and CO emissions.

The catalyst/mesh filter combination with water spray cooling for the filter provides good reductions of CO, THC and particulates but has no effect on NO_x. In this case, addition of HydroShear water/fuel emulsification adds a moderate NO_x reduction with continued substantial particulate reductions. The catalyst/mesh filter combination when run dry, without water spray, gives similar results to water cooled operation except that SO_2 is no longer reduced by the filter. There is significant reduction of sulphates across the dry filter as with the wet version although the wet filter is much more effective. Some H_2SO_4 impact remains, however, to offset the advantage of CO and THC reduction. The mesh filter alone also produces good particulate reduction without an H_2SO_4 impact, although the CO impact remains the same as with the uncontrolled engine. There is, perhaps, more justification for applying a catalyst in combination with water emulsion systems in order to reduce the trend for increased CO and THC emissions. The latter trend was found to be more severe with the 413 engine than with the 714 engine, which is a result requiring further clarification in future studies.

On the Deutz F6L-714 engine, the Gaspe water scrubber showed modest particulate reduction capability. Good reduction of CO and THC was offered when the scrubber was combined with a catalyst. In addition, the scrubber was found to provide good removal of SO_2 as well as about 30% of the sulphate which was generated over the catalyst. However, NO_x emissions remain unchecked and also some undesirable NO to NO_2 formation was observed through the water scrubber. However, an H_2SO_4 impact remained, so that there is a trade-off, and a judgement required, as to which is more beneficial: good reduction of CO and THC emissions at the expense of increased H_2SO_4 emissions, or uncontrolled CO and THC emissions with no change to H_2SO_4 emissions. Addition of EGR to this system provides the expected control of NO_x emissions to a level of about 80% reduction with the penalty, however, of greatly increased particulate emissions. In general, these effects were greater at high EGR (20%) and at high speed, full load operation and were moderated at lower EGR and off-load conditions.

Load/speed conditions are also important in assessing the best trade-off. Testing should ultimately be carried out over a typical mines duty cycle to assess the total emission impact, and it is expected such work will be carried out in a subsequent phase of work. A preliminary assessment of the available control technology, may be tried, at present, by gathering the miscellaneous engine test data to try to determine the impact of the emission characteristics of the various emission control approaches on the air quality index (3) and TLV's. This places weighting factors on the impact of reducing various exhaust emission components, and can produce a ranking of emission control device effectiveness relative to air quality and complexity of device. For example, is it better to have high particulate reduction and lower NO_x reduction, or higher NO_x reduction and low particulate reduction, or both high particulate and high NO_x reductions. If the latter, how complex does the device have to be? This topic will be addressed in the following section.

TABLE 9.1

Effect on $SO_2/SO_4^=$ Emissions

Deutz F6L 714 Diesel Engine

Emission Control Devices - PTX Catalyst, USBM Filter

Location wrt.Filter	Sampling Pt. Temp. °C	Cooling Water Flow kg/min.	SO_2 ppm	% Reduction	$SO_4^=$ ppm	% Reduction	Total S ppm	% Reduction	Accountability of Total S % of Total	% of Total S as $SO_4^=$
Inlet	425	-	21.1		20.6		41.7		92	49.4
Outlet	100	1.5	14.9	29	0.4	98	15.3	63		
Inlet	425	-	18.5		23.8		42.3			56.3
Outlet	96	1.5	14.7	21	0.7	97	15.4	64	95	
Inlet	425	-	17.8		22.6		40.4			
Outlet	74	2.2	11.8	34	2.4	89	14.2	65	90	55.9
Inlet	440	-	20.5		23.2		43.7			
Outlet	76	2.2	12.7	38	1.5	93	14.2	68	98	53.1

Speed: 2200 rpm
Load: 93 kW
Torque: 407 N.m
PTX Avg. Temp: 510°C
Calculated Totals S = 44.7 ppm
Fuel Sulphur Conc. = 0.1%
Pressure Drop Across Filter: 36-55 cm H_2O

TABLE 9.2

Effect of Uncooled Catalyst/Filter Combination on $SO_2/SO_4^=$ Emissions

Deutz F8L 413 Engine, Mesh Filter - 185 kg/m^3

Test No.	Speed (rpm)	Load (kW)	Average Catalyst Temp. (°C)	Sample Point*	Sulphur Dioxide (SO_2) ppm	Sulphur Dioxide (SO_2) g/kW.hr	Sulphur Dioxide (SO_2) g/hr	Sulphur Dioxide (SO_2) g/kg Fuel	Sulphates ($SO_4^=$) ppm	Sulphates ($SO_4^=$) g/kW.hr	Sulphates ($SO_4^=$) g/hr	Sulphates ($SO_4^=$) g/kg Fuel	Sulphate Collection Efficiency (%)
1	2300	139	532	Inlet	61.5	0.786	109	2.96	30.8	0.590	82.0	2.22	75
				Outlet	61.8	0.790	110	2.97	7.6	0.146	20.2	0.548	
2	1600	112	461	Inlet	18.5	0.215	24.0	0.96	38.5	0.670	75.1	3.06	69
				Outlet	18.4	0.219	24.5	0.96	11.8	0.210	23.5	0.923	
3	2000	99	348	Inlet	23.5	0.433	42.8	1.75	21.0	0.580	57.4	2.34	29
				Outlet	26.5	0.478	47.4	1.86	15.3	0.414	41.0	1.61	
4	2300	69	306	Inlet	27.0	0.701	48.4	2.13	10.5	0.409	28.2	1.24	44
				Outlet	30.7	0.754	52.0	2.43	6.2	0.228	15.8	0.736	
5	2300	103	381	Inlet	18.1	0.299	30.8	1.08	25.0	0.619	63.7	2.24	24
				Outlet	14.4	0.238	24.5	0.86	19.0	0.470	48.5	1.70	
6	2300	139	487	Inlet	22.1	0.270	37.5	1.06	40.9	0.749	104	2.95	37
				Outlet	22.0	0.269	37.4	1.06	25.6	0.469	65.2	1.85	
7	2300	139	543	Inlet	52.2	0.663	92.1	2.50	40.2	0.763	106	2.88	52
				Outlet	35.7	0.453	63.0	1.71	19.2	0.365	50.8	1.38	

* Location relative to Mesh filter

NOTE: Filter bale cleaned between tests 4 and 5 and between tests 6 and 7.

TABLE 9.3

Effect of Uncooled Catalyst/Filter Combination on SO_2/SO_4 Emissions

Deutz F8L 413 Engine, Mesh Filter -- 130 kg/m^3

Test	Flow (m^3/min.)	SO_2 ppm	SO_2 g/h	SO_2 g/kW.h	SO_2 g/kg Fuel	SO_4 ppm	SO_4 g/h	SO_4 g/kW.h	SO_4 g/kg Fuel	SO_4 Reduction (%)
1 Inlet	11.36	46.4	83.9	0.604	2.22	33.5	90.8	0.654	2.40	61
Outlet		49.7	89.8	0.646	2.38	13.1	35.5	0.256	0.939	
2 Inlet	10.91	42.9	74.5	0.536	2.05	37.7	98.2	0.706	2.71	46
Outlet		35.5	61.6	0.443	1.70	20.5	53.4	0.384	1.47	
3 Inlet	11.13	42.3	74.9	0.539	2.02	39.6	105.2	0.757	2.84	55
Outlet		45.7	80.9	0.582	2.19	17.8	47.3	0.340	1.27	
4 Inlet	11.00	41.7	73.0	0.525	1.99	45.3	118.9	0.855	3.25	59
Outlet		43.3	75.8	0.545	2.07	18.7	49.1	0.353	1.34	
5 Inlet	11.00	40.4	70.7	0.509	1.93	38.3	100.6	0.724	2.75	69
Outlet		33.9	59.3	0.427	1.62	12.0	31.5	0.227	0.861	
6 Inlet	11.02	54.1	94.9	0.683	2.59	38.7	101.8	0.732	2.78	79
Outlet		65.1	114.2	0.821	3.11	8.2	21.6	0.155	0.589	

Note: All tests at 2300 rpm and 139 kW

TABLE 9.4

Comparison of Particulate Removal Efficiencies of Mesh Filter with and Without the Catalyst Installed

(Values Normalized to same Pressure Drop Across the Filter)

(Deutz F81-413 Engine)

Speed/Load (rpm/kW)	Insoluble Particulate % Efficiency Catalyst Plus Filter	Insoluble Particulate % Efficiency Filter Only	Total Particulate % Efficiency Catalyst Plus Filter	Total Particulate % Efficiency Filter Only
2300/142	79	87	63	80
2300/107	80	91	55	85
2300/71	76	82	47	62
2000/127	81	90	73	77
2000/95	83	89	61	73
2000/63	81	57*	66	53
1600/114	87	89	77	64

*Suspected spurious result.

TABLE 9.5

The Effect of the PTX Catalyst, Mesh Filter and 21% EGR
on the Particulate Emissions of a Deutz F6L 714 Diesel Engine

Speed rpm	Load kW	Torque N.m	Pressure Drop Across Filter cm H_2O	Engine Back Pressure cm H_2O	Time Elapsed at Start hr	Location wrt Filter	Avg. Particulate Concentrations and Emission Rates								
							Total Particulate			Insoluble Matter			S.O.F.		
							mg/m^3	g/hr	% red'n	mg/m^3	g/hr	% red'n	mg/m^3	g/hr	% red'n
2200*	71	305	33-38	46-52	5.25	Inlet	72.1	27.3	84	63.1	23.8	87	9.1	3.4	65
						Outlet	11.6	4.4		8.4	3.2		3.2	1.2	
2200	71	305	40-43	88-100	6.50	Inlet	77.6	29.3	84	72.5	27.4	87	5.1	1.9	46
						Outlet	12.5	4.7		9.7	3.7		2.8	1.0	
1500	48	305	37-57	66-90	7.75	Inlet	132.4	36.6	90	127.9	35.3	93	4.5	1.3	42
						Outlet	12.7	3.5		10.1	2.8		2.6	0.7	

* PTX catalyst was NOT used during this test

TABLE 9.6

The Effect of the Mesh Filter on the Gaseous Emissions of a Deutz F6L 714 Diesel Engine

Emission Control Devices - PTX, USBM Filter, 21% EGR

Speed rpm	Load kW	Torque N.m	Location wrt Filter	Concentrations and Emission Rates (PTX, 21% EGR Controlled)							
				NO		NO_2		THC		CO	
				ppm	g/hr	ppm	g/hr	ppm	g/hr	ppm	g/hr
2200	71	305	Inlet	210	99	< 1	< 1	20	4.3	24	10.6
			Outlet	200	94	< 1	< 1	18	4.7	24	10.6
1500	48	305	Inlet	195	67	< 1	< 1	4	0.8	18	5.8
			Outlet	195	67	< 1	< 1	4	0.9	18	5.8

TABLE 9.7

The Effect of 21% EGR on the Gaseous Emissions of a Deutz F6L 714 Diesel Engine

Emission Control Devices - PTX, 21% EGR

Speed rpm	Load kW	Torque N.m	EGR %	Concentrations and Emission Rates (PTX Catalyst Controlled)								
				NO			NO_2		THC		CO	
				ppm	g/hr	% red'n	ppm	g/hr	ppm	g/hr	ppm	g/hr
2200	71	305	0	570	341	71	50	46	6	2.1	18	10.0
			21	210	99		< 1	< 1	20	4.3	24	10.6
1500	48	305	0	400	175	62	90	60	3	0.8	14	5.7
			21	195	67		< 1	< 1	4	0.8	18	5.8

TABLE 9.8

Gaseous Emissions - Baseline and with EGR/Corning Filter

(Deutz F81-413 Engine)

Speed (rpm)	Load (kW)	% EGR	Total Oxides of Nitrogen ($NO + NO_2$)					Carbon Monoxide					Total Hydrocarbons as Methane				
			ppm	g/kW.h	g/h	g/kg Fuel	% Increase*	ppm	g/kW.h	g/h	g/kg Fuel	% Increase*	ppm	g/kW.h	g/h	g/kg Fuel	% Increase*
2300	138		730	4.36	601	16.6	(Baseline)	340	1.88	260	7.17	(Baseline)	82	.287	39.7	1.09	(Baseline)
2300	104		610	4.83	501	17.6	(Baseline)	163	1.21	125	4.38	(Baseline)	48	.222	23.0	.808	(Baseline)
2000	63		525	6.94	440	24.1	(Baseline)	81	.99	62	3.4	(Baseline)	41	.304	19.2	1.06	(Baseline)
2300	138	9.5	445	2.58	356	9.43	-40.8	670	3.63	500	13.2	92.3	85	.289	39.9	1.06	0.5
2300	138	9.5	445	2.49	343	9.43	-42.9	670	3.50	483	13.3	85.8	85	.279	38.6	1.06	-2.2
2300	104	9.1	475	3.41	353	12.4	-29.5	185	1.24	128	4.50	2.4	60	.248	25.7	.902	11.7
2300	104	9.2	450	3.25	337	11.7	-32.7	200	1.35	140	4.86	10.7	62	.258	26.7	.933	16.1
2300	104	14.6	330	2.28	236	8.61	-52.9	210	1.35	140	5.11	10.7	85	.338	35.0	1.28	52.1
2300	104	14.6	330	2.29	237	8.61	-52.7	210	1.36	141	5.11	12.8	90	.361	37.4	1.36	62.6
2000	63	10.3	395	4.53	287	16.0	-34.8	95	1.02	64.5	3.58	4.0	55	.354	22.4	1.25	16.7
2000	63	11.3	325	3.65	231	13.2	-47.5	95	.987	62.6	3.58	1.0	67	.420	26.6	1.52	38.5
2000	63	17.3	300	3.13	198	10.7	-55.0	130	1.27	80.3	4.34	29.5	78	.462	29.3	1.58	52.6
2000	63	17.3	300	3.25	206	10.9	-53.2	130	1.31	83.3	4.41	34.3	78	.479	30.4	1.61	58.3

TABLE 9.9

Baseline Particulate Emissions

from the Bare Engine

Deutz F8L 413

Speed (rpm)	Load (kW)	Insoluble				Soluble				Total			
		mg/m^3	g/kW.h	g/h	g/kg Fuel	mg/m^3	g/kW.h	g/h	g/kg Fuel	mg/m^3	g/kW.h	g/h	g/kg Fuel
2300	138	85.7	.407	56.1	1.55	25.4	.121	16.6	.460	111.0	.527	72.7	2.01
2300	138	70.8	.337	46.4	1.28	11.7	.056	7.67	.212	82.5	.392	54.1	1.49
2300	138	78.6	.374	51.5	1.42	15.3	.073	10.0	.277	93.9	.446	61.6	1.70
2300	104	33.9	.216	22.4	.782	20.7	.132	13.7	.478	54.6	.349	36.1	1.26
2300	104	40.9	.258	26.8	.944	6.9	.044	4.52	.159	47.8	.302	31.3	1.10
2300	104	35.9	.227	23.6	.828	15.6	.099	10.2	.360	51.5	.326	33.8	1.19
2000	63	21.0	.220	14.0	.758	24.9	.261	16.6	.900	45.9	.482	30.5	1.66
2000	63	20.9	.216	13.7	.755	31.1	.321	20.3	1.12	52.0	.537	34.0	1.88
2000	63	22.2	.230	14.6	.802	22.8	.236	15.0	.823	45.0	.466	29.5	1.62

TABLE 9.10

Particulate Emissions from the Engine Equipped with Corning Filters

Deutz F8L 413

Speed (rpm)	Load (kW)	Insoluble					Soluble					Total				
		mg/m^3	g/kW.h	g/h	g/kg Fuel	% Efficiency	mg/m^3	g/kW.h	g/h	g/kg Fuel	% Efficiency	mg/m^3	g/kW.h	g/h	g/kg Fuel	% Efficiency
2300	138	8.80	.041	5.70	.159	88.8	4.9	.023	3.18	.088	71.8	13.7	.064	8.88	.247	85.7
2300	138	4.70	.022	3.03	.085	94.0	2.8	.013	1.81	.050	83.9	7.5	.035	4.84	.135	92.2
2300	138	10.2	.048	6.61	.182	87.0	17.0	.080	11,0	.304	2.3	27.2	.128	17.6	.486	71.6
2300	104	5.6	.036	3.71	.136	84.8	9.9	.063	6.56	.240	31.3	15.5	.099	10.3	.375	69.8
2000	104	5.7	.037	3.80	.138	84.6	13.9	.089	9.26	.034	3.5	19.6	.126	13.1	.474	61.8
2000	104	5.8	.038	3.94	.140	84.3	6.6	.043	4.49	.160	54.2	12.4	.081	8.43	.300	75.8
2000	63	2.5	.027	1.70	.092	88.3	9.8	.105	6.65	.361	62.7	12.3	.132	8.34	.453	74.2
2000	63	3.6	.039	2.48	.133	83.2	10.9	.119	7.51	.401	58.6	14.5	.158	9.99	.534	69.6
2000	63	2.6	.027	1.73	.096	87.9	8.1	.085	5.39	.298	69.2	10.7	.011	7.11	.394	77.6

Note: Average emission results from Table 9.9 were used to determine efficiencies on a mass emissions basis at each load/speed condition

Table 9.11

Particulate Emissions from the Engine with EGR Application

(Deutz F81-413 Engine)

Speed (rpm)	Load (kW)	EGR (%)	Insoluble				% Increase * wrpt Baseline	Soluble				% Increase * wrpt Baseline	Total				% Increase * wrpt Baseline
			mg/m^3	g/kW.h	g/h	g/kg Fuel		mg/m^3	g/kW.h	g/h	g/kg Fuel		mg/m^3	g/kW.h	g/h	g/kg Fuel	
2300	138	8.0	157	.700	96.5	2.58		15.5	.069	9.53	.255		172	.768	106	2.84	
2300	138	7.8	156	.685	94.5	2.58	82.8	11.7	.051	7.08	.193	-31.6	168	.737	102	2.77	61.9
2300	138	7.8	148	.655	90.3	2.44		11.1	.049	6.77	.183		159	.704	97.1	2.63	
2300	104	12.9	53.9	.294	30.5	1.04		10.5	.057	5.93	.203		64.4	.351	36.4	1.25	
2300	104	12.8	45.7	.251	26.1	.886	20.0	9.1	.050	5.19	.176	-32.8	54.8	.301	31.2	1.06	5.3
2300	104	12.8	53.6	.298	30.9	1.04		13.8	.077	7.96	.268		67.4	.375	38.9	1.31	
2000	63	15.4	25.7	.218	13.8	.763		24.7	.200	13.3	.733		50.4	.427	27.1	1.50	
2000	63	15.4	28.7	.243	15.4	.852	15.4	14.9	.126	8.01	.442	-43.8	43.6	.370	23.4	1.30	-17.0
2000	63	15.4	36.4	.309	19.6	1.08		14.6	.124	7.85	.433		51.0	.433	27.4	1.51	

* Based on mass emissions

Note: Average emissions results from Table 9.9 were used to determine efficiencies on a mass emissions basis at each load/speed condition.

TABLE 9.12

Particulate Emissions from the Engine with EGR/Corning Filter - Deutz F8L 413

Speed (rpm)	Load (kW)	% EGR	Insoluble					Soluble					Total				
			mg/m^3	g/kW.h	g/h	g/kg Fuel	% Efficiency *	mg/m^3	g/kW.h	g/h	g/kg Fuel	% Efficiency *	mg/m^3	g/kW.h	g/h	g/kg Fuel	% Efficiency *
2300	138	9.5	9.0	.042	5.76	.153	88.8	5.5	.026	3.52	.093	69.1	14.5	.0673	9.28	.246	85.2
2300	138	9.5	12.8	.057	7.89	.217	84.6	6.8	.030	4.19	.115	63.2	19.6	.088	12.1	.332	80.7
2300	138	9.5	10.9	.049	6.74	.185	86.9	13.9	.062	8.60	.236	24.6	24.8	.111	15.3	.421	75.6
2300	104	9.3	3.1	.018	1.84	.065	92.4	2.5	.014	1.49	.052	84.3	5.6	.032	3.33	.117	90.1
2300	104	8.9	5.3	.030	3.15	.111	87.0	0.68	.004	.400	.014	95.8	6.0	.034	3.56	.125	89.5
2300	104	9.2	4.6	.026	2.72	.095	88.8	0.92	.005	.551	.019	94.2	5.5	.032	3.29	.115	90.3
2300	104	14.6	4.3	.024	2.48	.090	89.8	3.5	.019	2.02	.073	78.7	7.8	.043	4.49	.163	86.7
2300	104	14.6	3.8	.021	2.23	.079	90.8	2.5	.014	1.47	.052	84.5	6.3	.036	3.69	.132	89.0
2300	104	14.6	3.8	.021	2.18	.079	91.0	2.4	.013	1.37	.050	85.5	6.2	.034	3.55	.129	89.5
2000	63	10.3	6.6	.061	3.84	.214	72.8	7.4	.068	4.31	.239	75.1	14.0	.129	8.15	.453	74.0
2000	63	10.5	5.5	.051	3.24	.183	77.0	5.7	.053	3.35	.189	80.6	11.2	.104	6.59	.372	79.0
2000	63	11.3	3.2	.029	1.81	.104	87.2	3.9	.035	2.20	.126	87.3	7.1	.063	4.01	.230	87.2
2000	63	17.1	2.7	.023	1.43	.077	89.9	2.3	.019	1.22	.066	92.9	5.0	.042	2.65	.143	91.6
2000	63	17.3	3.1	.027	1.70	.090	87.9	4.8	.042	2.64	.140	84.7	7.9	.069	4.34	.230	86.2
2000	63	17.3	2.0	.017	1.05	.058	92.6	2.9	.024	1.52	.084	91.2	4.9	.041	2.57	.143	91.9

* Based on mass emissions

Note: Average emissions results from Table 9.9 were used to determine efficiencies on a mass emissions basis at each load/speed condition.

TABLE 9.13

Test Data EGR and Corning Filter

(Deutz F8L-413 Engine)

Speed (rpm)	Load (kW)	% EGR	Fuel to Air Ratio (lb Fuel/lb Air)	Intake Air (°C)	Cooling Air (°C)	Left Bank Exhaust		Right Bank Exhaust		Average Back Pressure (kPa)	Projected Filter Life hours
						Filter Inlet (°C)	Filter Outlet (°C)	Filter Inlet (°C)	Filter Outlet (°C)		
2300	138	-	.0435	26	25	528	489	568	545	3.8	-
2300	138	9.5	.0470	29	13	543	508	578	554	4.1	constant burn-off
2300	104	-	.0325	30	27	408	381	440	422	3.9	24
2300	104	9.1	.0365	41	16	425	393	445	427	4.6	33
2300	104	14.6	.0365	40	10	398	370	425	412	5.3	17
2000	63	-	.0215	26	21	270	255	274	268	3.2	52
2000	63	10.7	.0240	25	14	270	260	270	260	3.6	24
2000	63	17.2	.0272	37	14	290	278	290	283	5.0	24

TABLE 9.14

The Effect of the PTX Catalyst, Mesh Filter and Water/Fuel Emulsion on the Particulate Emissions of a Deutz F6L 714 Diesel Engine

Speed (rpm)	Load (kW)	Torque N.m	Pressure Drop Across Filter cm H_2O	Engine Back Pressure cm H_2O	Time Elapsed at Start hr.	Location wrt Filter	Average Particulate Concentrations and Emission Rates								
							Total Particulate			Insoluble Matter			S.O.F.		
							mg/m^3	g/hr	% Reduction from Baseline	mg/m^3	g/hr	% Reduction from Baseline	mg/m^3	g/hr	% Reduction from Baseline
2200	93	407	40-49	80-86	11.0	Baseline	61.6	28.3	30	56.0	25.8	45	5.6	2.6	-
						Inlet	43.1	19.8		31.1	14.3		7.1	3.3	
						Outlet	10.6	4.9	88 *	4.2	2.0	92	3.1	1.4	46
1625	70	407	29-35	51-56	12.25	Baseline	78.7	27.8	43	71.8	25.4	50	6.9	2.5	40
						Inlet	44.7	15.8		36.1	12.8		4.4	1.5	
						Outlet	9.3	3.3	93 *	4.2	1.5	94	3.3	1.2	52

* Overall % reduction for combination

TABLE 9.15

The Effect of the PTX Catalyst on the Gaseous Emissions of a Deutz F6L 714 Diesel Engine

Emission Control Devices-PTX, ∿14% w/w Water Emulsion

Speed (rpm)	Load (kW)	Torque N.m.	Water %	Location wrt PTX	Concentrations and Emission Rates (PTX Catalyst Controlled)							
					NO		NO_2		THC		CO	
					ppm	g/hr	ppm	g/hr	ppm	g/hr	ppm	g/hr
2200	90	385	0	Inlet	530	305	<1	<1	22	7.6	176	94.4
				Outlet	520	299	<1	<1	2	0.7	10	5.4
			15	Inlet	345	198	<1	<1	30	10.3	180	96.6
				Outlet	340	195	<1	<1	2	0.7	9	4.8
1625	70	407	0	Inlet	430	190	<1	<1	20	5.2	168	69.3
				Outlet	405	179	35	24	6	1.6	10	4.1
			13	Inlet	310	137	<1	<1	38	9.9	133	54.9
				Outlet	310	317	10	6.7	4	1.0	10	4.1
2200	71	305	0	Inlet	600	359	20	18	30	10.4	112	62.5
				Outlet	570	341	50	46	6	2.1	18	10.1
			15	Inlet	410	245	<1	<1	25	8.7	112	62.5
				Outlet	360	215	30	28	5	1.7	22	12.3
1500	48	305	0	Inlet	480	210	30	20	15	3.8	73	29.7
				Outlet	400	175	90	60	3	0.8	14	5.7
			13	Inlet	320	140	20	13	35	8.8	92	37.5
				Outlet	300	131	40	27	9	2.3	12	4.9

TABLE 9.16

Particulate Emissions from Bare Engine and Engine Equipped with Corning Filter, EGR, Water Emulsion

Deutz F8L 413 F/W

Speed rpm	Load KW	% H_2O	% EGR	FC kg/min	* BSFC	Insoluble				% * Decrease	Soluble				% * Decrease	Total				% * Decrease
						mg/m^3	g/kW-hr	g/hr	g/kg Fuel		mg/m^3	g/kW-hr	g/hr	g/kg Fuel		mg/m^3	g/kW-hr	g/hr	g/kg Fuel	
2300	104			.553	.309	41.5	.273	28.3	.885		23.5	.155	16.0	.501		65.0	.428	44.3	1.39	
2300	104			.526	.304	47.4	.308	32.0	1.01		10.8	.070	7.27	.230		58.2	.378	39.2	1.24	
2300	104			.535	.310	35.4	.234	24.2	.755		16.3	.108	11.2	.348		51.7	.341	35.4	1.10	
2300	104	13.0	14.4	.594	.564	36.2	.179	18.5	.520		17.1	.084	8.72	.245		53.3	.263	27.3	.765	
2300	104	13.0	14.4	.596	.566	37.5	.186	19.3	.539	51.6	11.4	.056	5.84	.163	27.3	48.9	.242	25.1	.702	44.5
2300	104	13.3	13.0	.511	.485	10.7	.052	5.4	.177		19.8	.096	9.98	.326		30.5	.149	15.4	.502	
2300	104	12.8	13.8	.518	.492	22.9	.110	11.4	.365		17.9	.086	8.87	.286		40.8	.195	20.2	.651	
2000	63			.336	.318	20.8	.235	14.9	.740		11.6	.131	8.32	.413		32.1	.363	23.0	1.14	
2000	63			.329	.311	23.4	.259	16.4	.833		26.6	.295	18.7	.947		50.0	.554	35.1	1.78	
2000	63			.327	.310	19.3	.213	13.5	.687		20.3	.224	14.2	.722		39.6	.436	27.7	1.41	
2000	63	14.0	14.6	.307	.477	2.8	.022	1.42	.077		2.9	.023	1.43	.078		5.7	.015	2.84	.154	
2000	63	15.2	13.8	.325	.505	2.6	.026	1.38	.071	90.4	3.1	.026	1.67	.085	86.9	5.7	.048	3.05	.156	88.5
2000	63	15.2	13.8	.298	.463	3.1	.037	1.52	.085		4.8	.037	2.33	.130		7.9	.061	3.85	.215	

* BSFC - Break Specific Fuel Consumption.

TABLE 9.17

Baseline Gaseous Emissions vs Emissions with Engine Equipped with Corning Filter, EGR, Water Emulsion

Deutz F8L 413 F/W

Speed rpm	Load kW	% H_2O (w/w)	% EGR	BSFC kg/hr/kW	Nitric Oxide				% * Decrease	Nitrogen Dioxide				Total Oxides of Nitrogen				% * Decrease
					ppm	g/kW-hr	g/hr	g/kg Fuel		ppm	g/kW-hr	g/hr	g/kg Fuel	ppm	g/kW-hr	g/hr	g/kg Fuel	
2300	104	-	-	.307	550	4.50	467	14.7		10	.226	13.0	.409	560	4.63	480	15.1	
2300	104	13.0	14.4	0.564	180	1.11	115	3.23	75.2	0.0				180	1.11	115	3.23	75.2
2300	104	13.0	14.4	0.566	175	1.08	112	3.14		0.0				175	1.08	112	3.14	
2300	104	13.0	13.0	0.485	210	1.28	132	4.32		0.0				210	1.28	132	4.32	
2300	104	13.0	13.8	0.492	170	1.02	105	3.39		0.0				170	1.02	105	3.39	
2000	63	-	-	.313	430	5.99	380	19.1		10	.214	13.5	.682	440	6.20	393	19.8	
2000	63	14.0	14.6	0.307	190	1.86	118	6.41	69.0	0.0				190	1.86	118	6.41	69.0
2000	63	15.2	13.8	0.325	185	1.94	123	6.31		0.0				185	1.94	123	6.31	
2000	63	15.2	13.8	0.298	185	1.78	112	6.31		0.0				185	1.78	112	6.31	

* wrpt g/hr

TABLE 9.18

Baseline Gaseous Emissions vs Emissions with Engine Equipped with Corning Filter, EGR, Water Emulsion

Deutz F8L 413 F/W

Speed rpm	Load kW	% H_2O (w/w)	% EGR	BSFC kg/hr/kW	Total Hydrocarbons				% Increase *	Carbon Monoxide				% Increase *
					ppm	g/kW-hr	g/hr	g/kg Fuel		ppm	g/kW-hr	g/hr	g/kg Fuel	
2300	104			.307	56	.264	27.3	.858		144	1.10	114	3.58	
2300	104	13.0	14.4	.564	2000	7.37	764	21.4		1800	10.4	1074	30.1	
2300	104	13.0	14.4	.566	2000	7.39	766	21.4		1800	10.4	1077	30.1	
2300	104	13.3	13.0	.485	1600	5.71	592	19.3	2950	820	4.65	482	15.7	670
2300	104	12.8	13.8	.492	3300	11.7	1208	38.9		1500	8.37	868	27.9	
2000	63			.331	41	.304	19.2	1.06		78	1.01	64.3	3.24	
2000	63	14.0	14.6	.307	90	.500	31.7	1.72		144	1.32	83.5	4.53	
2000	63	15.2	13.8	.325	110	.655	41.5	2.13	93.1	144	1.41	89.4	4.59	32.1
2000	63	15.2	13.8	.298	110	.600	38.0	2.13		144	1.29	82.0	4.59	

* wrpt g/hr

TABLE 9.19

Average % Changes in Steady State Emissions Relative to Bare Engine Assignable to Various Control Systems

	Particulates				Gaseous			
	Insol.	SOF	Total	SO_2/H_2SO_4 Conversion	NO_x	NO/NO_2 Conversion	CO	THC
Deutz F8L-413 Engine (at 2300 rpm/104 kW)								
• Corning Filter	-84%	-43%	-69%	0%	0%	0%	0%	0%
• 10%* EGR/Corning Filter	-90	-90	-90	0	-30	0	+5	+15
• 15% EGR/Corning Filter	-90	-85	-90	0	-50	0	+10	+55
• 15% H_2O Emuls/15% EGR/ Corning Filter	-50	-25	-45	0	-75	0	+670	+2300
• Catalyst	0	0	0	+58	0	14	-85	-65
• Catalyst/Mesh Filter (dry, parallel flow)	-80	**	-55	20->44	0	-	-85	-65
• Mesh Filter (dry, parallel flow)	-90	**	-85	0	0	0	0	0
Deutz F6L-714 Engine (at 2200 rpm/93 kW)								
• H_2O Emulsion	-41	+3	-40	0	-35	0	+2	+36
• 15% H_2O Emuls/Catalyst/ Mesh Filter (wet, pendicular flow)	-90	-45	-88	0	-35	-	-95	-90
• Catalyst/Mesh Filter (wet, perpendicular flow)	-85	-5	-80	0	0	-	-95	-90
• Mesh Filter (wet, perpendicular flow)	-80	**	-83	0	0	0	0	0
• 15% H_2O Emuls/Catalyst	-40	-5	-40	+55	-35	0	-95	-90
• Catalyst/Gaspe Scrubber	-30	-15	-25	+40	-15	+5->25	-95	-75
• 20% EGR/Catalyst/Gaspe	+370	-40	+270	+40	-80	0	-65	-60

* All % EGR and water emulsification settings are approximate

** SOF reductions for this test series were highly variable and ranged from 0 to 50%

TABLE 9.20

Comparison of Emission Reduction Effect of Various Emission Control Strategies Applied to the Deutz F8L 413 Engine

Load/Speed Condition	Device	% Change Relative to Bare Engine			
		Total Particulate	NO_x	CO	THC
2300 rpm/ 104 kW	Corning Filter	-69%	0	0	0
	EGR/Corning Filter **	-88%	-53%	+12	+57
	H_2O Emulsion *	+215	-22%	+236	+2590
	H_2O Emuls/EGR/Corn.Filt	-45%	-75%	+67	+2300
2000 rpm/ 63 kW	Corning Filter	-74%	0	0	0
	EGR/Corning Filter	-90%	-54%	+32	+55
	H_2O Emulsion	+21	-33%	+36	+180
	H_2O Emuls/EGR/Corn.Filt	-89%	-69%	+32	+93

* Results more beneficial with 714 engine than present 413 engine.

** Approximately 15% EGR application

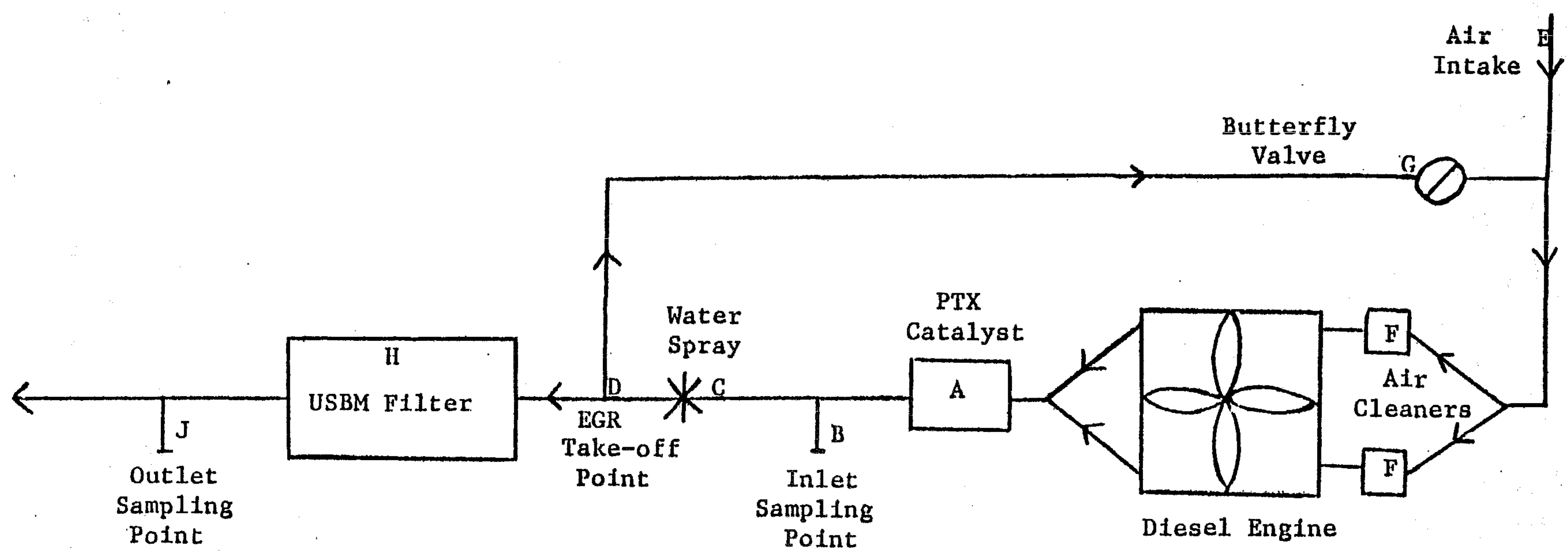


FIGURE 9.1 Schematic of the Test Rig for the EGR/PTX Catalyst/USBM Filter Emission Control Package

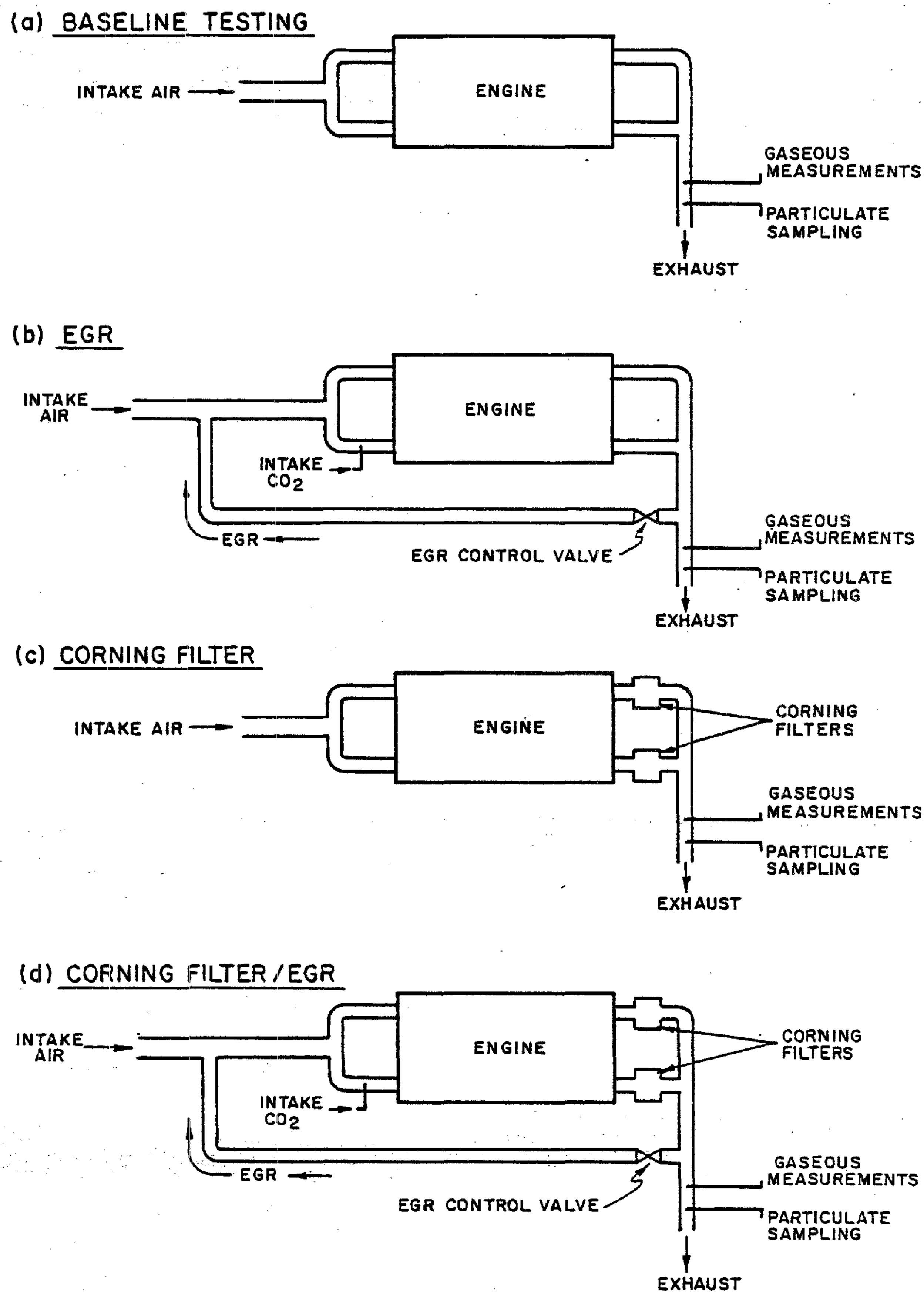


FIGURE 9.2 ENGINE TEST CONFIGURATIONS

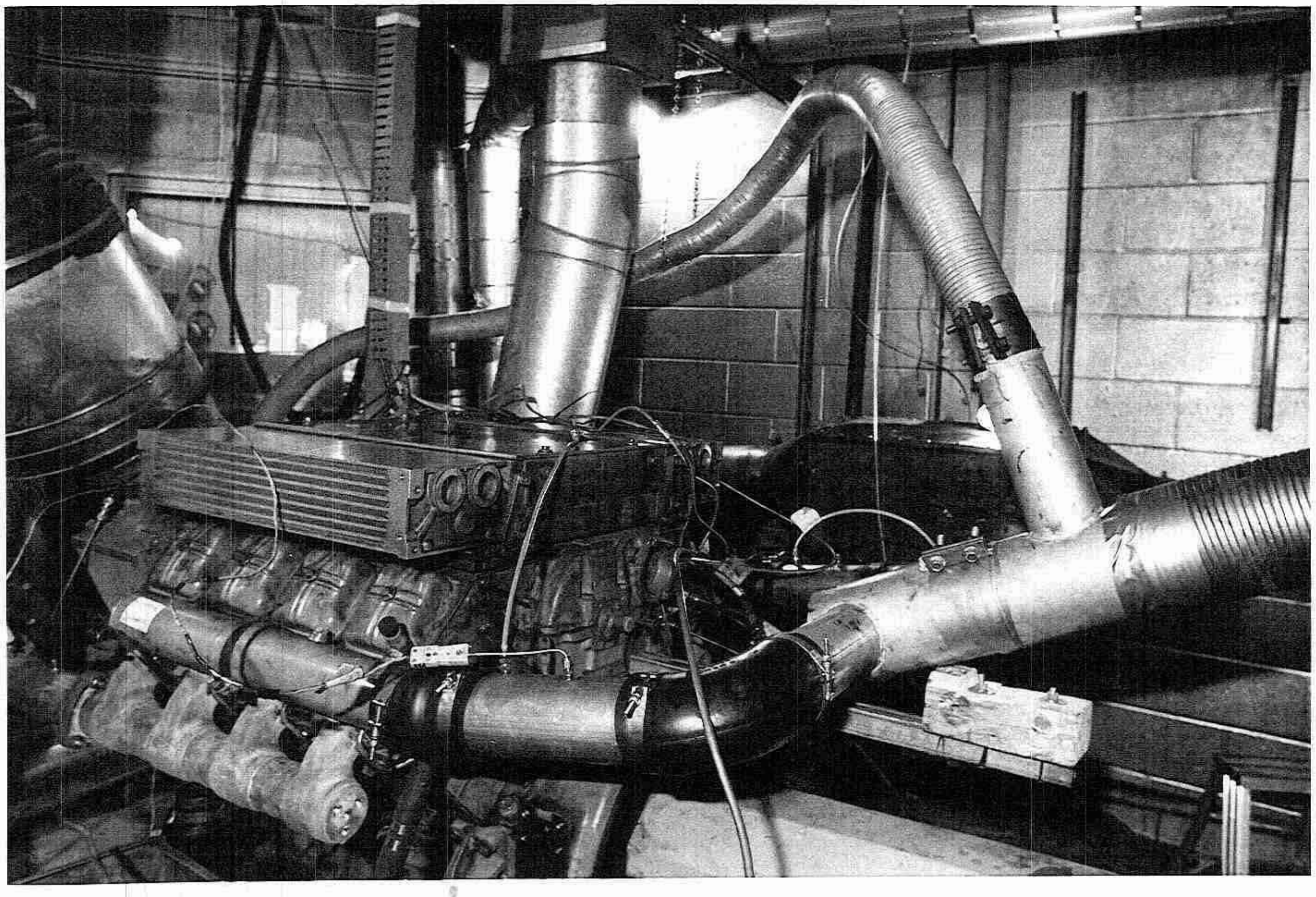


FIGURE 9.3(a) EGR Intake System.

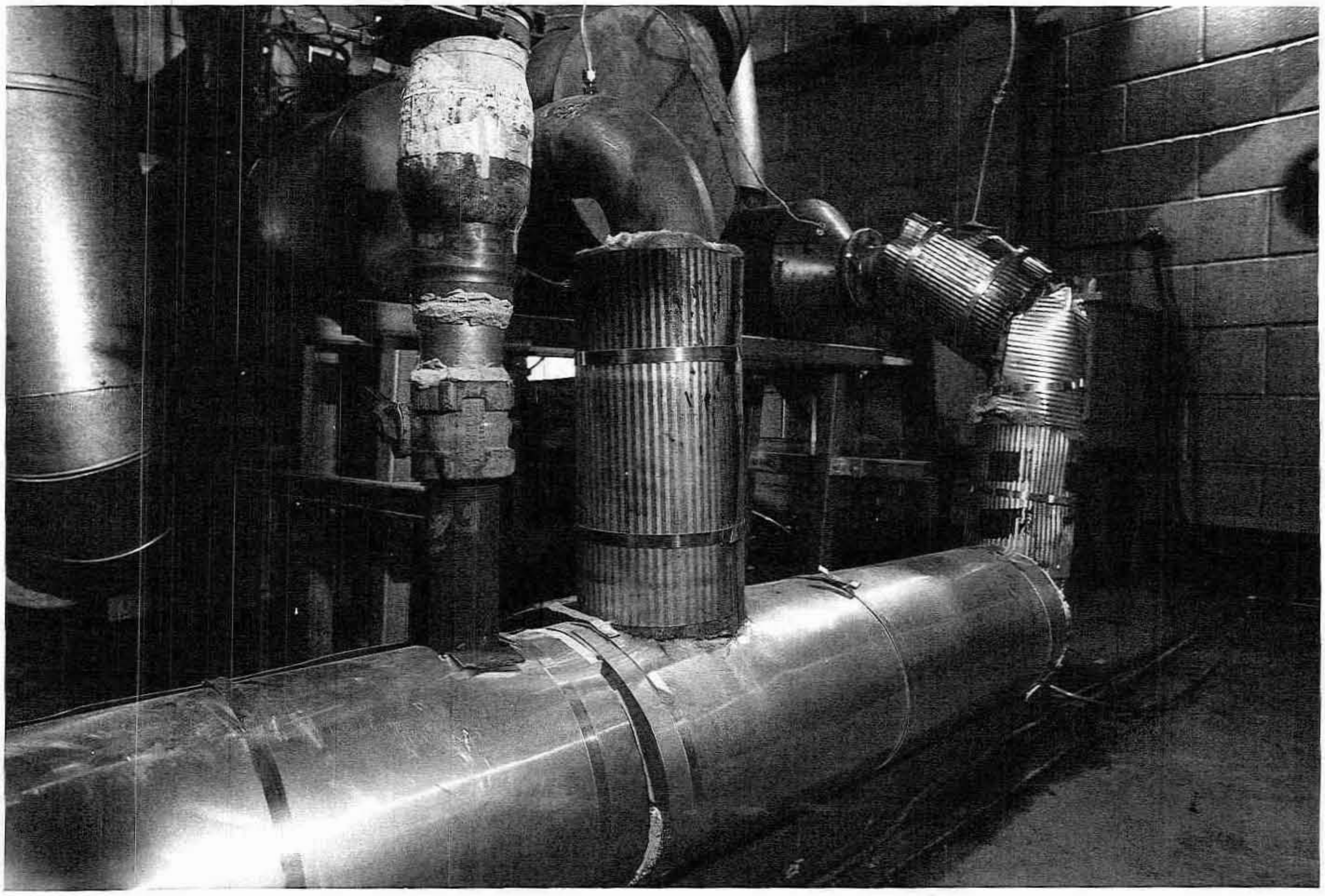


FIGURE 9.3(b) EGR Control Valve on EGR Filter System.

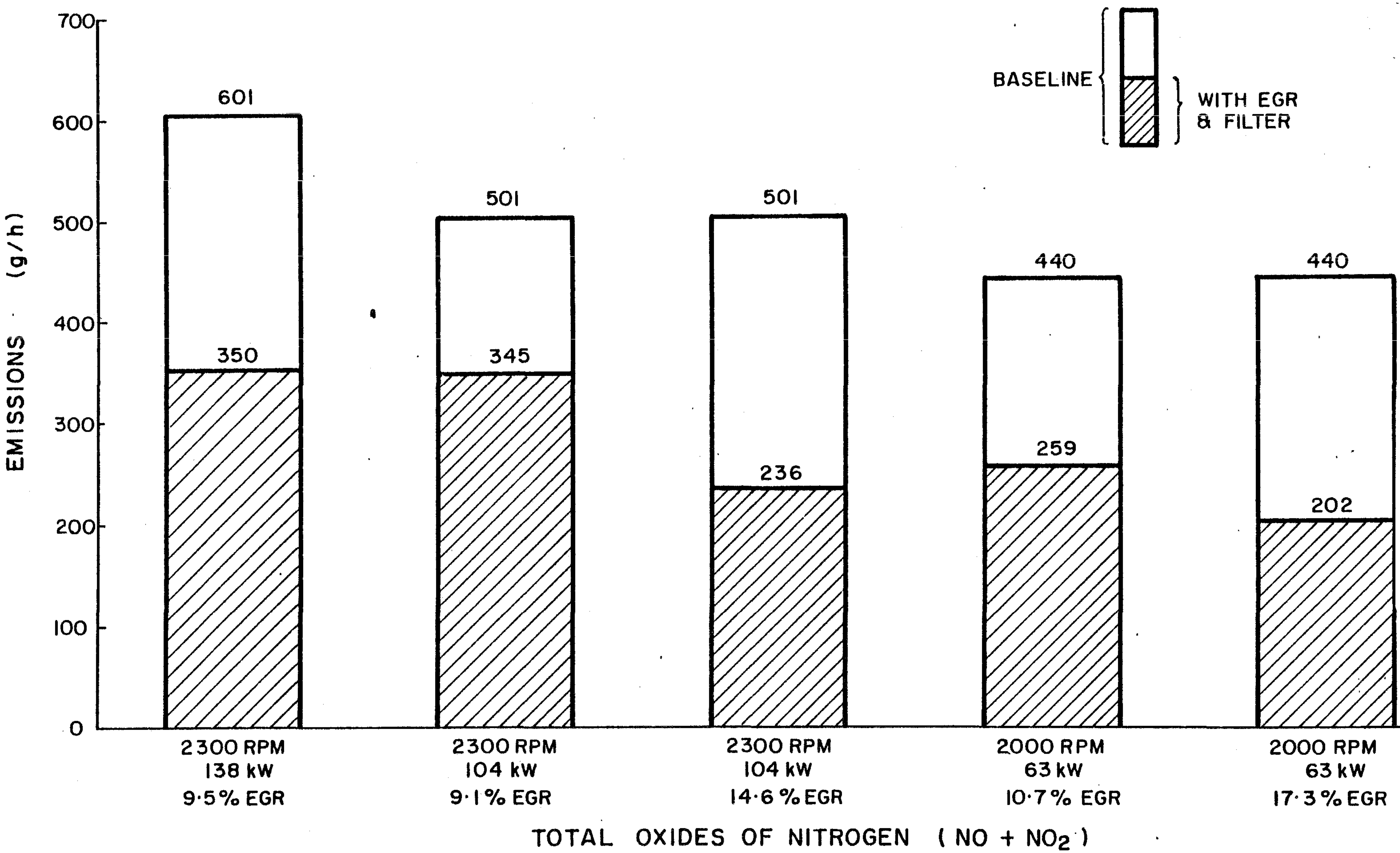


FIGURE 9.4 GASEOUS EMISSIONS – BASELINE vs EGR / FILTER

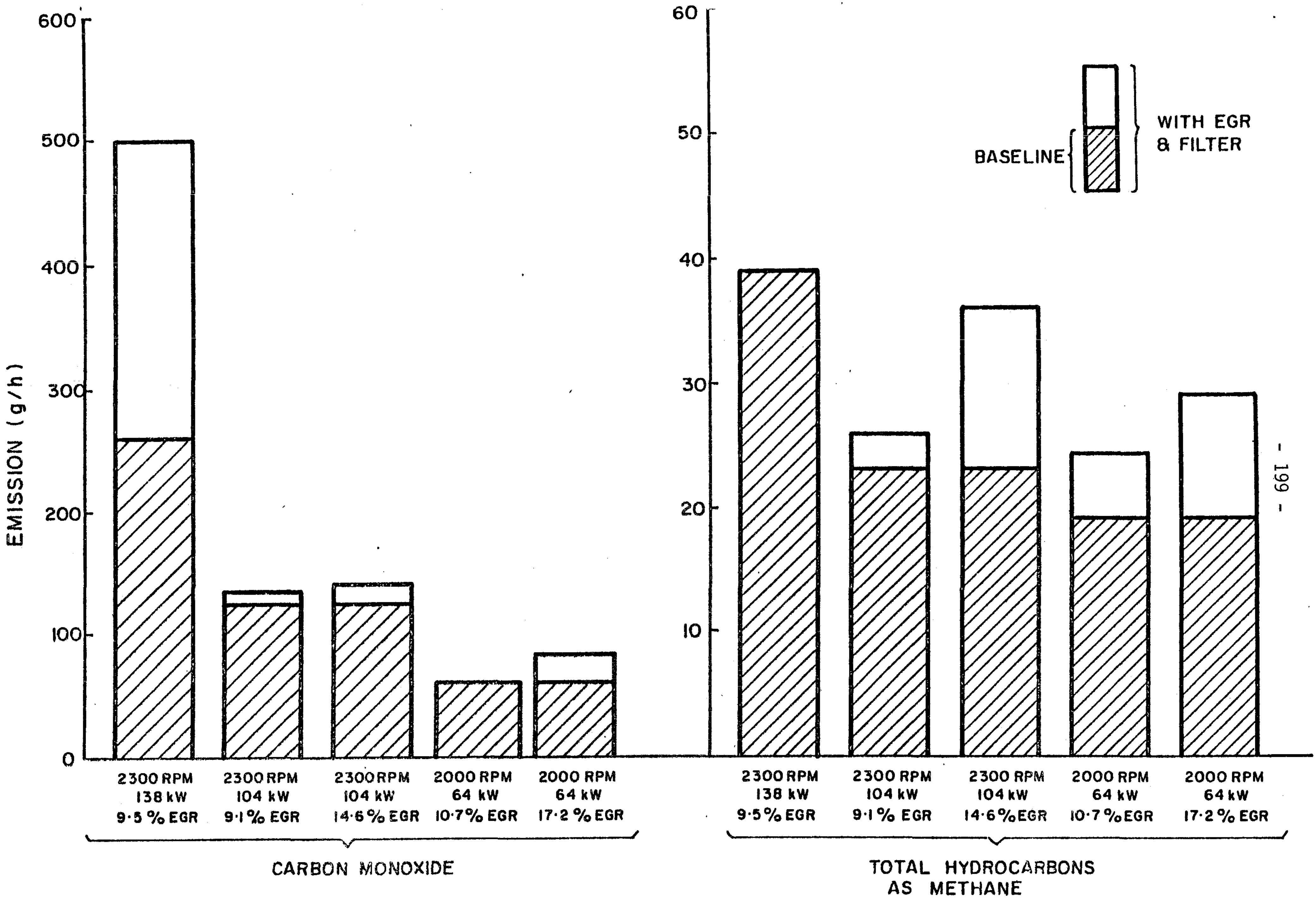


FIGURE 9.5 GASEOUS EMISSIONS - BASELINE vs EGR / FILTER

Figure 9.6

Effect of Various Emission Control Strategies on the Particulate Emission Rates 2300 rpm / 138 kW

(Deutz F8L-413 Engine)

Corning Filter Technology

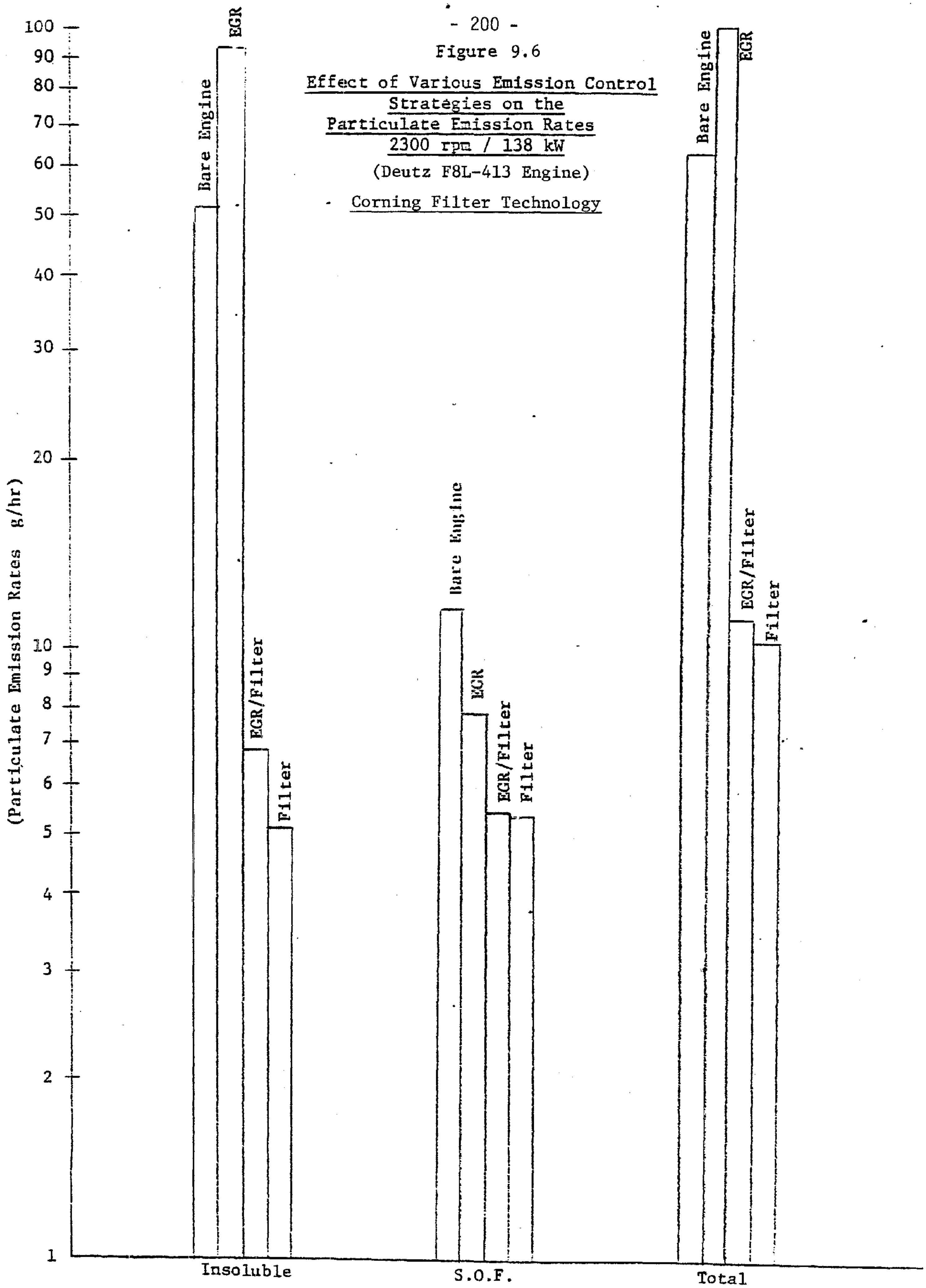


Figure 9.7

Effect of Various Emission Control Strategies on the Particulate Emission Rates 2300 rpm / 104 kW

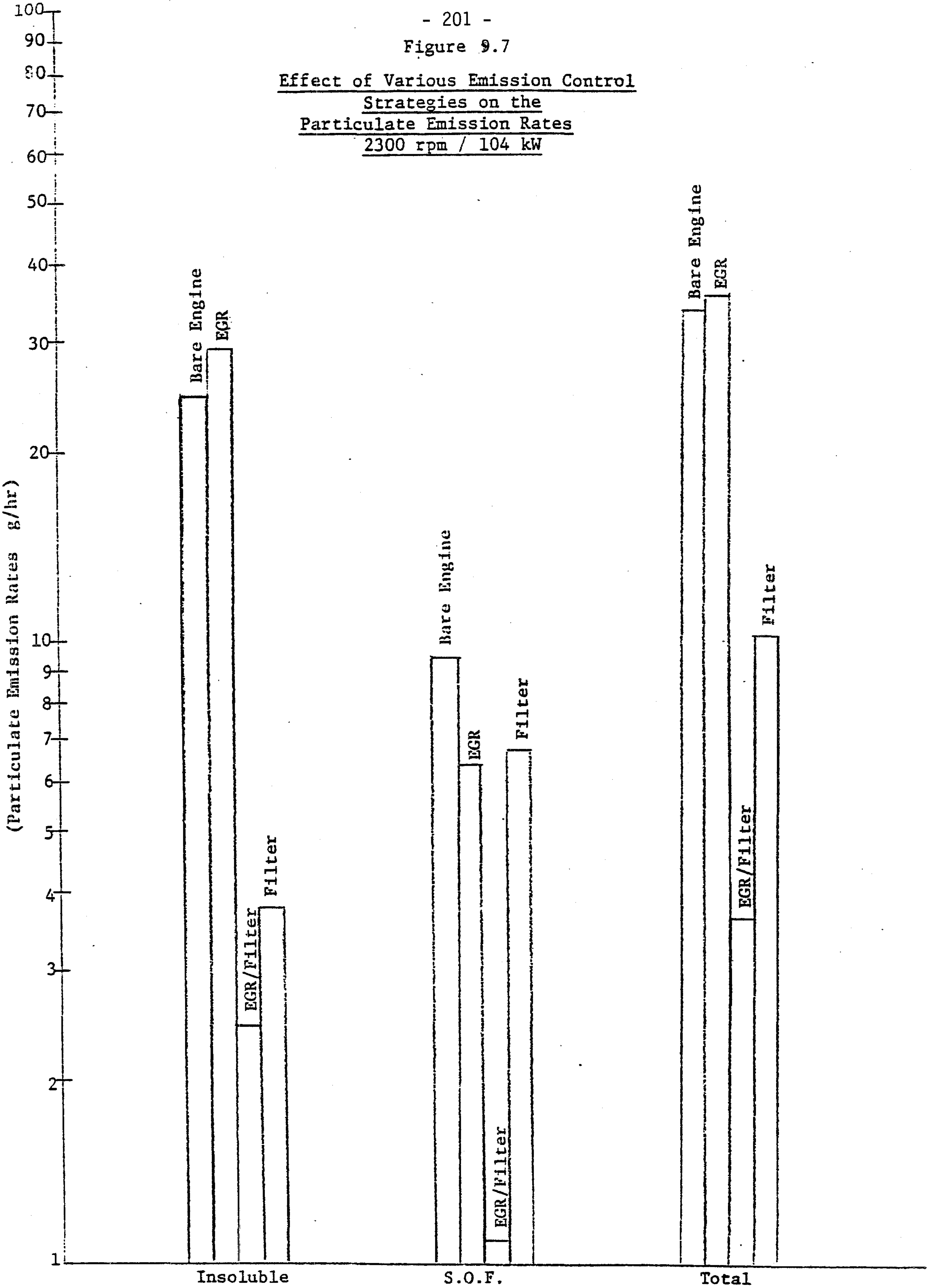


Figure 9.8

Effect of Various Emission Control Strategies on the Particulate Emission Rates 2000 rpm / 63 kW

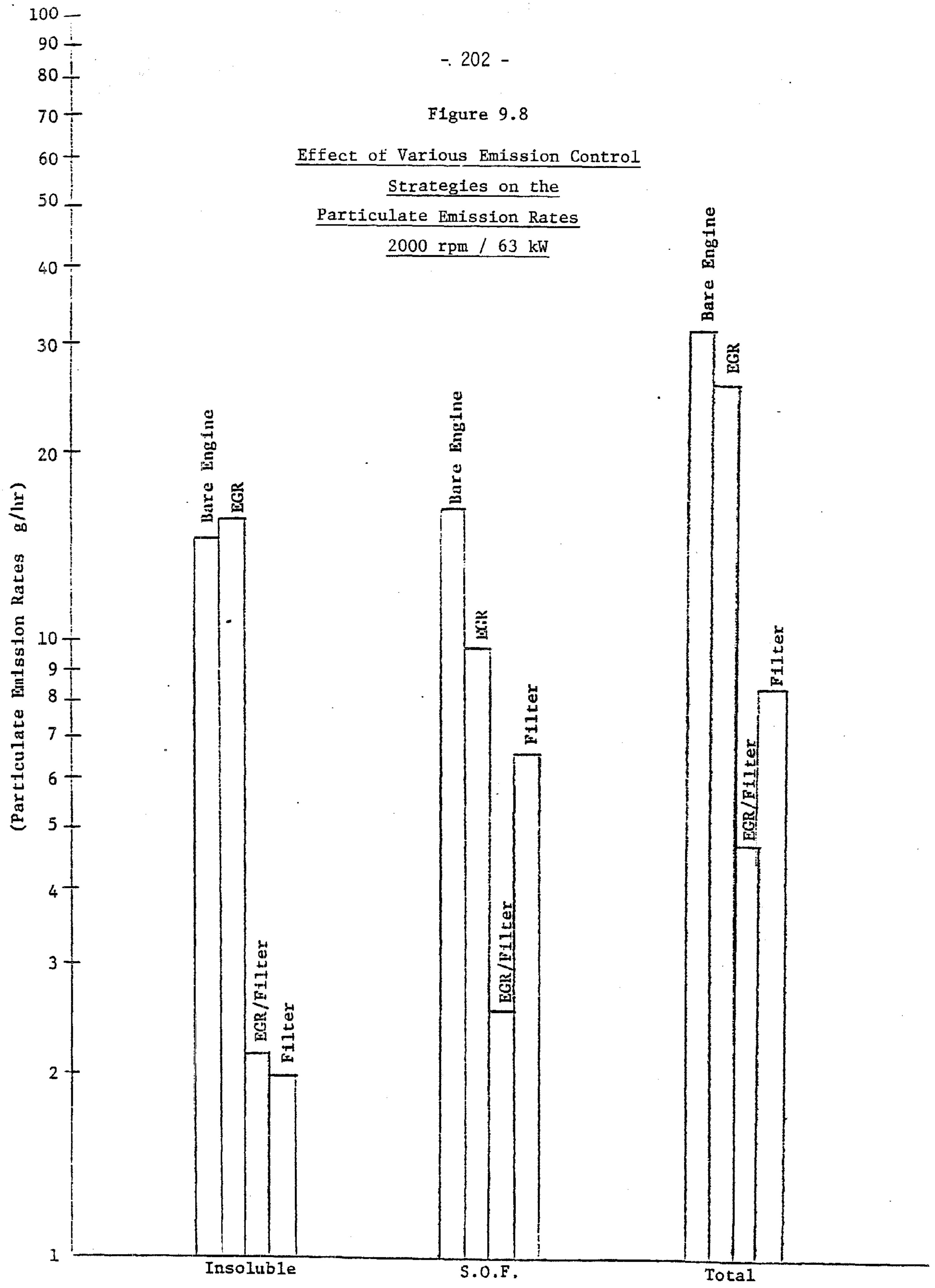
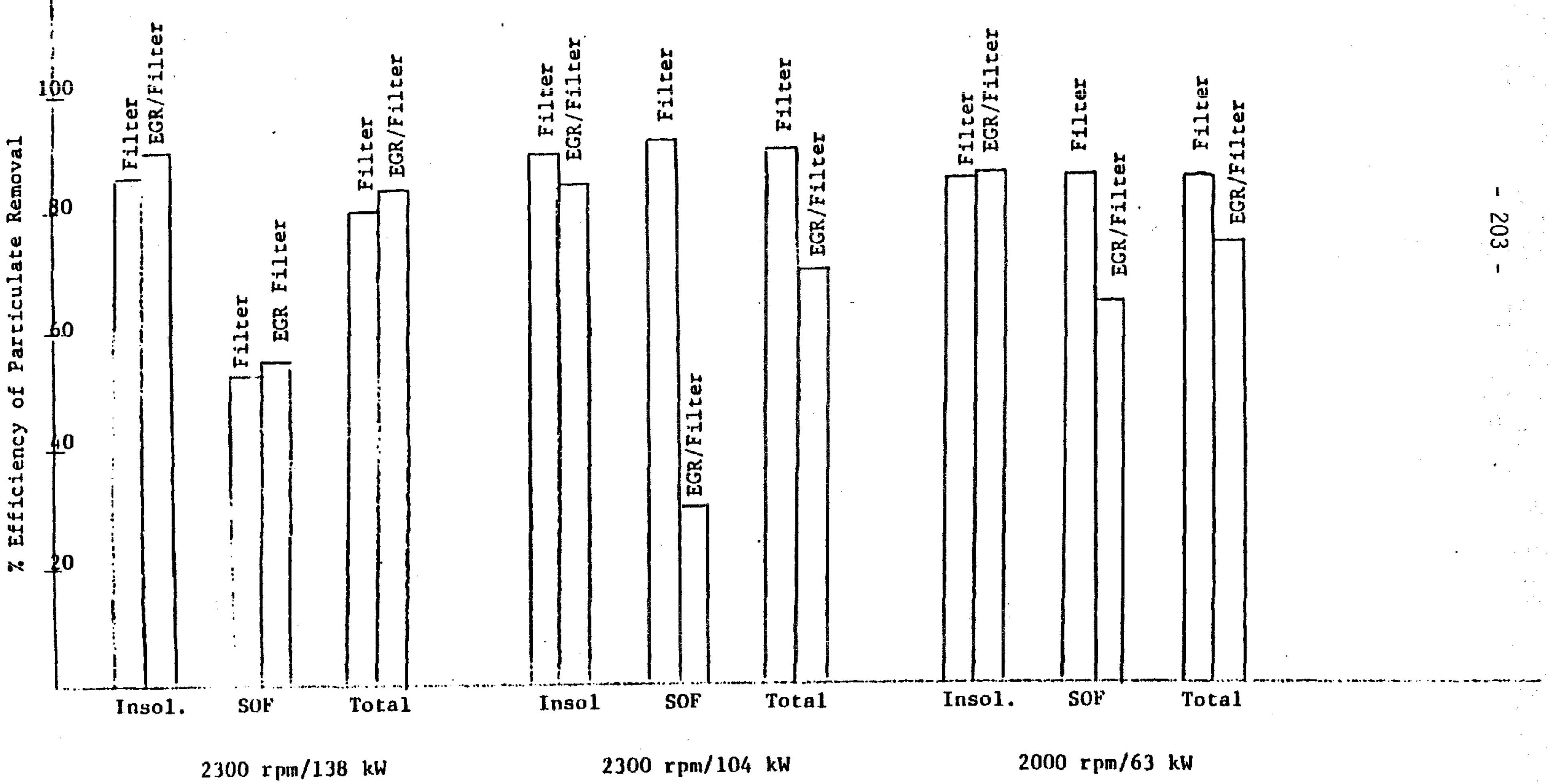


Figure 9.9

Comparison of the Efficiencies of EGR/Filter and Filter only for the Reduction of Particulate Emissions



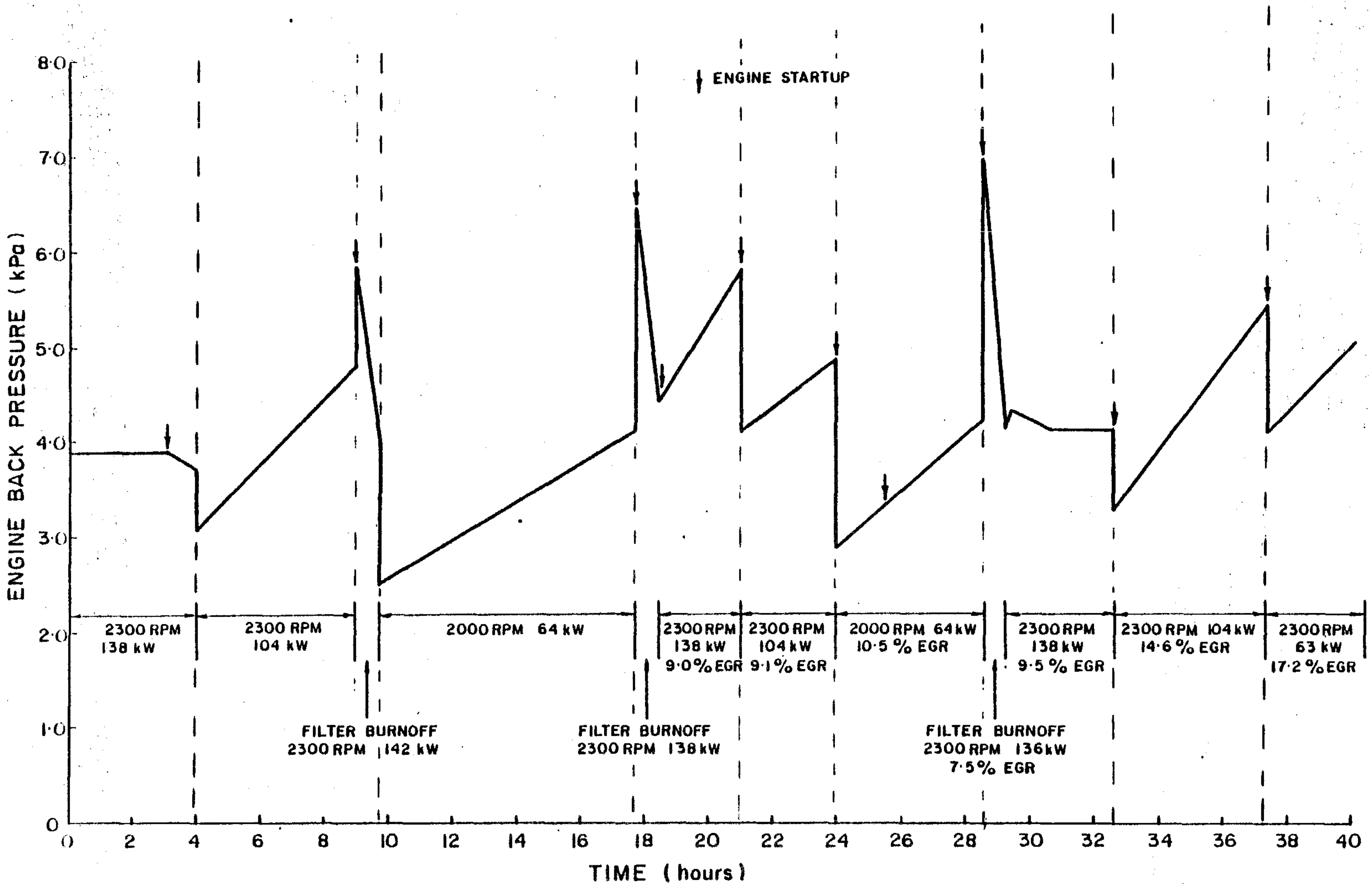


FIGURE 9.10 ENGINE BACK PRESSURE COMPOSITE - CORNING FILTER vs EGR / CORNING FILTER

Note: Engine Conditions Not Otherwise Labelled are 0% EGR.

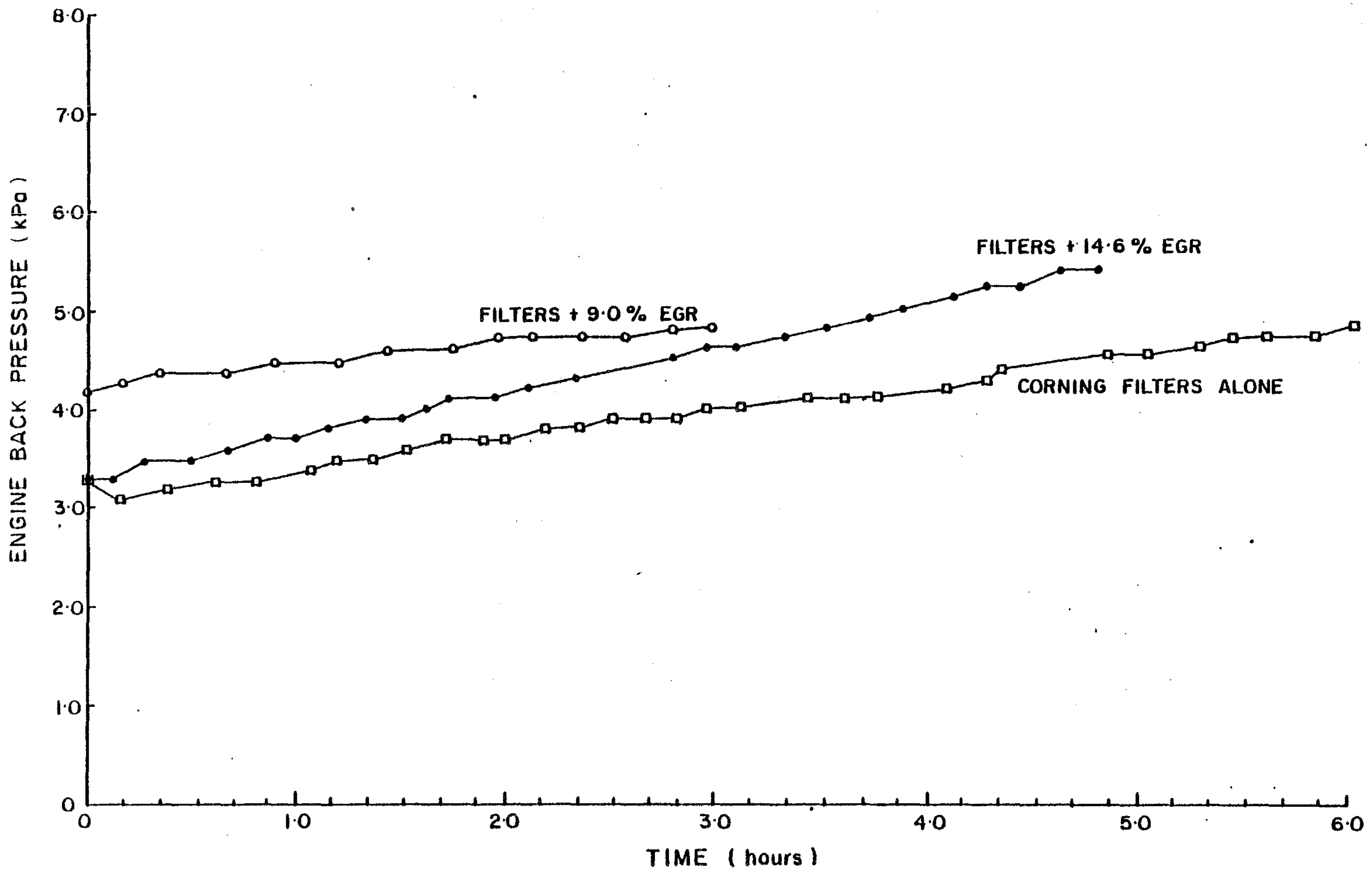


FIGURE 9.11 ENGINE BACK PRESSURE vs TIME, at 2300 rpm, 104 kW. CORNING FILTER AND EGR / CORNING FILTER

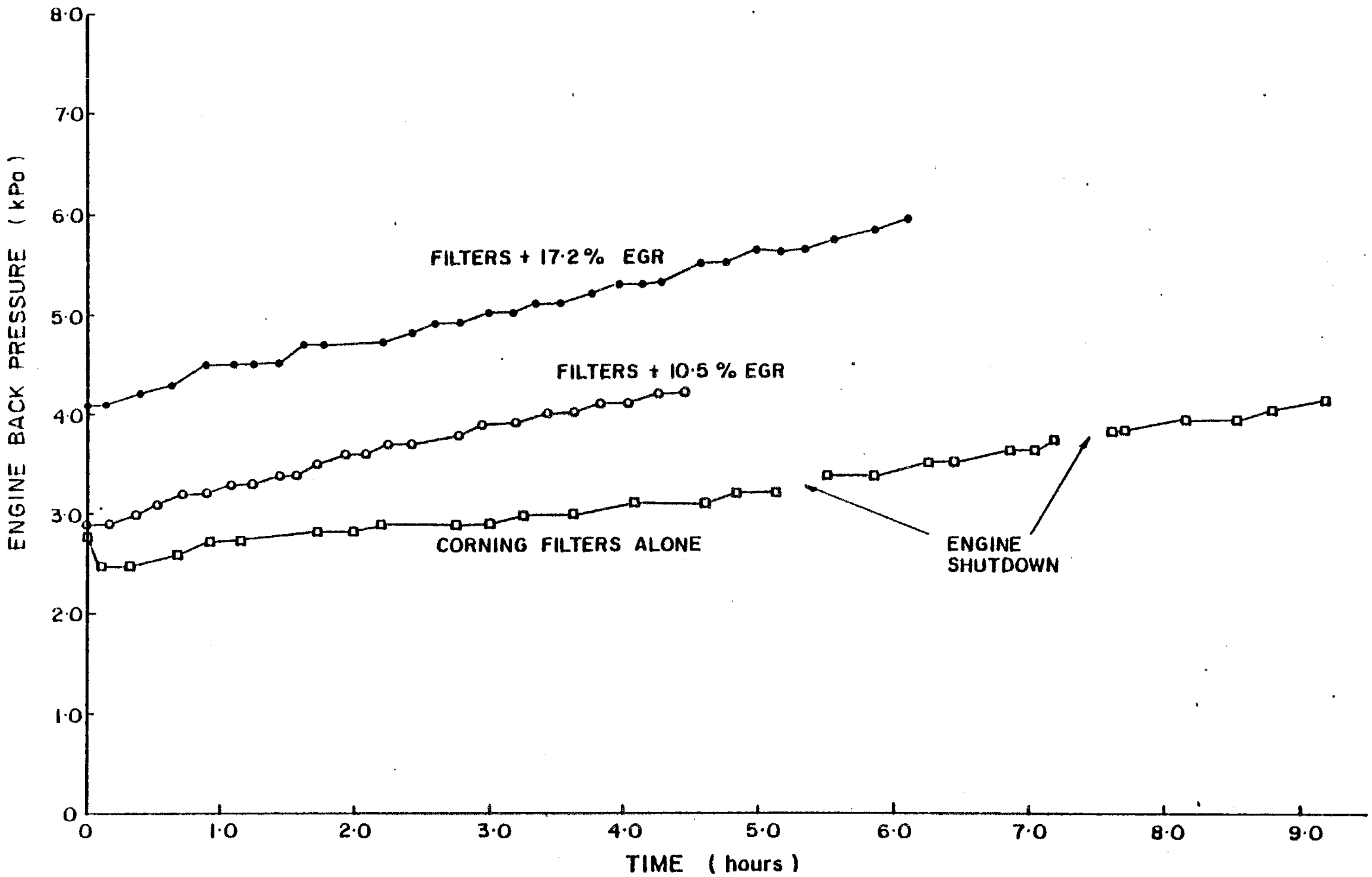


FIGURE 9.12 ENGINE BACK PRESSURE vs TIME at 2000 rpm, 64 kW. CORNING FILTER & EGR / CORNING FILTER.

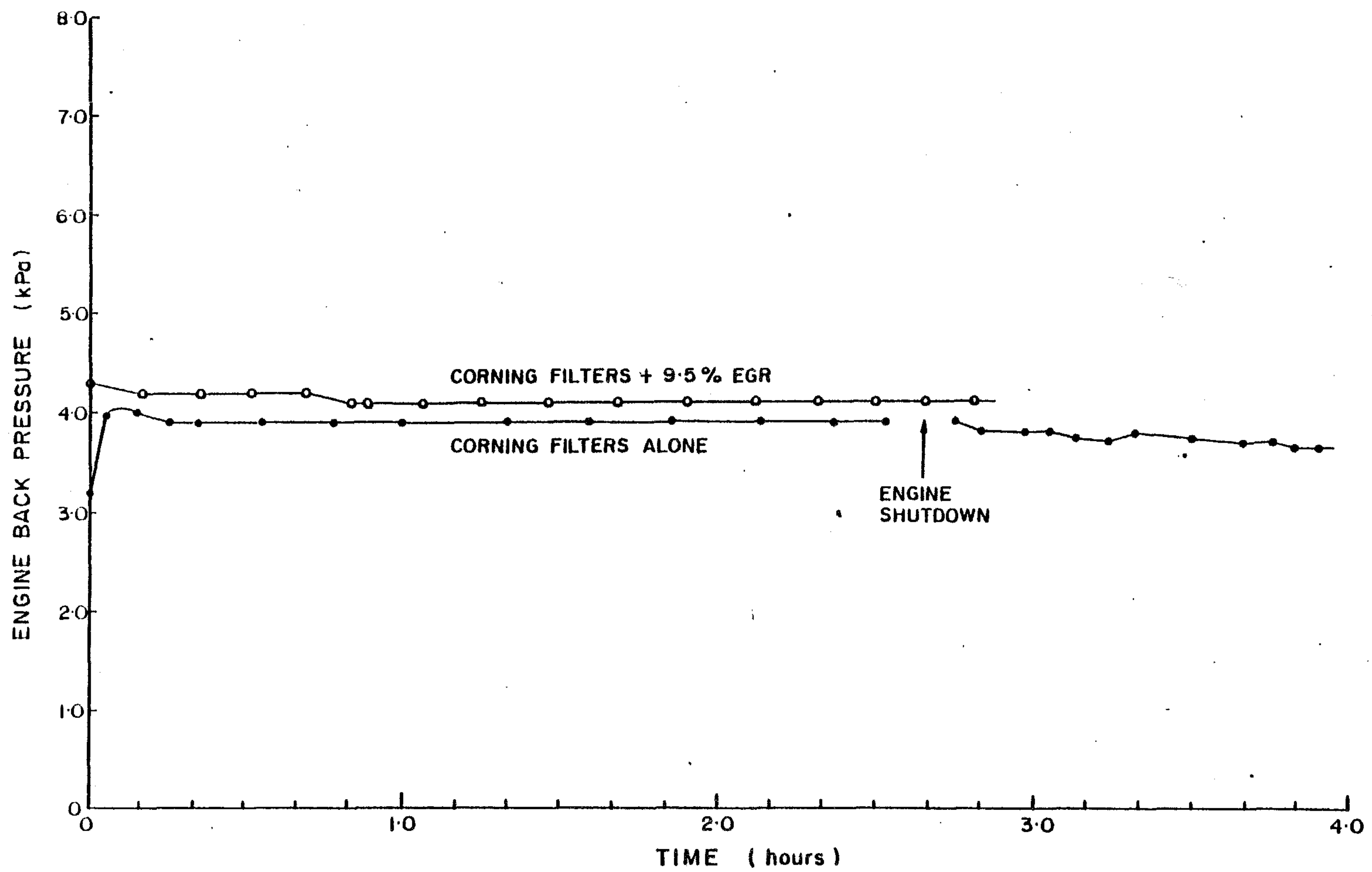


FIGURE 9.13 ENGINE BACK PRESSURE vs TIME at 2300rpm, 138 kW. CORNING FILTER & EGR / CORNING FILTER

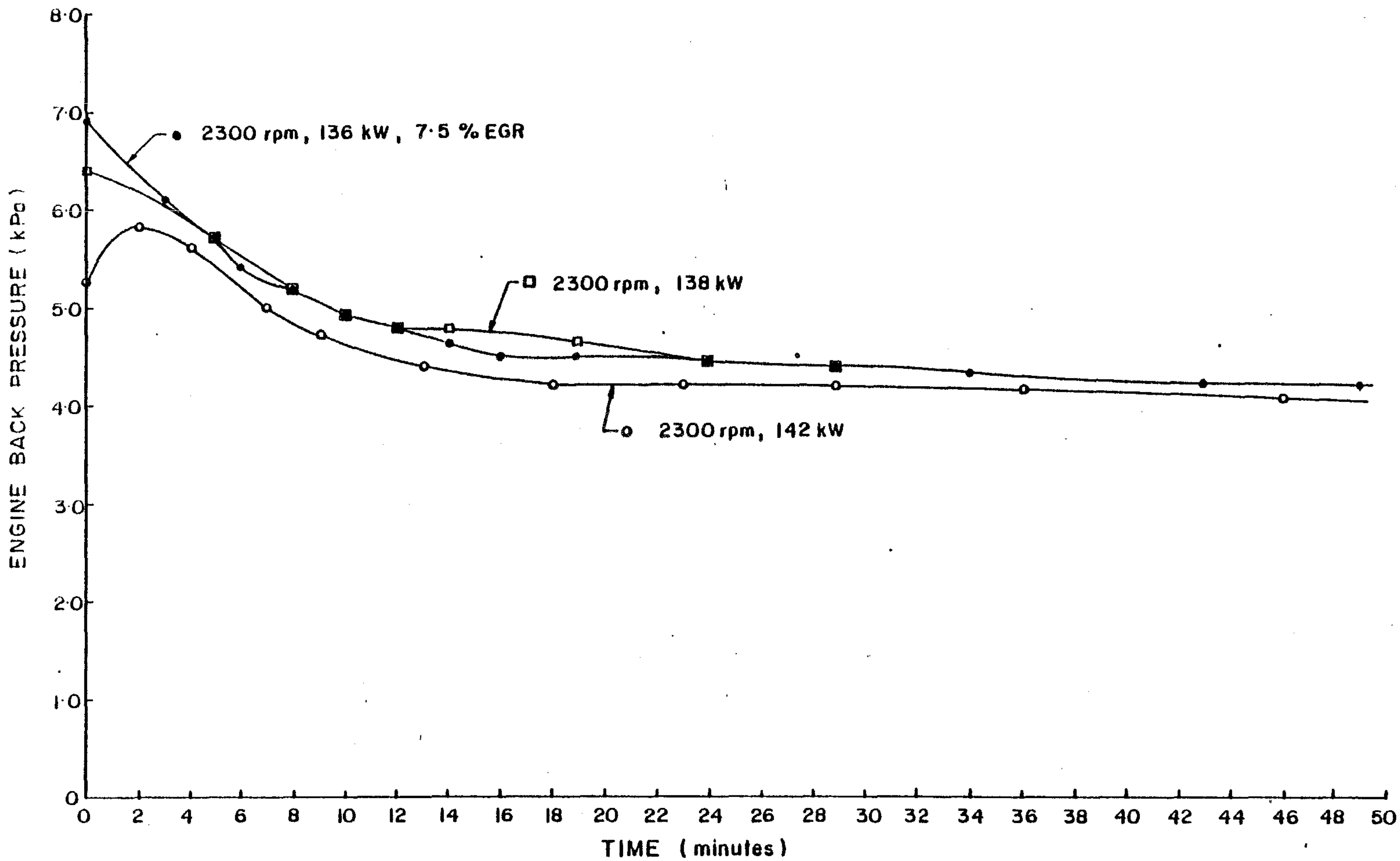


FIGURE 9.14 PARTICULATE BURN-OFFS WITH & WITHOUT EGR. ENGINE BACK PRESSURE vs TIME

Figure 9.15

Effect of Various Emission Control Strategies on the Particulate Emission Rates 2300 rpm / 104 kW

(Deutz F8L-413)

Corning Filter Technology

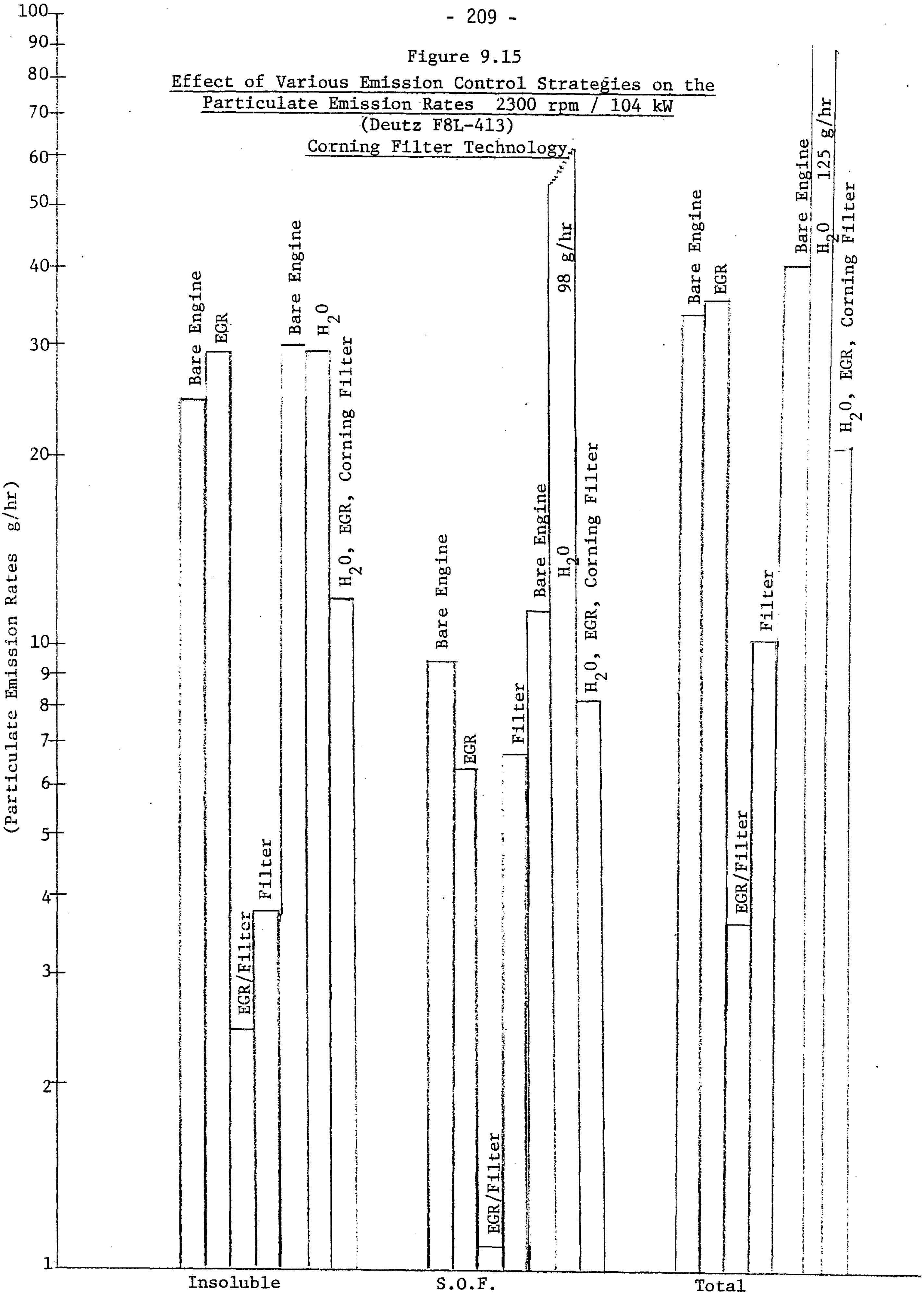
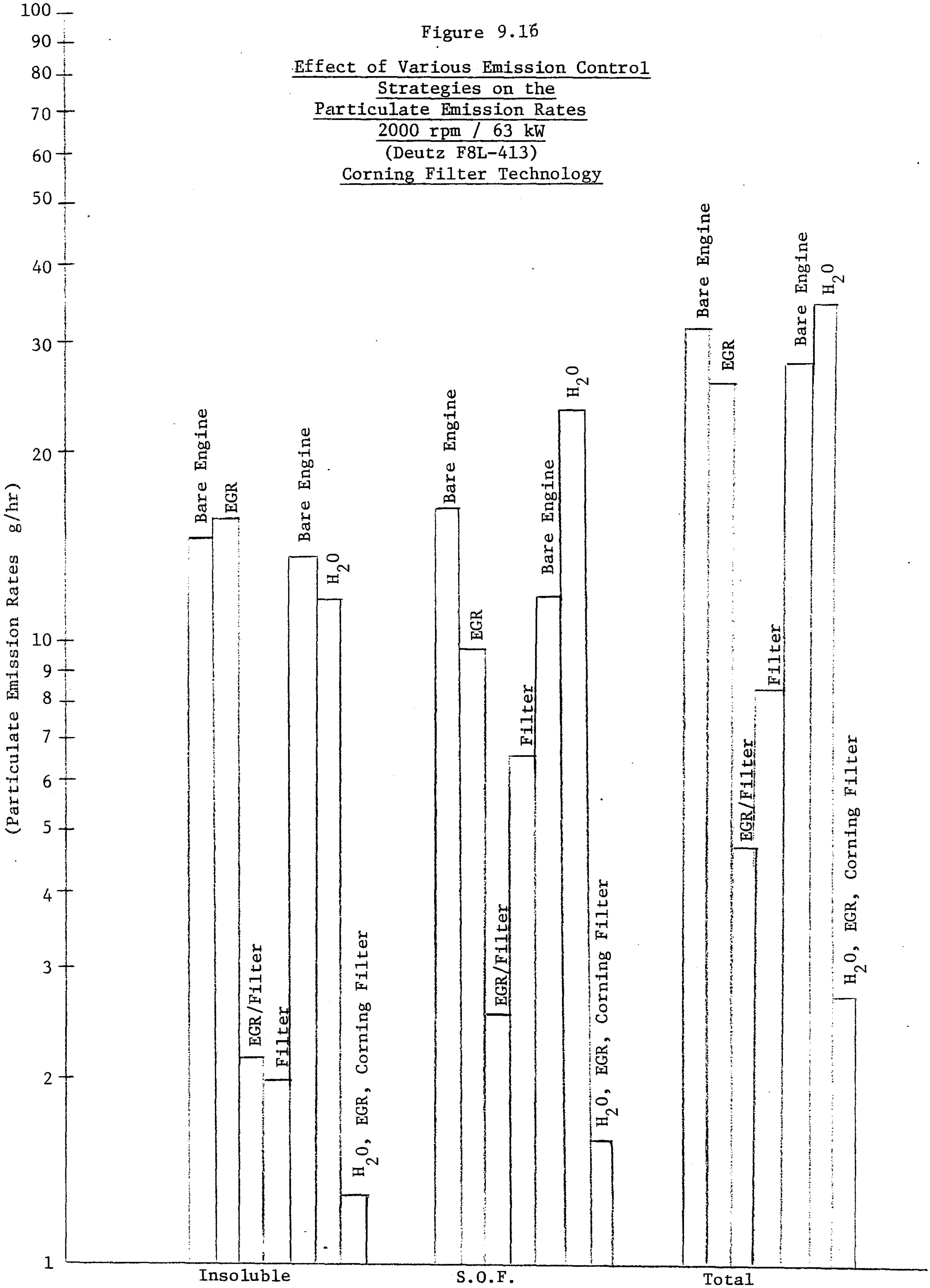


Figure 9.16

Effect of Various Emission Control Strategies on the Particulate Emission Rates
2000 rpm / 63 kW
(Deutz F8L-413)
Corning Filter Technology



10. SYSTEM COMPARISONS

10.1 Exhaust and Air Quality Indices

A number of methods are used presently to determine the impact of diesel exhaust emissions on underground mine air quality, and the amount of ventilation air which is considered necessary to reduce toxic component concentrations to levels for which no long term threat to the workers health is anticipated. In Ontario, there is a defined quantity of fresh air which must be supplied per kilowatt of engine power, or per kilogram of fuel burned. In the U.S.A. the requirement is that the concentration of diluted components shall not exceed 0.25% CO_2, 50 ppm CO, and 12.5 ppm NO_x.

These methods, however, do not address the possible synergistic effects of one component in the presence of another, increasing the toxicity of combined exposure. In recognition of this, a group of Canadian consultants under contract to CANMET, Energy Mines and Resources Canada, examined the literature on the health effects of exposure to a mixture of toxic diesel exhaust components.[3] They were able to fomulate the following expression containing synergistic exposure terms:

$$V = \frac{(CO)}{50} + \frac{(NO)}{25} + \frac{(RCD)}{2} + \frac{(H_2SO_4)}{1} + 1.5 \times \left[\frac{(SO_2)}{3} + \frac{(RCD)}{2}\right] + 1.2 \left[\frac{(NO_2)}{3} + \frac{(RCD)}{2}\right]$$

where:

(CO)	=	carbon monoxide concentration in ppm
(NO)	=	nitric oxide concentration in ppm
(SO_2)	=	sulphur dioxide concentration in ppm
(NO_2)	=	nitrogen dioxide concentration in ppm
(RCD)	=	respirable combustible dust in mg/m^3 (considered eqúivalent to the particulate level of diesel exhaust) (20).

The two bracketed terms indicate the synergistic effect of SO_2 and NO_2 respectively with diesel particulate. This reflects the ability of the diesel particulate to increase exposure to SO_2 and NO_2 by deposition of particulate, containing the adsorbed gases, on the lung membrane. The term V (ventilation factor) can best be described as an Air Quality Index (AQI), which is recommended not to exceed a value of 3 (or 4 if protective equipment such as filter helmets are used).

The above expression was designed for use with ambient mine air pollutant concentrations. If tailpipe emission data is applied to the same expression, then it is possible to consider that an Exhaust Quality Index (EQI) will result. The $\frac{EQI}{3}$ then indicates the required dilution ratio, and the dilution ratio multiplied by the exhaust volume results in a value for the recommended quantity of fresh ventilating air.

There are, however, limitations to this approach. Since the expression was designed as an air quality index, the use of tailpipe undiluted emission values creates a different impact on the EQI values, due to the lack of accountability for the ultimate fate of emission components which are emitted to the mine atmosphere. For example, NO emissions will be oxidized to NO_2 at a rate dependent on mine air residence time, and environment. NO_2 may subsequently be removed from the mine atmosphere by interaction with water. Similar considerations apply to H_2SO_4 emissions. An accurate assessment can only be made, therefore, by applying pollutant concentrations actually measured underground. A further limitation is evident with the synergistic terms of the expression which are capable of making a large impact on the AQI/EQI. For example, it is a matter of judgement as to whether the same synergistic health impact will result from exposure to a large concentration of particulate matter when only low concentrations of SO_2 and NO_2 are present. The weighting factors of these terms under such conditions might become unduly severe. In effect one must judge whether NO_2 or SO_2 values ever become zero, and the synergistic terms disappear from the expression. This will be illustrated later when the EQI data is discussed.

Despite these limitations, the expression is probably the best tool presently available, in order to compare the different impacts on exhaust quality of various emission control strategies. It is considered appropriate and relevant but not necessarily conclusive, therefore, to use EQI values to provide a view of the ranking of different emission control approaches, and try to assess which approaches show the greatest benefits.

10.2 Representation of Emission Control Strategies Relative to Exhaust Quality Indices

Using the data contained in this report, (and data from relevant literature where available in this report). EQI values were calculated at two engine load/speed conditions, and for two engines, the Deutz F6L-714 and the Deutz F8L-413. The EQI values vary with engine type and load/speed conditions, but, for the same engine and the same load/speed condition, it is possible to compare EQI values of the controlled versus the baseline uncontrolled engine. It must be kept in mind that the representation of the effect of control strategies in this manner neglects the impact of duty cycle patterns over time on ambient air quality. This is so since the effectiveness of different devices often varies widely as a function of engine load/speed condition. However, this calculation of EQI's,using steady state test stand data, provides a preliminary view of control strategy relationships at load/speed conditions typically seen in the duty cycle patterns of LHD mining vehicles. Table 10.1 shows EQI values for the deutz F6L-714 engine at two different load/speed conditions, with the application of various emission control devices. At 2200 rpm full load, the worst strategy is the application of 21% EGR alone to the engine, which results in an EQI value 530% greater than the baseline value. A catalyst/scubber system used in combination with the EGR, does not overcome the high particulate impact of EGR application, even although the NO_x is considerably reduced, and the EQI values remain greater than the baseline value. Similarly, the emulsification/catalyst system appears a poor combination, with the test stand H_2SO_4 data impact of the catalyst over-whelming the advantages of reduced NO_x and particulate created by the water emulsion, even though the catalyst effectively reduced the increased CO and THC emissions created by the emulsion application. Emulsion application alone produced a better result with an EQI 67% of the baseline value. Using exhaust gas cooled by water injection, the mesh filter, and catalyst mesh filter combination, both produced EQI values 36-39% of the baseline engine value. However, the disadvantage of storing water on board may tend to offset the advantage of the low EQI value when used in gassy mines.

The same consideration applies to the water emulsion/catalyst/mesh filter system, although in this case the water may be used for the dual purpose of water emulsion application, and exhaust cooling. This system produced the lowest EQI value for the 714 engine at 2200 rpm/93 kW.

Table 10.1 shows a set of data in parenthesis for the three EGR systems. These data were calculated assuming that NO_2 and particulate was absent. This shows the powerful effect of the synergistic term which makes a difference in the EQI values of as much as 300 units. Whether the synergistic term should have so great a weighting factor when there is a large particulate concentration, but only a small NO_2 concentration, remains a subject to be resolved. It is understood that such considerations are currently under investigation by Ian French Associates. It should be noted, however, that even if the synergistic term is ignored, the ranking of exhaust treatment devices remains the same.

Table 10.1 also shows a similar set of EQI values for the 714 engine at rated speed and three-quarter full load condition. Because the engine is operating at off full load condition, the EGR penalty is less severe, and the EGR/catalyst/scrubber combination, for example, now performs with an EQI value 93% of the baseline. The 21% EGR/mesh filter combination performs with an EQI value 36% of baseline. It is clear from the earlier set of data that such a technique is more likely to be successful at full load condition, when the quantity of EGR application is reduced.

Table 10.2 shows EQI values calculated for the controlled and uncontrolled Deutz F8L-413 engine, at two load/speed conditions, rated speed/full load, rated speed/three-quarter load. In this case, emulsification, catalyst and EGR techniques, used alone, are unattractive at either load/speed condition. At full load/speed condition, the Corning filter and EGR/Corning filter system produce the best performance, reducing the EQI values to 33% and 29% of baseline values respectively. This result, by itself, would seem to indicate that there is no great advantage in combining EGR with the Corning filter, since the addition of EGR further reduces the EQI value by only 4 percentage points, while the complexity of the device is significantly increased. However, when the EQI values are examined at 2300 rpm/103 kW, it is apparent that there is now a significant improvement in the EQI value when the EGR is added to the Corning filter to form a combined system. This shows the significance of assessing EQI values at different load/speed conditions, and the need for performance evaluation over a typical underground vehicle duty cycle. The latter will be included in a follow-on phase to this project. It is to be concluded, therefore, that, for the 413 engine, the EGR/Corning filter system offers the best opportunities, in terms of effectiveness and minimum complexity, for development into field usable hardware.

Further comments are necessary at this stage regarding the relationship between EQI values and the dilution ratio with ventilation air necessary to reduce the Air Quality Index to the recommended value of three. Dilution ratios can be calculated for the EQI values for various emission control approaches. For example, for the Deutz F6L-714 engine, the dilution ratio for the uncontrolled engine at 2200 rpm/93 kW (full load/speed) amounts to 59:1, whereas if the engine is controlled with the emulsification/catalyst/mesh filter combination, the dilution ratio (D.R.) is reduced to 16.6:1. D.R. values are however, limited by the dilution necessary to reduce CO_2 concentrations produced by the engine to below the threshold limit value (TLV) for CO_2 which is 5000 ppm. Since the CO_2 concentration at full load/speed condition for this engine is 9.9%, then a D.R. value of 19.8 is required to maintain CO_2 concentrations below the TLV. There is therefore, little value in applying exhaust control technology which will result in EQI values less than 60 (at 2200 rpm/93 kW) since further reductions in EQI values will not result in a reduction in ventilation air requirement, due to the CO_2 limitation. It is apparent that the system: emulsification/catalyst/mesh filter has reached this condition for the 714 engine at 2200 rpm/93 kW load/speed.

For the 413 engine, at full load/speed condition the limiting dilution ratio for CO_2 is 18.6:1, corresponding to a limiting EQI value of 56. The EGR/Corning filter system at this load/speed condition, shows an EQI value of 82, which justifies application of this system to reduce ventilation requirements. At 2300 rpm/103 kW however, the limiting EQI value amounts to 47, and hence the EGR/Corning filter system reduces the EQI value from that of the uncontrolled engine to the limiting value as controlled by CO_2 dilution requirements. This discussion, however, must be considered as preliminary, since final evaluation must be conducted by assessing EQI values obtained over a typical mines vehicle duty cycle containing engine transient operation.

TABLE 10.1

Composite EQI Values for Comparison of Various Emission Control Strategies

(derived from steady state engine test stand data)

(Deutz F6L-714 Engine)

RPM/kW	Device	EQI	% Baseline
2200/93	21% EGR	944 (653)	530%
	21% EGR/Cat/Scrubber	747 (262)	419%
	10% EGR/Cat/Scrubber	363 (254)	204%
	Emulsification/Catalyst	220	124%
	Baseline	178	100%
	Gaspe Scrubber	135	76%
	Emulsification	120	67%
	Cat/Mesh Filter (Wet)	69	39%
	Mesh Filter (Wet)	64	36%
	Emuls/Cat/Mesh Filter (Wet)	50	28%
2200/71	21% EGR	151	102%
	Base Engine	148	100%
	21% EGR/Cat/Scrubber	137	93%
	Gaspe Scrubber	114	77%
	21% EGR/Cat/Mesh Filter (Cooled)	72	49%
	21% EGR/Mesh Filter (Cooled)	54	36%
	Limiting EQI Value (CO_2 dilution)		

TABLE 10.2

Composite EQI Values for Comparison of Various Emission Control Strategies

(derived from steady state engine test stand data)

(Deutz F8L-413 Engine)

RPM/kW	Device	EQI	% Baseline
2300/138	PTX Catalyst	364	131%
	10% EGR	332 (295)	118%
	Emulsification	281 (205)	100%
	Baseline	279	100%
	Cat/Mesh Filter (Dry)	131	47%
	Mesh Filter (Dry)	107	38%
	Corning Filter	92	33%
	10% EGR/Corning Filter	82	29%
	Limiting EQI value (CO_2 dilution)	56	
2300/103	Emulsification	251	174%
	PTX Catalyst	235	163%
	Baseline	144	100%
	10% EGR	123	86%
	EGR/Emuls/Corning Filter	86	60%
	Corning Filter	71.9	50%
	10% EGR/Corning Filter	40	28%
	Limiting EQI Value (CO_2 dilution)	47	

11. CONCLUSIONS AND RECOMMENDATIONS

A number of emission control devices have been tested, both singly and in combination, for effectiveness in controlling the emissions from Deutz diesel engines for application in underground mines. The devices included in these tests were water scrubbers, catalysts, filters, water/fuel emulsification, and EGR techniques. The following are the conclusions and recommendations arising from this work.

(1) The use of a single index number to evaluate overall air quality is a much needed development. The Air Quality Index (AQI) is an important breakthrough in providing a usable formula for this purpose.

Application of the AQI formula, however, has some limitations particularly when used as an Exhaust Quality Index (EQI) of undiluted tailpipe emissions data from steady state test-stand engine operation. EQI calculations and comparisons from steady state test stand data, should presently be used as a guide to further investigations rather than a basis for definitive conclusions, in the absence of other data arising from field data under real duty cycle conditions.

(2) Of all the various approaches evaluated, the EGR/Corning filter system has shown the greatest capability for improving exhaust quality, under tested engine operating conditions, with the least complexity. This has been shown to an extent that promises that ventilation requirements can be reduced close to the minimum levels necessary to maintain ambient CO_2 concentrations below the threshold value.

When fully developed with appropriate filter regeneration techniques, this system would be suitable for use in non-gassy, non-coal mines and is judged best in terms of effectiveness and ease of application. It is considered the most likely system to achieve earliest commerical development.

(3) Control strategies utilizing various combinations of mesh filters (of the type tested in this study), catalysts and water/fuel emulsification have also shown great effectiveness in improving exhaust quality at the tested engine operating conditions. An emulsion/catalyst/mesh filter system shows emission control potential generally equivalent to an EGR/Corning filter system. This type of system, although needing further development in the area of mesh filter durability and emulsion system development, may be particularly relevant for gassy and coal mines application where the requirement for carrying water on board for flame proofing already exists.

(4) A number of control devices have shown themselves to have negative aspects for underground diesel use as judged by data taken at the tested engine operating conditions. These include EGR, and catalysts, each when used alone without other control system elements. Water/fuel emulsification, when used alone on the 4.3 engine, also showed negative aspects, but when applied to the 714 engine, positive results were obtained, indicating that clarification of the benefits of using water emulsions alone is required. Combinations using a water scrubber together with EGR and catalyst or using water/fuel emulsification with catalyst but without filter, also show the potential of deteriorating overall exhaust quality relative to an uncontrolled engine.

Since results based solely on steady state engine test stand data are subject to variations unrelated to real working conditions, the importance is emphasized, for all candidate systems, of final testing under actual duty cycle and field conditions as well as of careful matching of control system components to ensure positive results.

(5) Further evaluation of the viable pollution control approaches should be carried out over complete mine vehicle duty cycles, and under real field operating conditions. This should be done, in the first place, for Corning filter systems in order to assess overall performance and determine filter lifetime and the degree of self regeneration over defined duty cycles and duty cycle segments.

(6) It has already been established by engine test stand data that self-regeneration of the Corning filter is possible at full load/speed conditions. However, further studies of regeneration are needed to assess the effectiveness of regeneration aids and to establish the nature of the emissions produced during regeneration. It is of importance to determine whether catalytic reduction of Corning filter ignition temperature is possible and advantageous. Other regeneration aids such as in-situ supplementary exhaust burners or electric heating schemes also may be possible.

The development of simple regeneration techniques will greatly aid the acceptance of filter emission control technology by underground workers.

(7) This program did not address all potential safety hazards from these devices. There may be potential hazards with the ceramic filters if regenerations are uncontrolled. When a filter becomes overloaded with soot and then the material burns off, temperatures hot enough to melt the ceramic substrate (2700^{o}F) have been observed by other researchers. High CO emissions have also been noted >3,300 ppm. ORF data (see Page 21 of Phase III) shows controlled regeneration peaks of 550 ppm CO. Once the technology development is completed to control regenerations, safety hazards should be eliminated.

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APPENDIX I

Operational Experience with
Deutz F8L 413 Diesel Engine

SUMMARY OF ENGINE PROBLEMS

The following is a documentation of engine problems experienced with the Deutz F8L 413 F/W series engine. Problems of this magnitude have never been experienced by ORF with any other engine tested at their facilities.

September 1980

The engine was started, but the specified peak rpm and HP (2300 rpm, 185 HP) could not be achieved. The injection pump was sent to Montreal for calibration. The pump was re-installed, but the same problem occurred. A mechanic from the Deutz approved fuel pump service shop in Mississauga was then called in, and the governor adjusted on the pump. Specified maximum rpm and HP were then achieved.

January 1981

Oil was observed blowing out from both exhaust manifolds. A mechanic from Deutz in Montreal was called in and found all cylinder walls glazed and the piston rings not properly seated. New rings of the same type were installed, and the cylinder walls deglazed.

May 1981

Abnormal gaseous emissions were observed together with actuation of the engine temperature warning light. Oil temperatures were 125°C which was in excess of the maximum allowable (120°C) specified for that engine. Deutz engineers suggested that there was a fuel pump problem, since the fuel pump setting was found to be 90 cc/1000 shots which is in excess of the specified 77 cc/1000 shots. However, at the latter setting, specified rpm and HP could not be achieved. The engine was, therefore, removed to the Deutz, Mississauga, shop where it was disassembled, and new piston rings again installed. The cylinder walls were again deglazed. After re-assembly, the same engine overheating conditions were again observed.

A new engine was, therefore, shipped from Montreal to Mississauga, but the new engine also overheated, and would not reach specified rpm and HP. Following discussions between Deutz, Montreal, and KHD Cologne, a new set of specifications were issued which increased the maximum allowable oil temperature (130^{o}C). The fuel pump setting was also changed to 81.55 cc/1000 shots, and KHD suggested that a different type of cooling fan be installed on the engine to increase the cooling air flow. The original engine was, therefore, returned to ORF.

June 1981

During the course of testing in June, abnormally high oil consumption was observed. Oil consumption was 0.2 ℓ/hr and increased to 0.7 ℓ/hr by July.

July 1981

A Deutz engineer again deglazed the cylinder walls, and replaced the piston rings with a new ring type. A new cooling fan was also installed. This reduced the rate of oil consumption.

August 1981

The Deutz approved fuel pump service shop received instructions from Deutz that they should alter the torque rise of the pump to a new specification. When they did this, however, only 125 HP could be achieved at 2300 rpm. The relief valve on the pump was found to be faulty and was replaced. The maximum HP was now 165 HP at 2300 rpm which was still unsatisfactory, and the fuel pump setting was again found to be incorrect at 79 cc/1000 shots. This was increased to 81.5 cc/1000 shots after which the specified 185 HP at 2300 rpm could be achieved.

After 10 hours of emission testing, however, a change in engine conditions developed with increased hydrocarbons, and uneven exhaust temperatures on right and left banks. Deutz Montreal, therefore, decided to ship a new fuel pump which had been set up and calibrated at the Montreal works. This new pump eliminated the hydrocarbon emission and uneven exhaust temperature problem, but the engine would not develop the specified 185 HP at 2300 rpm. Despite all previous communication regarding this problem, the fuel pump had again been set to 79 cc/1000 shots, and had to be increased to 81.5 cc/1000 shots before specified power characteristics could be achieved. It was also revealed that the original pump had incorrect components installed due to a lack of supply of the new components required for this pump. The new pump has been equipped with the new components. In addition, Deutz advised ORF that the present type of intake and exhaust valves could result in a change occurring to emission characteristics after an unspecified number of hours of engine operation. They advised that the valves should be replaced with a new set, of different type, and this was carried out. Valve seals were not replaced, however. The engine is now performing satisfactorily, and it is hoped that no further problems will occur.

APPENDIX II

Analytical Instrumentation and Methodology

1. Particulate Testing

All particulate tests were conducted using modified EPA Method 5 source sampling trains. With this system, sampling is conducted in situ where a portion of the exhaust gas is drawn via a heated stainless steel sampling probe from the exhaust pipe through a pre-weighed 12.5 cm Pallflex, teflon coated filter. The filter is maintained at a temperature not less than 121^{o}C, to minimize moisture condensation on the filter. A nozzle connected to the sampling probe is directed upstream of, and parallel to the exhaust flow at a location approximately 8 exhaust duct diameters downstream of the nearest flow disturbance (i.e. elbow). After passing through the filter the sample gas is cooled in four impingers which are contained in an ice bath. The first two impingers contain approximately 125 ml of distilled water each, the third is dry and the fourth contains a known mass of silica gel. The cooled, dry sample gas is then passed through a calibrated dry gas meter for subsequent determination of the volume sampled.

Following each test the sampling equipment is disassembled and the probe rinsed with cyclohexane (cyclohexane/isopropyl alcohol 50% w/w for catalyst tests). Rinsings are collected in a jar for subsequent analysis. The filter is removed from its holder and stored in a glass petri dish and the filter holder rinsed with the appropriate solvent. All samples collected are then transferred to the laboratory for analysis.

Probe rinse solutions are filtered to remove the insoluble fraction and the filtrate evaporated to allow for the determination of the soluble fraction. Any residue remaining after evaporation is considered soluble particulate. The 12.5 cm sampling filter is allowed to condition for 24 hours and re-weighed to determine the total particulate material collected. Filters are then extracted for a minimum of 4 hours with water to remove sulphates in the case of tests performed with catalysts on. With catalysts removed the cyclohexane extractions can begin immediately. Following the cyclohexane extraction which lasts for 4 hours, the filters are removed and transferred to the conditioning room where they are allowed to condition for 24 hours before re-weighing. The difference between the total weight and weight after extraction is considered to be soluble particulate material.

All pertinent data collected using the above method were used in a computer program to determine particulate soluble and insoluble concentrations (mg/m^3) and emission rates in g/kW-h, g/hr, g/kg of fuel.

2. Gaseous Emissions Testing

Testing for gaseous emissions included the measurement of CO, CO_2, O_2, NO, NO_2 and total hydrocarbons (THC as methane). A portion of the hot exhaust gas is drawn from the exhaust duct through a heated (180°C) stainless steel sample line. Prior to any sample gas cooling, a portion of the hot exhaust is sent to the THC analyzer. Cricital components in this analyzer are maintained at approximately 190°C to minimize hydrocarbon condensation. This analyzer, therefore, displays concentrations on a 'wet' basis.

The following analyzers were used during the test program:

CO_2 - Horiba, Model A1A23, non-dispersive infra-red.
CO - Horiba, Model A1A23AS, non-dispersive infra-red.
O_2 - Taylor Servomex, Model OA272, paramagnetic.
(NO + NO_2)
NO_x - Thermo-Electron, Model 10A, chemiluminescent.
THC - Ratfisch IPM, Model RS5 heated flame ionization.

Following the THC analyzer, the sample gas is cooled in a condensing coil and the condensate removed. Sample gases are then filtered and sent to each analyzer using a stainless steel metal bellows pump. Flow rates to each analyzer are monitored and controlled using rotameters.

All analyzers are zeroed and calibrated for span prior to testing on a given day. Analyzer outputs are displayed on strip chart recorders for a hard copy of data. Following emissions testing, all pertinent information was entered into a computer program for calculation of concentrations and emission rates for each load/speed condition.

APPENDIX III

Analysis of Glass Fibre Emissions from Operation of the USBM Filter

FIBRE LENGTH DISTRIBUTION ON TWO FILTER DEPOSITS

The lengths of the fibres in the deposit on the filter as pictured in Figure 1 were measured using a digitizer. The photo is a 4.8 X magnification of the original filter. The fibre length distribution data are presented in Table I and plotted as a histogram in Figure 2. This technique allowed for a lower detection limit of a 0.1 mm long fibre, although shorter fibres may have been present.

It was difficult to detect whether fibres were present on the deposit of the filter labelled T24 Outlet. Fibres were visible in reflected light on the microscope but they may have been fibres in the filter itself. Some of the deposit was scraped onto a microscope slide and viewed in transmitted illumination on the microscope. A representative photo is presented in Figure 3. The fibres present could have come from the deposit or may have been detached from the filter. The fibres in the photo are in the range of 30 to 60 micrometres in length.

TABLE I
PARTICLE SIZE DISTRIBUTION FOR FIBRES ON PHOTO

SIZE CLASS INTERVAL (MM)		MEAN OF INTERVAL (MM)	FREQUENCY	FREQUENCY PER 1000	CUMULATIVE PER CENT
0.1-	0.2	0.2	19	89.2	8.92
0.2-	0.3	0.3	51	239.4	32.86
0.3-	0.4	0.4	36	169.0	49.77
0.4-	0.5	0.5	31	145.5	64.32
0.5-	0.6	0.6	17	79.8	72.30
0.6-	0.7	0.7	10	46.9	77.00
0.7-	0.8	0.8	8	37.6	80.75
0.8-	0.9	0.9	8	37.6	84.51
0.9-	1.0	1.0	9	42.3	88.73
1.0-	1.1	1.1	7	32.9	92.02
1.1-	1.2	1.2	2	9.4	92.96
1.2-	1.3	1.3	1	4.7	93.43
1.3-	1.4	1.4	2	9.4	94.37
1.4-	1.5	1.5	3	14.1	95.77
1.5-	1.6	1.6	2	9.4	96.71
1.6-	1.7	1.7	0	0.0	96.71
1.7-	1.8	1.8	1	4.7	97.18
1.8-	1.9	1.9	1	4.7	97.65
1.9-	2.0	2.0	0	0.0	97.65
2.0-	2.1	2.1	3	14.1	99.06
2.1-	2.2	2.2	1	4.7	99.53
2.2-	2.3	2.3	0	0.0	99.53
2.3-	2.4	2.4	1	4.7	100.00
2.4-	2.5	2.5	0	0.0	100.00
2.5-	2.6	2.6	0	0.0	100.00

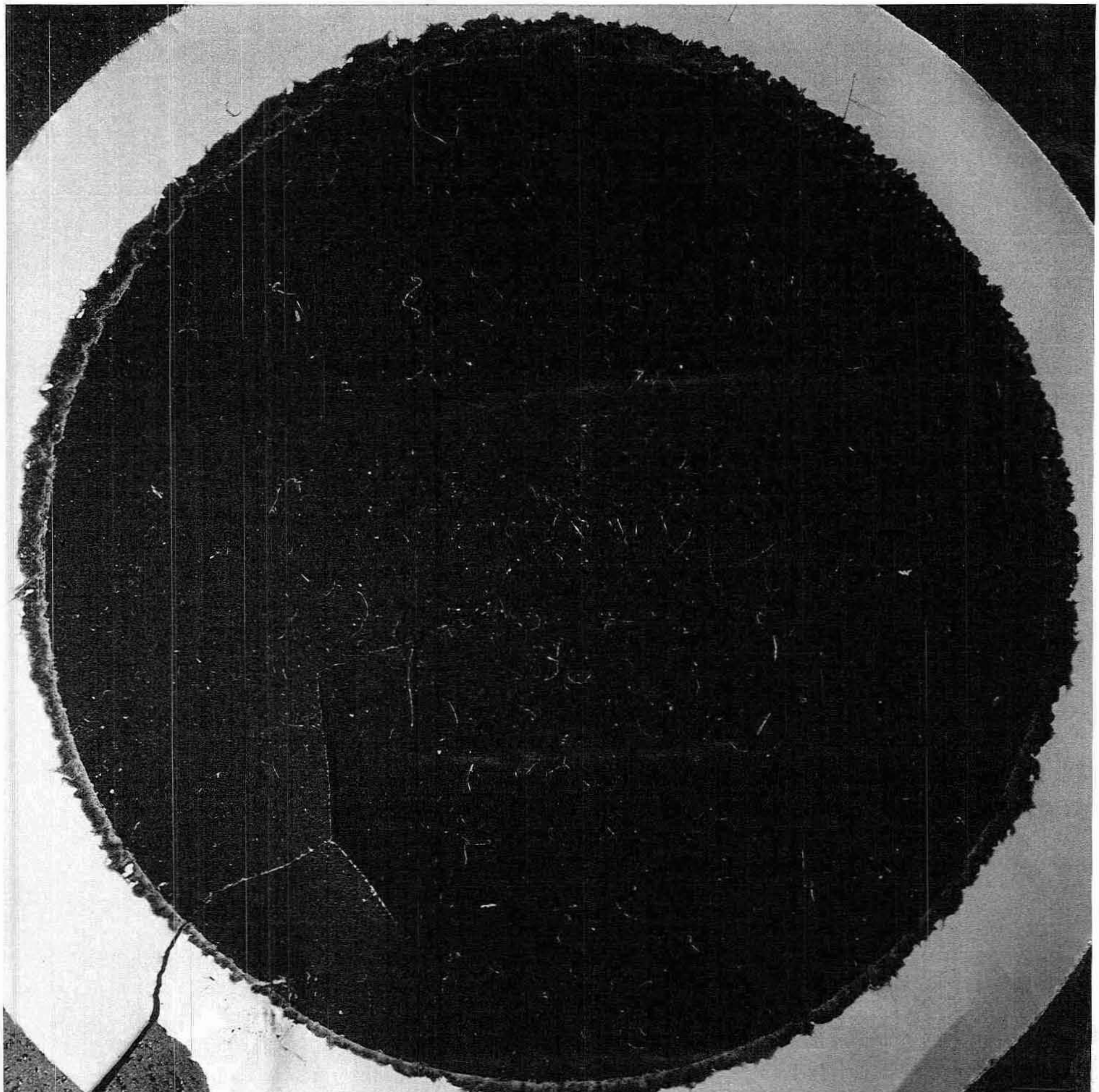

FIGURE 1: A 4.8 X Magnification of the Original Filter.

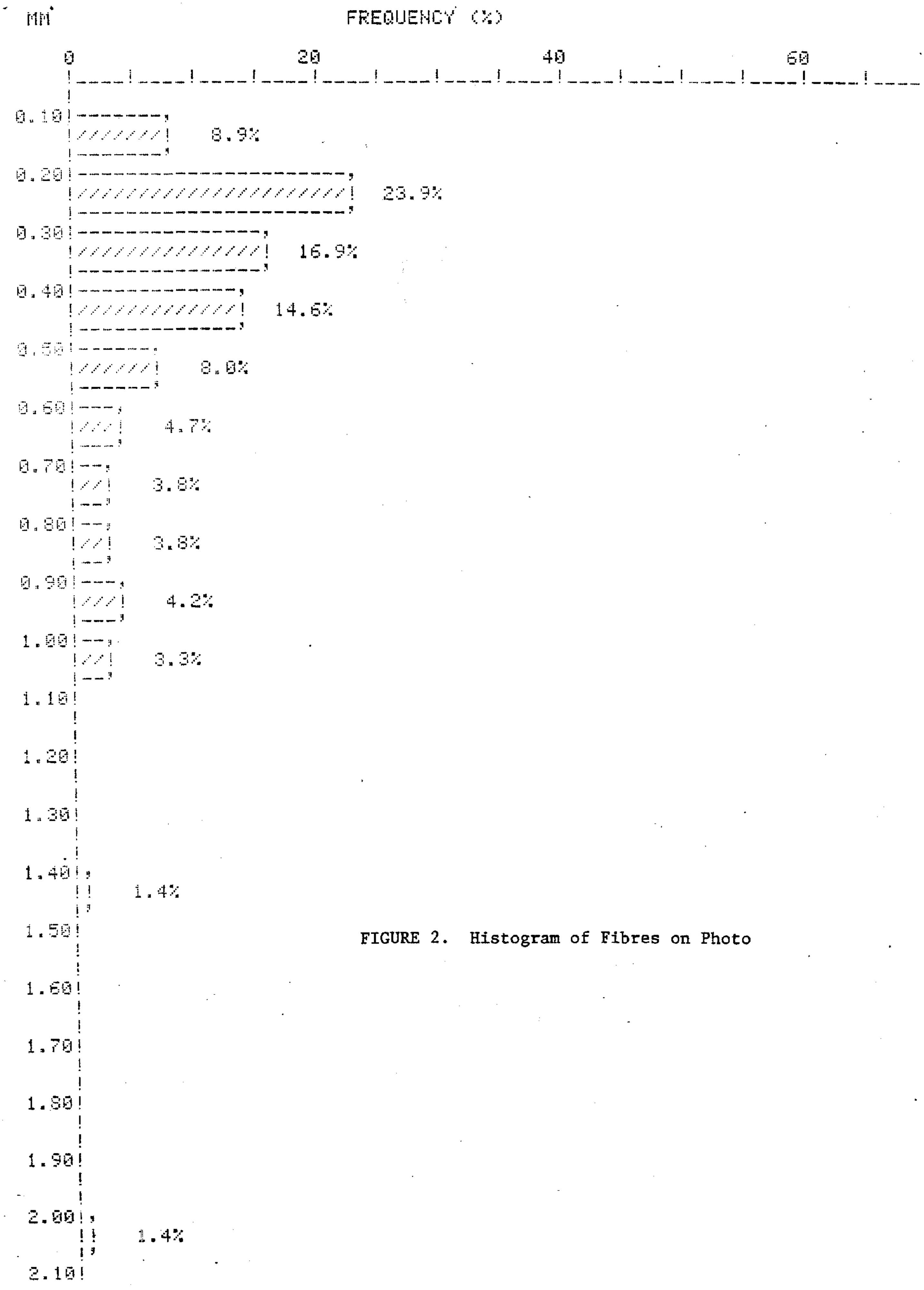

FIGURE 2. Histogram of Fibres on Photo

App. III-5

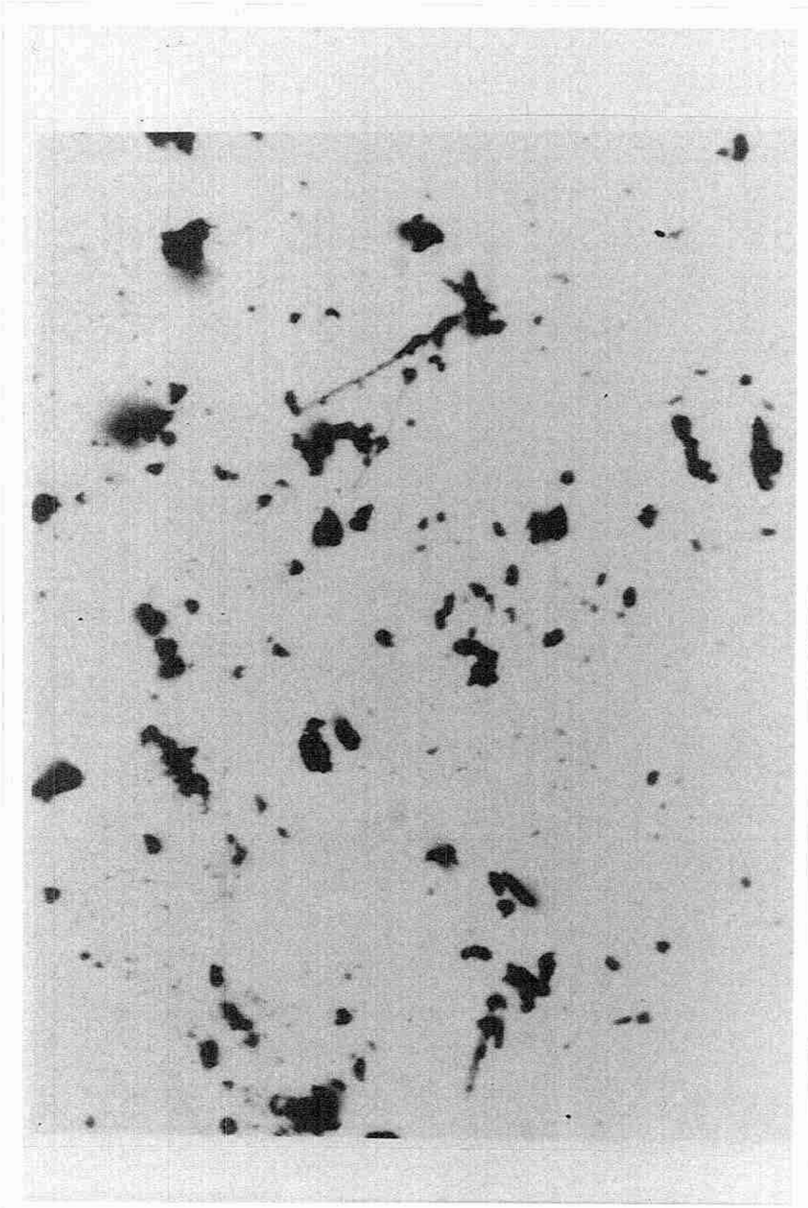

FIGURE 3 Fibres on the T24 Outlet Filter
- 315X.

CONTROL OF DIESEL EMISSIONS IN UNDERGROUND MINES

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TABLE OF CONTENTS

		Page
SUMMARY	....	248
12.	INTRODUCTION...........................	249
13.	EGR SYSTEMS APPLIED TO MINE DUTY CYCLES.	250
	13.1 White Pine Mine Installation.......	251
	13.2 Evaluation of EGR/Ceramic DPF System	252
	13.2.1 Effect of EGR on Emissions During Steady State Engine Operation..................	253
	13.2.2 Effect of EGR on Gaseous Emissions During MTU Cycle..	254
	13.2.3 Effect of EGR on Emissions During MTU MOD 4 Cycle (Hot MTU Cycle).................	256
	13.3 Regeneration of DPFs and Development of Hotter Cycles..................	256
	13.3.1 Development of Hotter Cycles	257
	13.3.2 Cycle Regeneration Tests....	258
	13.4 Conclusions on EGR Systems..........	259
14.	DIESEL PARTICULATE FILTER REGENERATION OPTIONS	292
	14.1 Face Heater.......................	293
	14.2 Burner Assembly...................	293
	14.3 Throttling........................	294
	14.4 High Temperature Soak.............	294
	14.5 Catalyzed Diesel Particulate Filter (DPF)...........	294

TABLE OF CONTENTS (continued)

		Page
	14.5.1 Particulate Ignition Temp...	294
	14.5.2 Particulate Test Results....	296
	14.5.3 Gaseous Emission Results....	296
	14.5.4 Sulphate Emission Results...	297
	14.6 Fuel Additives....................	299
	14.6.1 Fuel Additive Test Results..	300
	14.6.2 Gaseous Emission Test Results	300
	14.7 Conclusions......................	300
15.	FIELD TESTS	
	15.1 Mine Section......................	314
	15.2 Mine Test Area....................	315
	15.3 Equipment Selection and Set-Up.....	316
	15.4 DPF Installation..................	316
	15.5 Vehicle Operation Results..........	318
	15.6 Mine Air Monitoring Test Results...	320
	15.7 Durability Tests..................	322
	15.7.1 Catalyzed DPF Durability Test	322
	15.7.2 Corning DPFs with Fuel Additive	323
	15.8 Conclusions......................	323

TABLE OF CONTENTS (continued).

		Page
16.	SYSTEM COMPARISONS	351
	16.1 Exhaust and Air Quality Indices	351
	16.2 Representation of Emission Control Strategies Relative to Exhaust Quality Indices	354
17.	CONCLUSIONS	369
	REFERENCES	373

LIST OF APPENDICES

APPENDIX I	Analytical Instrumentation and Methodology	374
APPENDIX II	Mine Air Monitoring	385
APPENDIX III	Durability Tests	394

TABLE OF CONTENTS (continued).

LIST OF TABLES

		Page
Tables 13.1 - 13.6	Effect of EGR on Steady State Emission Rates from EGR/Corning Filter.	276
Tables 13.7 -13.12	EGR/Corning Filter Test, Engine Conditions.	282
Table 13.13	Effect of Fixed Position EGR on Duty Cycle Emission Rates from EGR/Corning Filter (MTU Cycle).	288
Table 13.14	Hot MTU Cycle Gaseous Emissions.	289
Table 13.15	Particulate Emissions and Control System Efficiencies.	290
Table 13.16	Duty Cycles - Temperature Profiles.	291
Table 14.1	Particulate Emissions for MTU MOD 4 LHD Cycle with Catalyzed DPFs.	301
Table 14.2	Gaseous Emissions over MTU Cycle Using Ceramic DPF Regenerative Approach.	302
Table 14.3	Engine and Sulphate Test Conditions, Catalyzed Ceramic Trap.	303
Table 14.4	$SO_4^=$, SO_2 Mass Emissions Catalyzed Ceramic Trap.	304
Table 14.5	Catalyzed DPFs $SO_2/SO_4^=$ Emissions During MTU Cycle and Burnoff.	305
Table 14.6	Catalyzed Corning DPF $SO_2/SO_4^=$ Emissions Summary MTU MOD 4 Cycle.	306
Table 14.7	Gaseous Emissions Over MTU Cycle Using Fuel Additive/Ceramic Trap Regeneration Approaches.	307

TABLE OF CONTENTS (continued).

		Page
Table 15.1	Scooptram #502 Engine History.	334
Table 15.2	Kidd Creek LHD Cycle RPM and Temperature.	335
Table 15.3	Kidd Creek Ramp Ascent RPM and Temperature.	340
Table 15.4	Kidd Creek LHD Cycle Analysis.	342
Table 15.5	Engine Exhaust Backpressures, Catalyzed DPFs.	343
Table 15.6	Engine Exhaust Backpressures, Standard DPF with Fuel Additive.	344
Table 15.7	Engine Exhaust Backpressures 6DM PTX Catalyst and Muffler.	345
Table 15.8	Mine Air Monitoring Test Results.	346
Table 15.9	Pollutant Concentrations (Downstream-Upstream)Ventilation Air.	347
Table 15.10	Filter Mass Gains and Mine Air Particulate Concentrations - Baseline Mine Air Quality Tests.	348
Table 15.11	Filter Mass Gains and Mine Air Particulate Concentrations - Catalyzed DPF Mine Air Quality Tests.	349
Table 15.12	Filter Mass Gains and Mine Air Particulate Concentrations - Standard DPF and Fuel Additive Mine Air Quality Tests.	350
Table 16.1	Composite EQI Values for Comparison of Various Emission Control Strategies - (Steady State - Deutz F6L-714 Engine)	359
Table 16.2	Composite EQI Values for Comparison of Various Emission Control Strategies - (Steady State - Deutz F8L-413 Engine)	360
Table 16.3	Composite EQI Values for Comparison of Various Emission Control Strategies - (MTU Cycles - Deutz F8L-413 Engine).	361

TABLE OF CONTENTS (continued)

		Page
Table 16.4	EQI Data - Deutz F6L-714 Diesel Engine -2200 RPM/93kW	363
Table 16.5	- " " " " -2200 RPM/71kW	364
Table 16.6	EQI Data - Deutz F8L-413 Diesel Engine -2300 RPM/103KW	365
Table 16.7	- " " " " -2300 RPM/138kW	366
Table 16.8	- " " " " -MTU Cycles.	367

LIST OF FIGURES

Figure 13.1	MTU Cycle Torque vs Time.	260
Figure 13.2	MTU Cycle Speed vs Time.	261
Figure 13.3	Effect of EGR on Gaseous Emissions at 2300 RPM.	262
Figure 13.4	" " " " " " " 1900 RPM.	263
Figure 13.5	" " " " " " " 1500 RPM.	264
Figure 13.6	Exhaust and Intake CO_2 Trends During MTU-LHD Cycle at a Nominal EGR Setting of 10%.	265
Figure 13.7	Exhaust and Intake CO_2 Trends During MTU - LHD Cycle at a Nominal EGR Setting of 10%.	266
Figure 13.8	Raw NO_x Trends During MTU-LHD Cycle with 0%, 10% and 15% EGR.	267
Figure 13.9	Corning Filter Regeneration: CO vs Time.	268
Figure 13.10	Filter Buildup During MTU-LHD Cycle.	269
Figure 13.11	Exhaust Temperature Trends During MTU-LHD Cycle with 10% EGR.	270
Figure 13.12	Exhaust Temperature Trends During MTU-LHD Cycle with 20% EGR	271
Figure 13.13	Exhaust Temperature Profile During MTU-LHD Cycle - No EGR.	272

TABLE OF CONTENTS (continued)

		Page
Figure 13.14	Engine Backpressure vs Time.	273
Figure 13.15	Exhaust Temperature Profile - Hot MTU Cycle and 15% EGR.	274
Figure 13.16	Engine Test Configurations.	275
Figure 14.1	Filter Ignition Temperature Test (Catalyzed Filter).	308
Figure 14.2	Comparison of Filter Buildup with MTU Cycle, at Various Combustion Air Temperatures (Catalyzed Filter).	309
Figure 14.3	Comparison of Engine Backpressure Profiles for Standard MTU Cycle and MTU MOD 4 Cycle with Catalyzed DPFs.	310
Figure 14.4	Conversion SO_2 to $SO_4^=$ vs Catalyst Temperature and Fuel/Air Ratio.	311
Figure 14.5	Post Catalyst Sulphate and Sulphur Dioxide Emission Rate vs Catalyst Temperature.	312
Figure 14.6	Comparison of Filter Buildup with MTU Cycle Using Fuel Additive.	313
Figure 15.1	Plan of 3000' Level (915 metre).	324
Figure 15.2	Test Site Layout	325
Figure 15.3	Layout of Mine Air Monitoring Equipment.	326
Figure 15.4	Instrumentation and Samplers Installed on the LHD.	327
Figure 15.5	Soltec Chart Recording of LHD Cycle RPM and Right Exhaust Bank Temperature Chart Speed .5cm/min.	328
Figure 15.6	Soltec Chart Recording of LHD Cycle RPM and Right Exhaust Bank Temperature Chart Speed 8cm/min.	329

TABLE OF CONTENTS (continued)

		Page
Figure 15.7	Kidd Creek LHD Cycle RPM	330
Figure 15.8	Kidd Creek LHD Cycle Temperature.	331
Figure 15.9	Kidd Creek Ascent RPM.	332
Figure 15.10	Kidd Creek Ramp Ascent Temperature.	333

SUMMARY

The Corning DPF, Corning DPF/EGR, Catalyzed Corning DPF and Corning DPF/fuel additive diesel emission control systems were evaluated for emissions and auto-regeneration. System evaluations were done during simulated LHD cycles. All systems showed excellent reduction of diesel emissions with the best systems incorporating EGR. There is significant SO_2-$SO_4^{=}$ conversion by the catalyzed DPF but it is hoped this problem can be alleviated with other catalyst formulas.

Auto-regeneration was achieved using the MTU and MTU MOD 4 cycle with both the catalyzed Corning and fuel additive techniques during transient dynamometer testing. The success using the MTU cycle however was borderline depending upon intake air temperatures and the type of fuel additive. Final systems testing was done at Kidd Creek Mine and the MTU experimental mine. The MTU tests were to compare emission results between test bed and underground mine tests. Kidd Creek testing was aimed primarily at evaluating real world systems durability. Both the catalyzed Corning and Corning/fuel additive systems were successful from a durability and auto-regeneration standpoint. Unfortunately emission reductions could not be verified as the mine air monitoring tests were inconclusive.

12. INTRODUCTION

Diesel engines are used extensively underground in Canada and in many parts of the U.S.A. Growing concern of the health effects of uncontrolled diesel exhaust emissions led to the development of many techniques for the control of diesel emissions. Phases I and II of the USBM program made an extensive survey of the control strategies available. Many of these control strategies were then evaluated and/or developed during steady state dynamometer testing. Performance of the various control systems tested were compared using the EQI (Exhaust Quality Index). Systems incorporating the Corning ceramic diesel particulate filter (DPF) were concluded to be the most efficient and practical.

Therefore Phase III of the program keyed on the ceramic DPFs and worked towards an underground mine evaluation of the final systems. In order to evaluate the Corning systems over transient condition, simulated mine LHD duty cycles were developed for tests on computer controlled transient test cells. Much of the cycle development work was done under a Ministry of Labour program. An essential component to a practical system is the auto-regeneration of the DPF. The DPF is very efficient at trapping diesel particulate so frequent cleaning or burning off of the trapped particulate is vital. Therefore a number of techniques were investigated to come up with a system which would be self-regenerating while on the vehicle.

Catalyzed DPFs and fuel additives were deemed the most practical so were further developed and evaluated in this program.

To complete the transition from the test bed to the real world an underground mine demonstration was carried out to assess durability, regeneration and emissions performance under actual mine operating conditions.

13. EGR SYSTEMS APPLIED TO MINE DUTY CYCLES

Previous work dealt with the basic effects of EGR on diesel emissions characteristics during steady state conditions. Steady state testing gives a general indication of what effects a system will have in the real world. However, the transient nature of actual mine duty cycles can substantially change the effect of certain parameters such as DPF regeneration. Testing was therefore keyed to simulated transient mine duty cycles. An LHD cycle was developed by Michigan Technological University (MTU) at White Pine Mines. Cycle data was obtained by MTU using a Deutz F8L-714 engine in a Wagner ST-5 scooptram. This cycle was altered by ORF for use on a Deutz F8L-413 FW engine. Much of the cycle development was done under a Ministry of Labour program. The cycle is 150 seconds long and is made up of four modes:

Mode 1 - Driving into the drift from a cross-cut

Mode 2 - Loading at the face (mucking)

Mode 3 - Hauling out of the drift from face of cross-cut

Mode 4 - Hauling from cross-cut to dump point, dumping, tramming to cross cut.

Typical speed and torque profiles of this MTU cycle are given in Figures 13.1 and 13.2.

Also, in this phase, an LHD vehicle was outfitted with an EGR/ceramic DPF system for underground evaluation at the MTU experimental mine.

13.1 White Pine Mine Installation

As part of the effort to relate dynamometer emission results to the real world of mining, ORF baselined a Deutz F8L-413 FW engine with its dynamometer/dilution tunnel test facility. The engine was then shipped to MTU and installed in a Wagner ST5D scooptram.

Exhaust Controls Inc. (ECI) and ORF then outfitted the scooptram with an EGR/DPF emissions control system. This system was then to be evaluated in an underground mining environment by MTU at White Pine Mines.

This system was configured with an individual EGR valve and DPF for each exhaust bank of the engine. There was effectively an individual system for each bank except that the final exhaust from both DPFs was combined. In order to eliminate particulate matter from being recirculated into the combustion air, the EGR takeoff was downstream of the DPFs and the EGR return upstream of the combustion air filters. In ORF experience with EGR applications, the normal paper element air filters have been found to plug up very quickly. Therefore, oil bath air cleaners were used in this installation. Oil bath air cleaners, although not quite as efficient as paper element types, have a much greater filtration capacity.

Special shock mounts were constructed for the ceramic DPFs. Due to the rough nature of the LHD cycles this was felt to be necessary to ensure the ceramic elements would not fracture due to mechanical stress.

Other concerns addressed in this installation were:

(1) keeping all components within the scooptram frame to avoid damage to the system from rocks, walls, etc.

(2) avoid hindering routine engine maintenance

(3) leave open pathways for engine cooling air flow

(4) allow the exhaust pipe to be either pointed 20^{0} up from the top surface of the vehicle or routed downward toward the original port.

All exhaust components, DPFs, EGR valves, oil bath air cleaners and DPF shock mounts were procured and/or constructed by ECI and ORF. All exhaust components were stainless steel. Components were shipped to MTU during the summer of 1983.

ORF and ECI staff travelled to Houghton, Michigan, September 5th, 1983. A meeting was held between ECI, ORF, MTU and White Pine staff at the Houghton shop where the scooptram was located. Discussions focused on the configuration of the final system installation on the LHD.

ORF and ECI staff fitted the system together for the remainder of the week with two White Pine Mines mechanics and a welder from Northern Industrial. The vehicle was then transported underground for comparison testing by MTU.

13.2 Evaluation of EGR/Ceramic DPF System on the Test Bed

In the test cell configuration, each exhaust bank was routed through its own ceramic DPF mounted directly on the exhaust manifold. The two filtered exhausts were then combined and the EGR flow withdrawn. A single butterfly valve was then used to control the combined EGR flow. The EGR return entered the combustion air flow upstream of two oil bath air cleaners. Combustion air flow was then directed to each of the two air cleaners and then into the intake air manifolds. See Figure 13.16 for exhaust configuration. For all testing the EGR valve was at a fixed setting which caused the amount of EGR to vary continuously over the cycle. Before starting transient tests the engine emissions were measured at steady state conditions over the complete range of engine operating conditions. Comparisons could thus be made between steady state and transient results.

13.2.1 Effect of EGR on Emissions During Steady State Engine Operation

The effects of applying various percentages of EGR to the steady state gaseous emission rates of the Deutz engine equipped with the EGR/Corning filter system, are shown in Tables 13.1 to 13.6. The test matrix covers engine loads of 100%, 80%, 60% and 40% of full load condition, at speeds of 2300, 2100, 1900, 1700, 1500 and 1300 rpm. Reductions in NO_x and increases in CO and THC observed, provide important steady state information for comparison with the transient effects measured during engine operation over simulated mine duty cycles.

Of special interest are the engine operating conditions measured over the same load/speed matrix shown in Tables 13.7 to 13.12. It should be noted that, at 100% load, the maximum torque available decreases with increase in EGR due to the derating effect of EGR. At all load speed conditions, the fuel consumption rate increases with EGR application. The increased fueling rate results in increased exhaust temperatures, a richer fuel/air ratio, decreased NO_x emissions from the lower peak flame temperatures in the combustion chamber, and increased particulate emissions. The latter effect is more prominent at 100% load conditions.

In general, the conclusions that can be drawn from Tables 13.1 to 13.6 and Figures 13.3 to 13.5 are:

(1) The percent reduction of NO and NO_2 is greatest at 100% engine load and gradually decreases as load decreases. Engine speed does not appear to affect the NO_x reduction.

(2) The increase in CO is significant at 100% loads but drops off rapidly once off full load. The increases at off full load conditions are not particularly significant.

(3) THC emissions, on the average, are changed very little at the 100% load condition. Off full load THC emissions are reduced 10% to 70% with no particular pattern.

13.2.2 Effect of EGR on Gaseous Emissions During the MTU Cycle

For this set of experiments the EGR valve was set to fixed positions corresponding to 0, 10 and 15% EGR measured at the steady state engine load/speed condition of 2200 rpm and 80% load. The engine was then operated over repeated duty cycles with the EGR valve in the preset position so that the amount of EGR applied varied over the duty cycle.

Real time traces of combustion intake and exhaust CO_2 values obtained over the duty cycle are shown in Figure 13.6 for 10% EGR, and Figure 13.7 for 15% EGR application. Intake CO_2 is a measure of the amount of EGR applied. Also shown is the variation of EGR over the cycle. Modes 1, 2, 3, and 4 of the cycle are indicated at the bottom of the plots.

With EGR varying in the manner shown above, it is of interest to observe the overall effect of the variable EGR over the cycle on real time emission traces. Figure 13.8 shows the real time concentration traces of NO_x emissions measured over the cycle with application of a nominal 0%, 10% and 15% EGR. It is apparent that the fixed position EGR valve is capable of reducing the NO_x emissions over all modes of the cycle. Table 13.13 shows the average emission rates of NO, NO_2, NO_x, CO, THC and CO_2 obtained with 0%, 10% and 15% EGR measured over one duty cycle. Also shown are the percent changes in average emission rates over the cycle with EGR application. A nominal 15% EGR application can reduce NO_x by 41% without significant adverse effects to emissions of CO and THC. It can be concluded, therefore, that a fixed position EGR valve is a simple and effective way of controlling NO_x emissions while the engine is operating over mine duty cycles.

13.2.3 Effect of EGR on Emissions During MTU MOD 4 Cycle (Hot MTU Cycle).

The details of this modification of the MTU cycle will be discussed in the next section. Basically, the MTU MOD 4 is a significantly hotter variation of the MTU cycle. Table 13.14 compares the gaseous emissions of the two cycles with and without 15% EGR. NO_x reductions were very good with a 41% reduction for the MTU cycle and 55% reduction for the MTU MOD 4 cycle. In both cycles there was no significant effect on THC emissions. There was a large increase in CO from 122 g/hr to 282 g/hr (131%) with the EGR application on the MTU MOD 4 cycle. The increase of CO for the MTU cycle was only marginal. This larger increase for the MTU MOD 4 cycle is partially due to particulate combustion on the filter as shown by the CO emissions in Table 13.14 before and after the DPFs. Gaseous emissions were also analyzed during a steady state (2300 rpm/100% load) burnoff and showed no change except for CO. Figure 13.9 shows CO peaking at 560 ppm from a normal concentration of 200 ppm.

Control system efficiencies for particulates are shown in Table 13.16. There are only slight variations in efficiencies between EGR and non EGR tests and between the two fuels tested. (Phillips D-2 and Gulf Diesel 40). All soluble and insoluble efficiencies are excellent for the combined EGR/DPF system; all being 94% or better.

13.3 Regeneration of DPFs and Development of Hotter Cycles

During emissions testing the MTU cycle was not hot enough to regenerate the DPFs with EGR application. Therefore, the DPFs had to be regenerated at a steady state engine condition of 2300 rpm/100% load.

Attempts were made to regenerate the DPFs over duty cycle operation. Figure 13.10 shows filter pressure drop traces measured over repeated duty cycles without EGR application. No apparent regeneration effect was observed. The same result was found with EGR application, also shown in Figure 13.10. The reason for this becomes apparent when Figures 13.11 and 13.12 are examined. Figure 13.11 shows the temperature traces measured over the cycle with 10% EGR application. Filter inlet temperatures rarely reach 480^{o}C, and filter outlet temperatures are smoothed out by the heat capacity of the filter and average out at less than 370^{o}C. Figure 13.12 shows the temperature traces when the EGR was increased to 20%. The DPF outlet temperature averages less than 425^{o}C and still appears too low with this cycle for effective filter regeneration. Therefore it was decided to investigate the development of hotter cycles to promote DPF regeneration

13.3.1 <u>Development of Hotter Cycles</u>

It is recognized that the ignition temperature of trapped diesel particulate is approximately 510^{o}C. The typical MTU temperature profile (see Figure 13.13) has an average temperature of 343^{o}C with no excursions close to the desired 510^{o}C. Before developing a hotter cycle a number of additional duty cycle temperature profiles from operating mine vehicles were examined. Swedish LHD duty cycles show a significantly higher temperature profile (24) as do typical temperature traces from a Wagner ST-8 LHD vehicle as measured at the Canadian Dennison Mine

(25). Table 13.16 summarizes the average exhaust temperature and the percentage time temperature exceeding 510°C for various cycles. It is apparent from this data that the MTU cycle is very much on the cool end. Average exhaust temperatures vary from 370-425°C for the other cycles examined with most showing significant excursions above 510°C. As shown, the MTU plus 20% EGR did reach 390°C average exhaust temperature with 5% of the cycle exceeding 510°C. However, regeneration was not achieved.

Four modifications were made to the MTU cycle as shown in Table 13.16. It was found that modifications 3 and 4 approached the average cycle temperatures of the hotter mine duty cycles examined. The MTU MOD 4 (Hot MTU) cycle, with an average exhaust temperature of 429°C and 5% of the cycle exceeding 510°C, was felt to have potential to regenerate DPFs with EGR application.

13.3.2 Cycle Regeneration Tests

Four different cycle conditions were tested for regeneration potential as follows: (1) MTU Cycle, (2) Hot MTU Cycle, (3) MTU Cycle and 15% EGR, and (4) Hot MTU Cycle and 15% EGR. Figure 11.14 shows that the MTU Cycle and the Hot MTU Cycle had similar backpressure rises of 0.289 and 0.275 kPa/h respectively. The MTU Cycle and 15% EGR produced a substantially higher rate of 0.793 kPa/hr due to the increased particulate emissions associated with EGR. The initial Hot MTU Cycle and 15% EGR had a pressure rise rate of only 0.363 kPa/hr despite having higher particulate emissions than the MTU Cycle.

This result suggests that partial regeneration was being achieved. A second test was performed on the Hot MTU Cycle and 15% EGR with gaseous analysis performed before and after the Corning filters. This test produced a significantly higher pressure buildup of 1.05 kPa/hr. No other significant differences between the two tests could be found.

Figure 13.15 illustrates the temperature profile of the MTU MOD 4 (Hot MTU) cycle with 15% EGR. This cycle has an average temperature of $496^{o}C$ with 48% of the cycle exceeding $510^{o}C$. These temperatures are high enough for regeneration. However, the exhaust gas oxygen content is reduced due to EGR effects. Another effect of EGR application is increased total particulate emissions so that a borderline regeneration may not keep up with the rate of particulate deposition. The two very different buildup rates for this cycle condition (.363 kPa/hr and 1.05 kPa/hr) suggest a borderline partial regeneration condition.

13.4 Conclusions on EGR Systems

The combined EGR/DPF control system is a simple and effective method of reducing particulate and NO_x emissions. However, operating on the MTU cycle regeneration of the DPFs could not be obtained. The development of hotter versions of the MTU cycle and the application of EGR still did not produce regeneration conditions, despite temperatures in excess of $510^{o}C$ with the application of EGR. It appears that the application of EGR does not assist regeneration of DPFs. However, EGR does improve NO_x emission quality so should be seriously considered for emission control systems.

FIGURE 13.1 : MTU CYCLE TORQUE VS TIME (Average - 320 Nm)

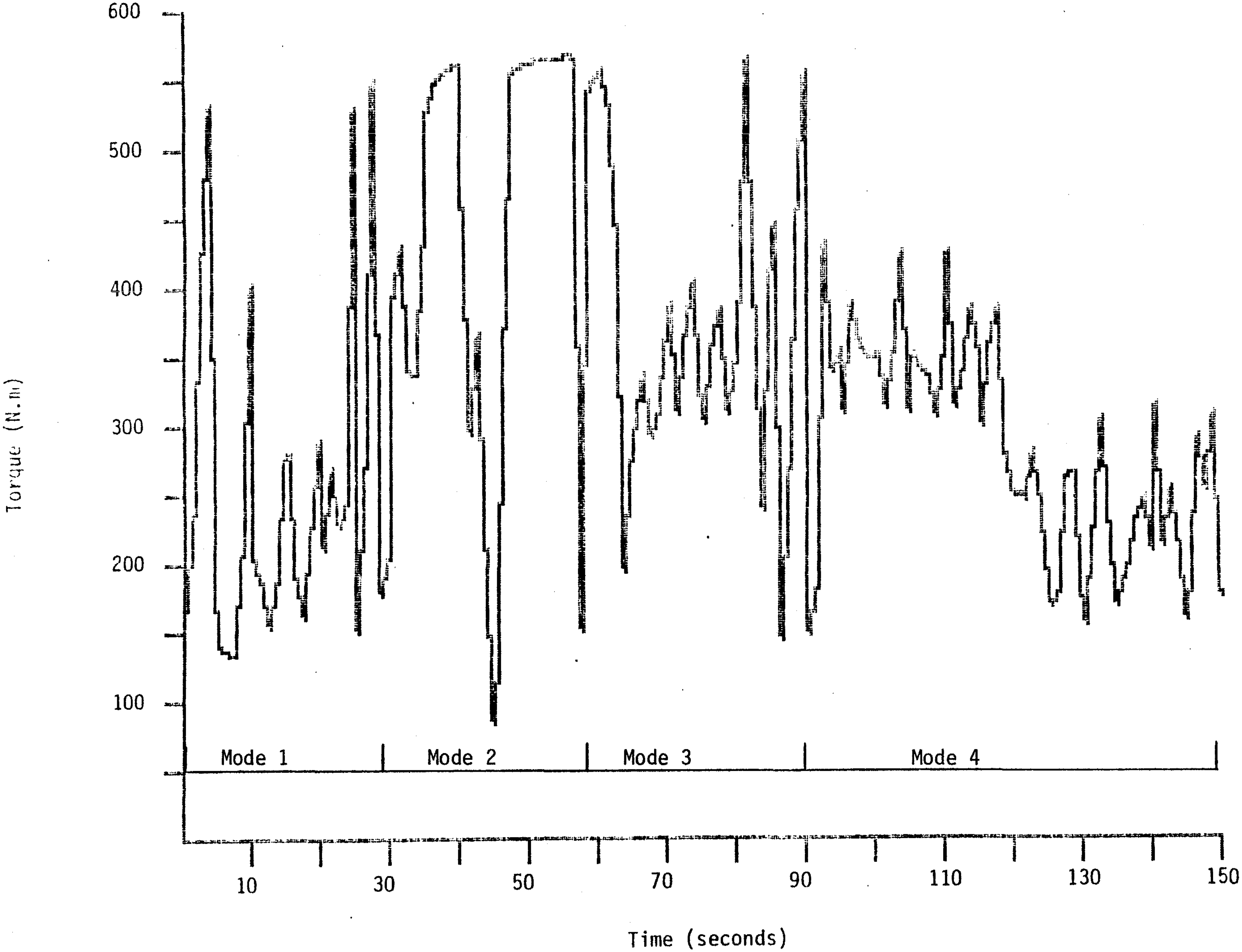
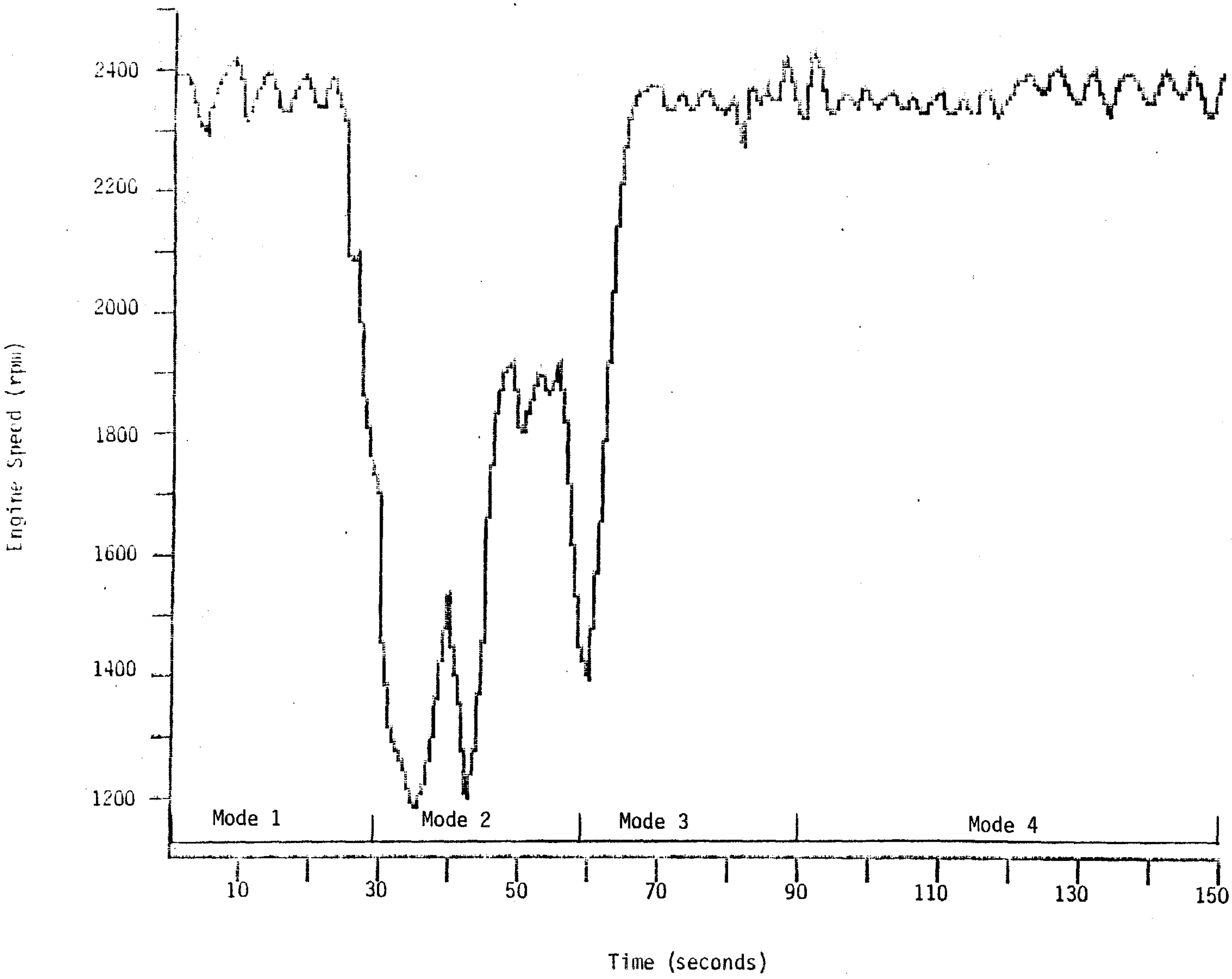


FIGURE 13.2 : MTU CYCLE SPEED VS TIME (Average 2160 rpm)



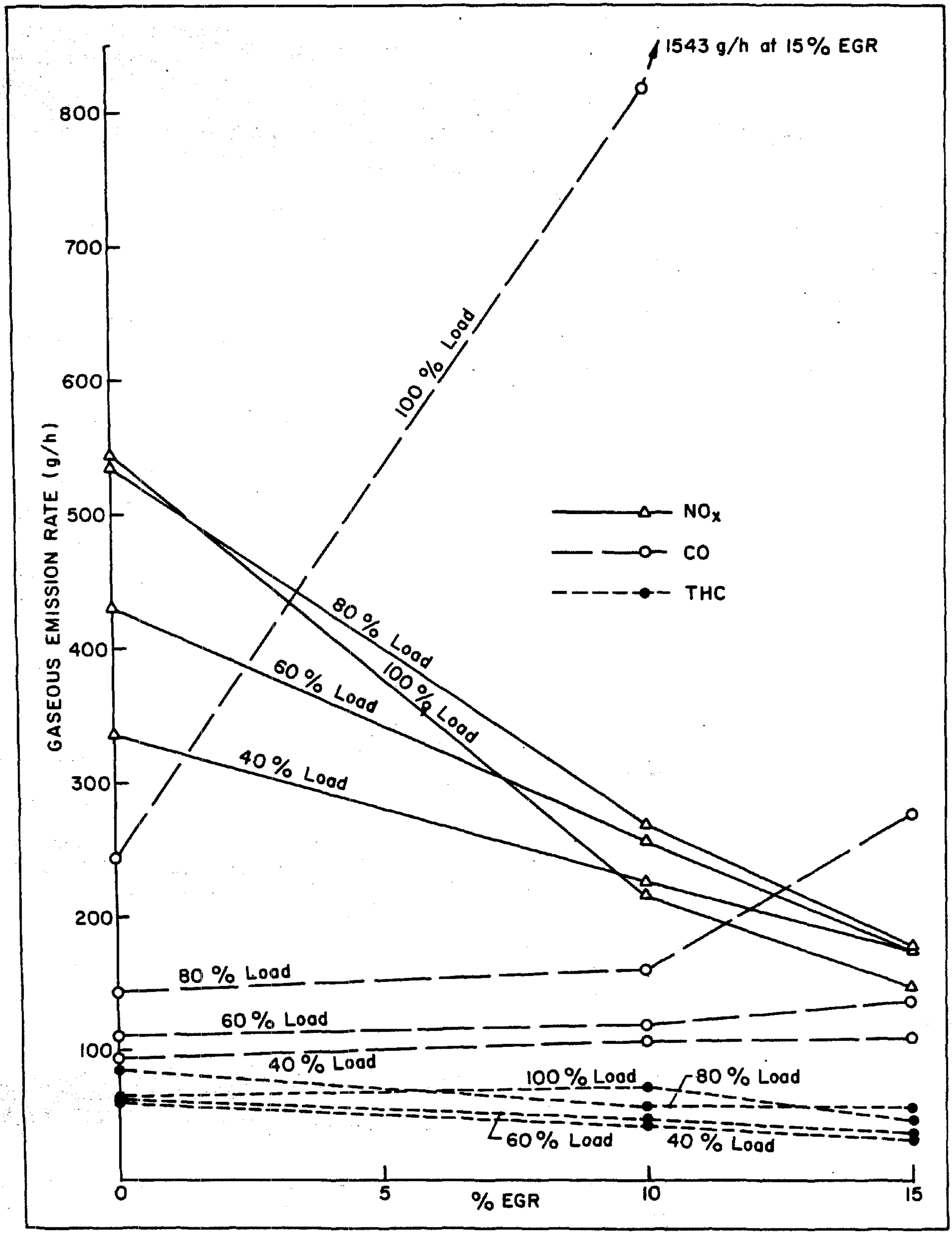


FIGURE 13.3 EFFECT OF EGR ON GASEOUS EMISSIONS AT 2300 RPM (EGR + DPF ON DEUTZ F8L-413 ENGINE)

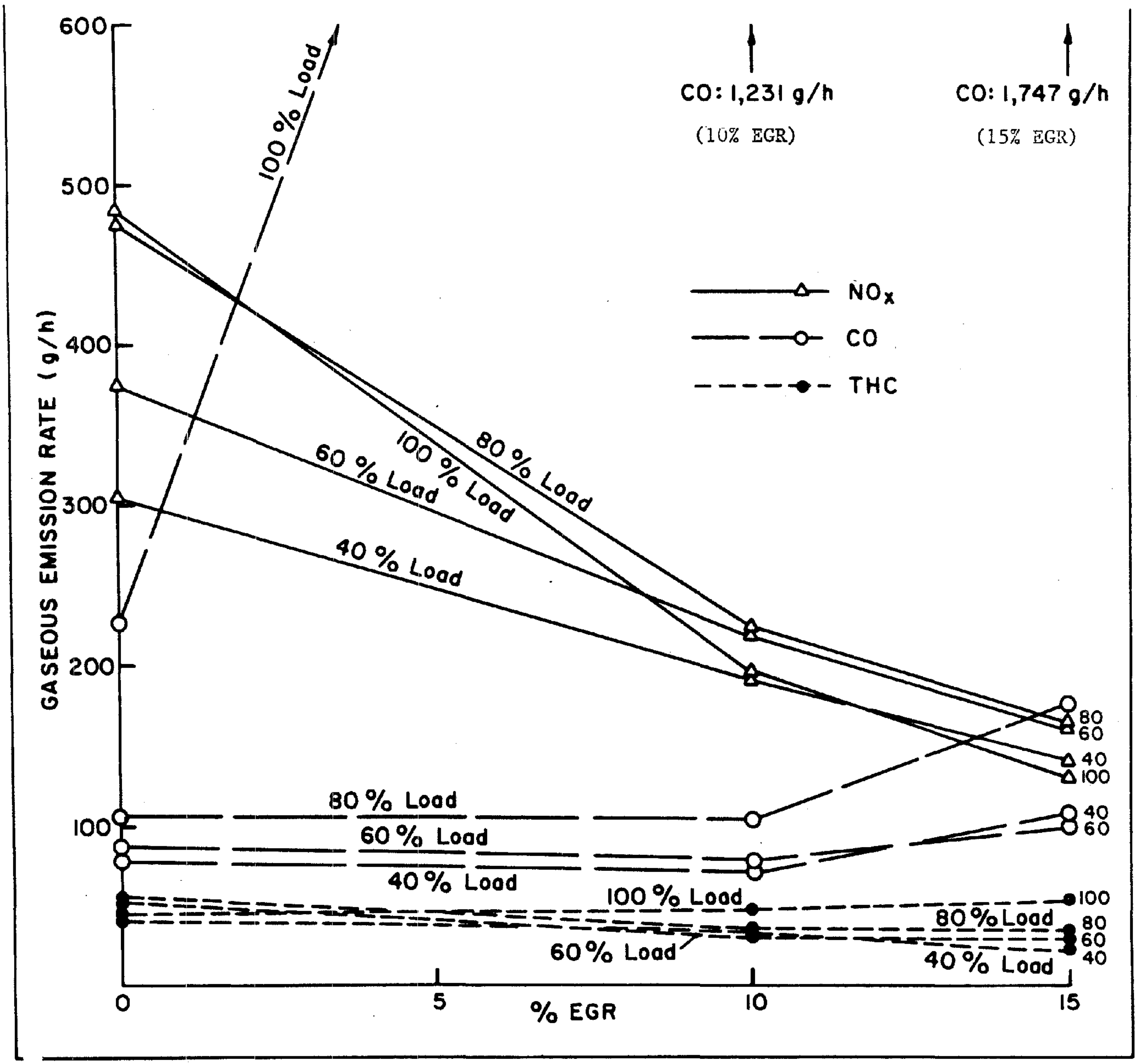


FIGURE 13.4 EFFECT OF EGR ON GASEOUS EMISSIONS AT 1900 RPM (EGR + DPF ON DEUTZ F8L 413 ENGINE)

FIGURE 13.5 EFFECT OF EGR ON GASEOUS EMISSIONS AT 1500 RPM (EGR + DPF ON DEUTZ F8L-413 ENGINE).

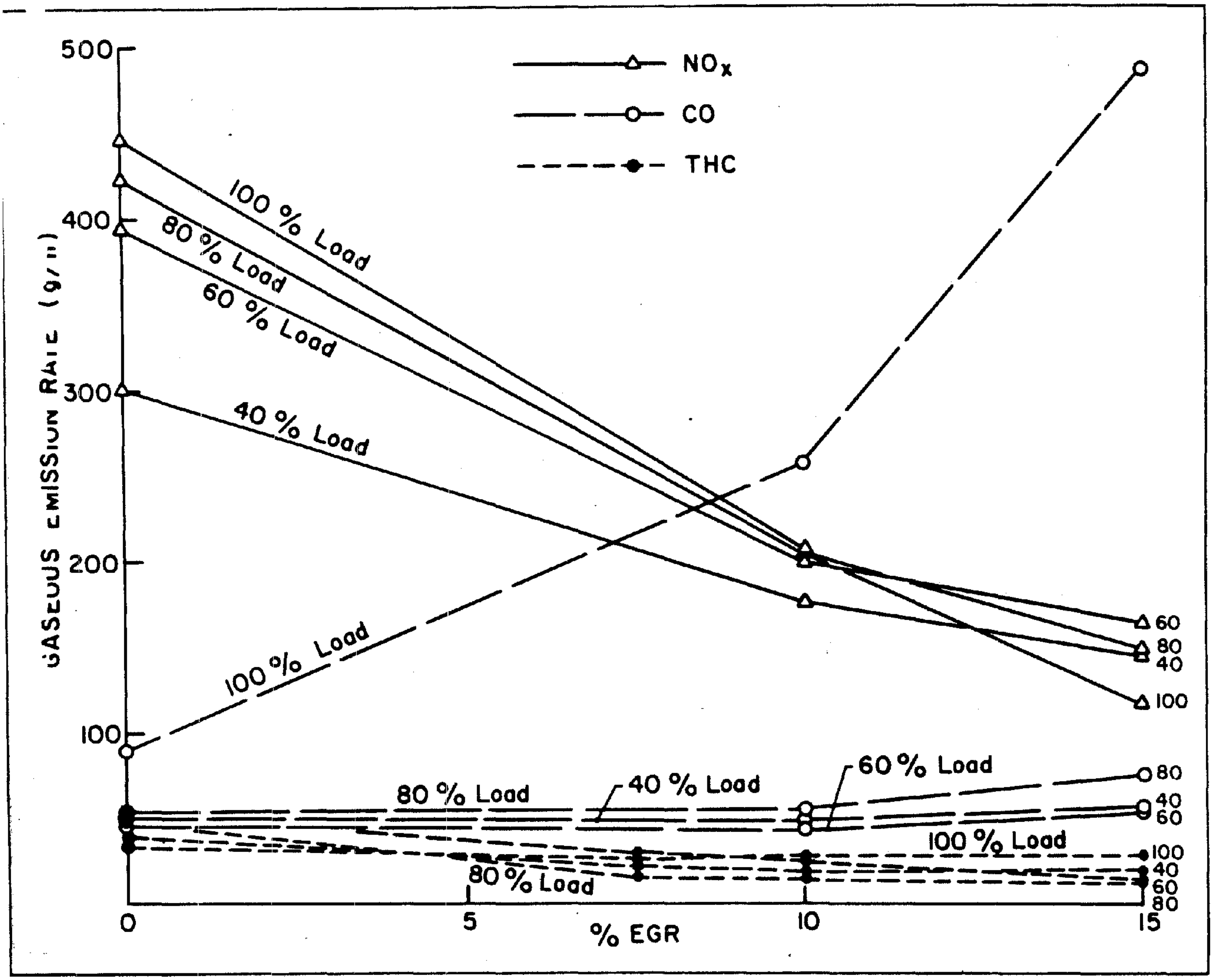
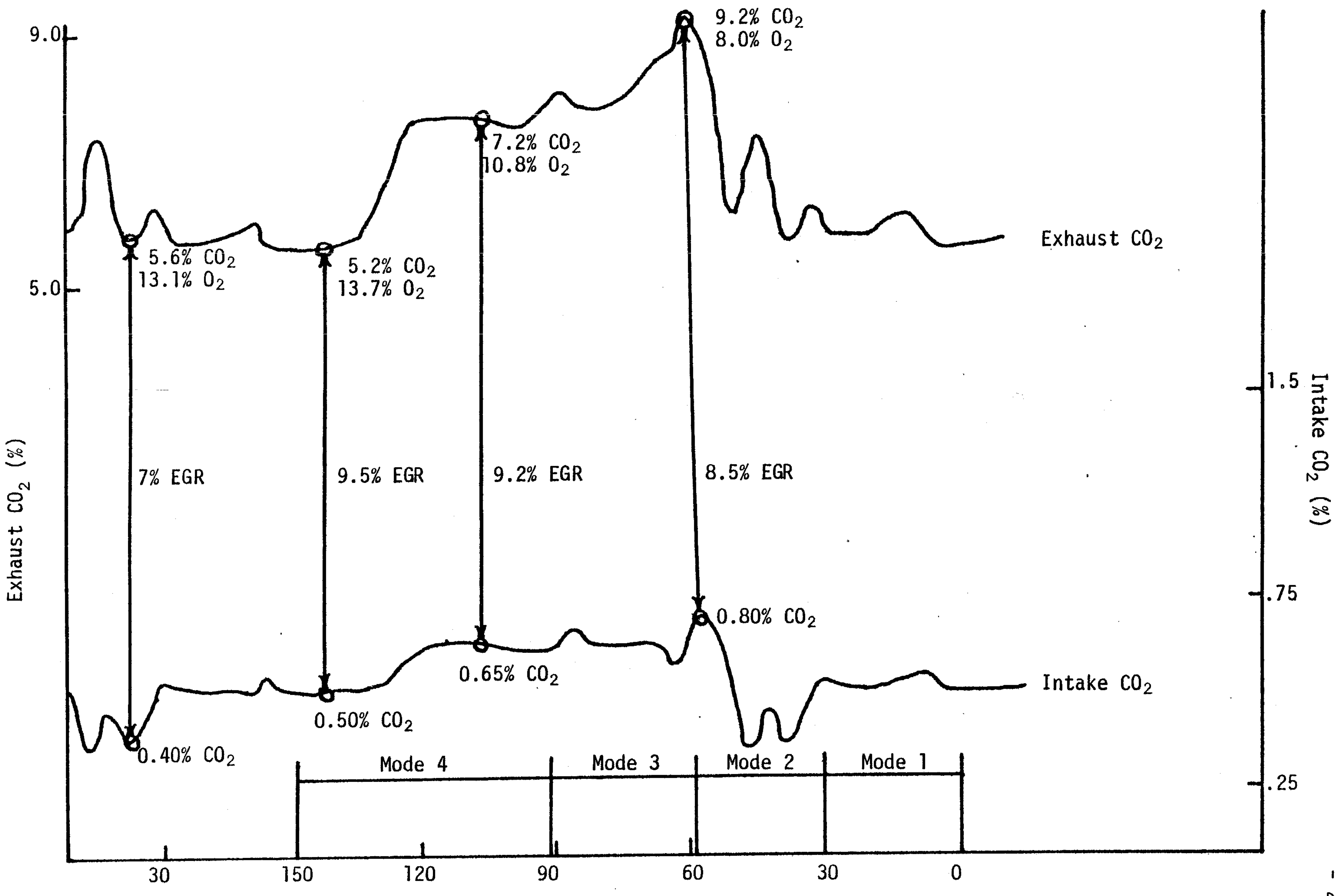
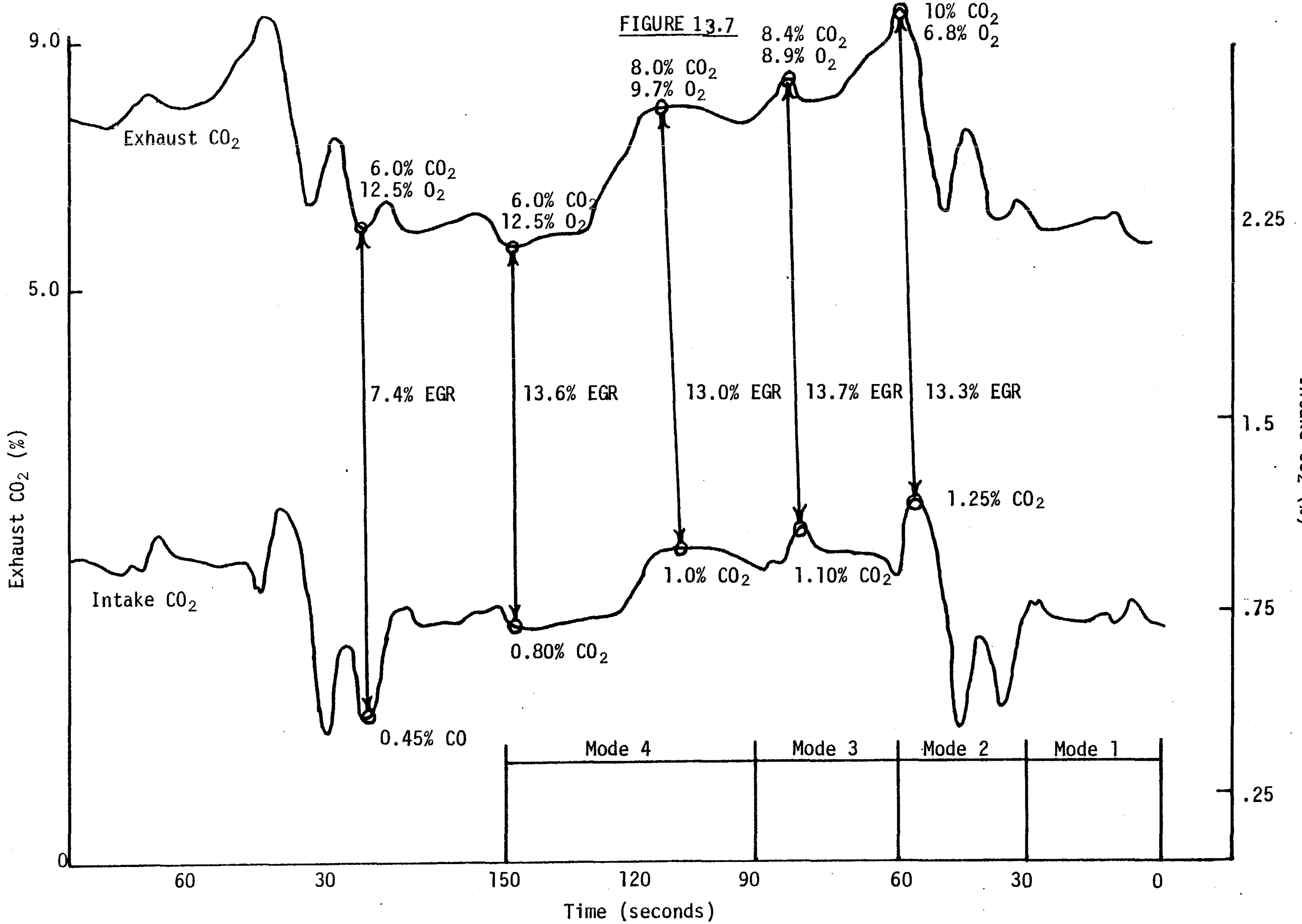


FIGURE 13.6



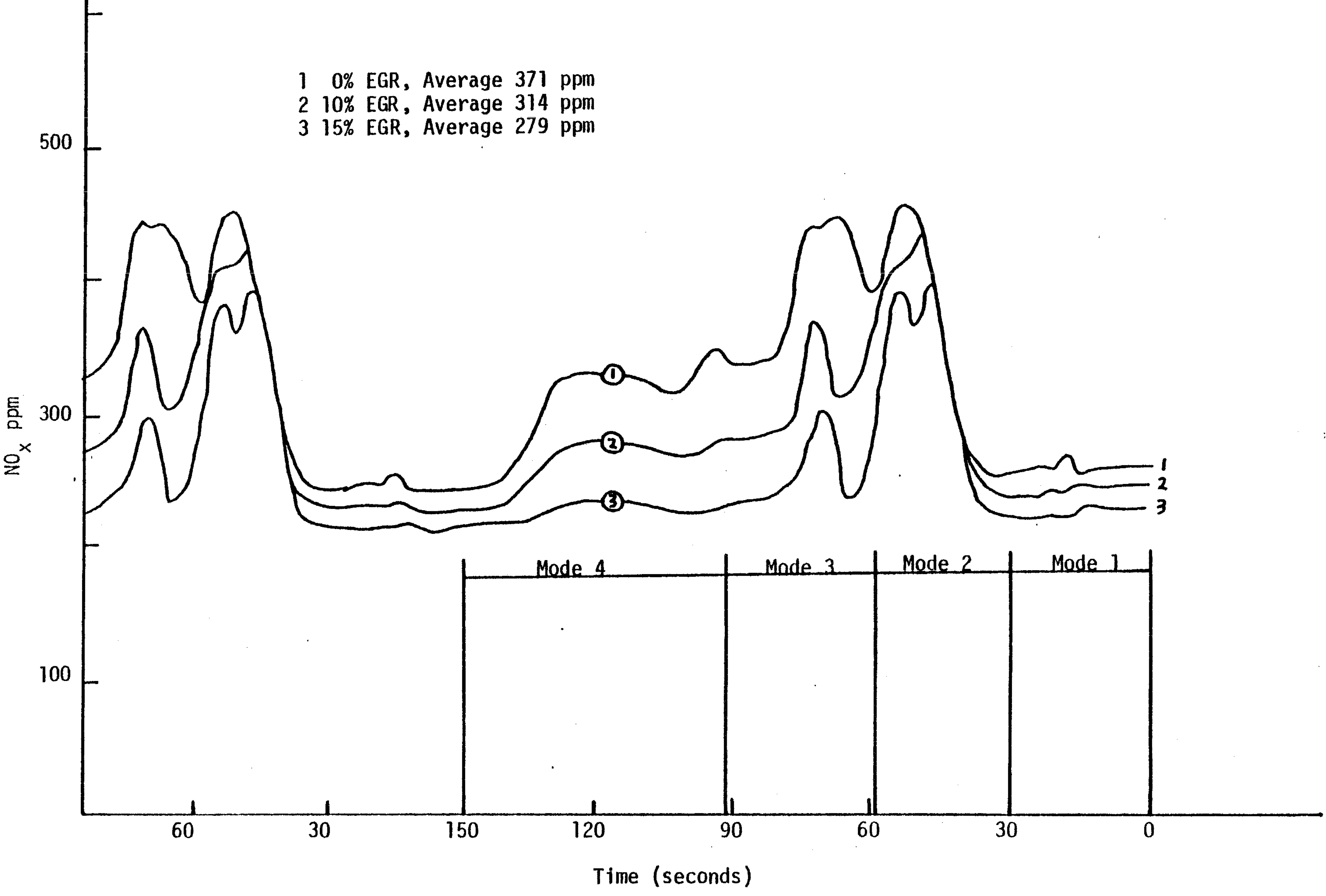
Exhaust and Intake CO_2 Trends During MTU-LHD Cycle at a Nominal EGR Setting of 10%

FIGURE 13.7



Exhaust and Intake CO_2 Trends During MTU-LHD Cycle at a Nominal EGR Setting of 15%

FIGURE 13.8



Raw NO_x Trends During MTU-LHD Cycle with 0%, 10% and 15% EGR

Figure 13.9

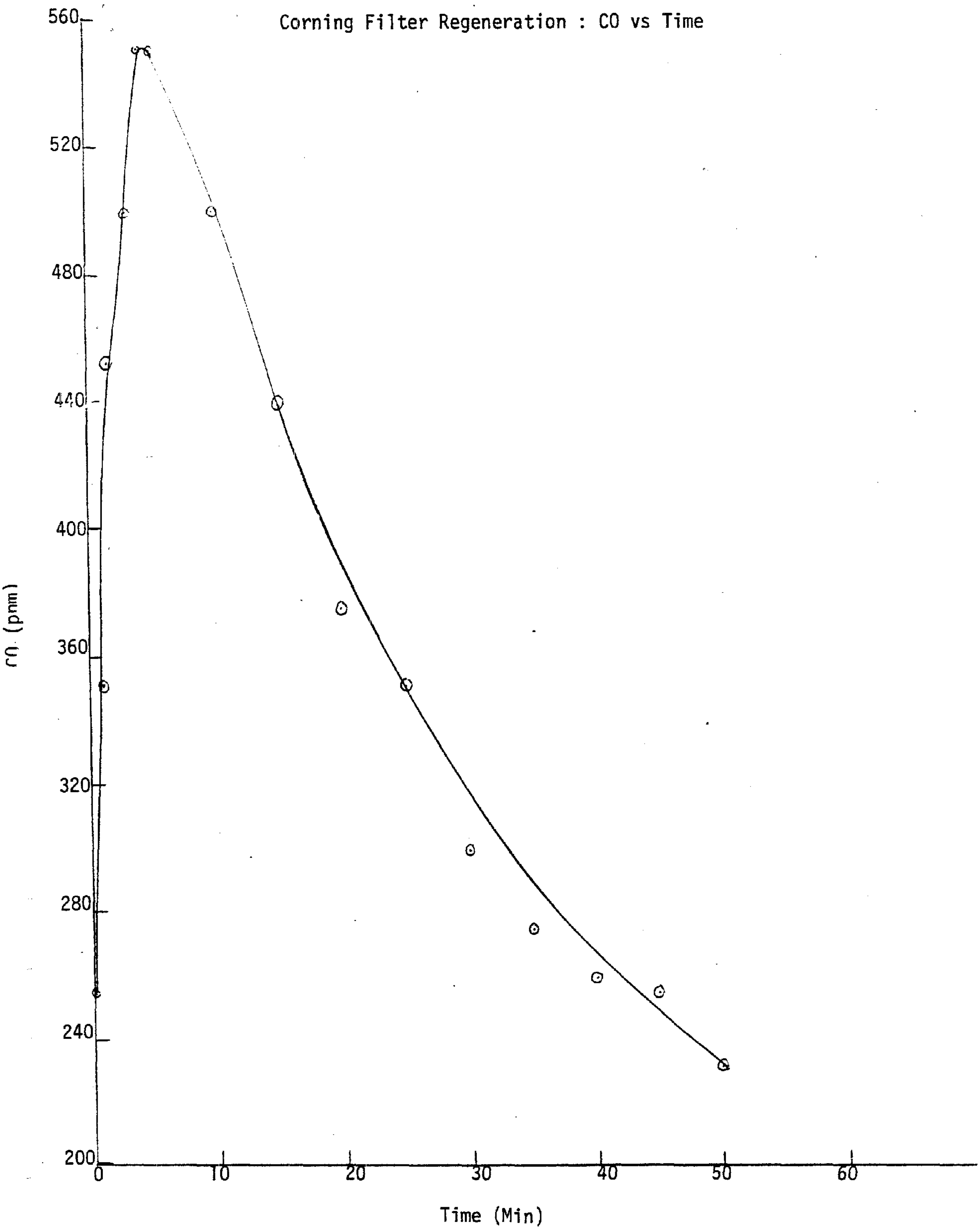

Corning Filter Regeneration : CO vs Time
560
520
480
440
400
360
320
280
240
200
CO (ppm)
0
10
20
30
40
50
60
Time (Min)

FIGURE 13.10

Filter Build Up During MTU-LHD Cycle

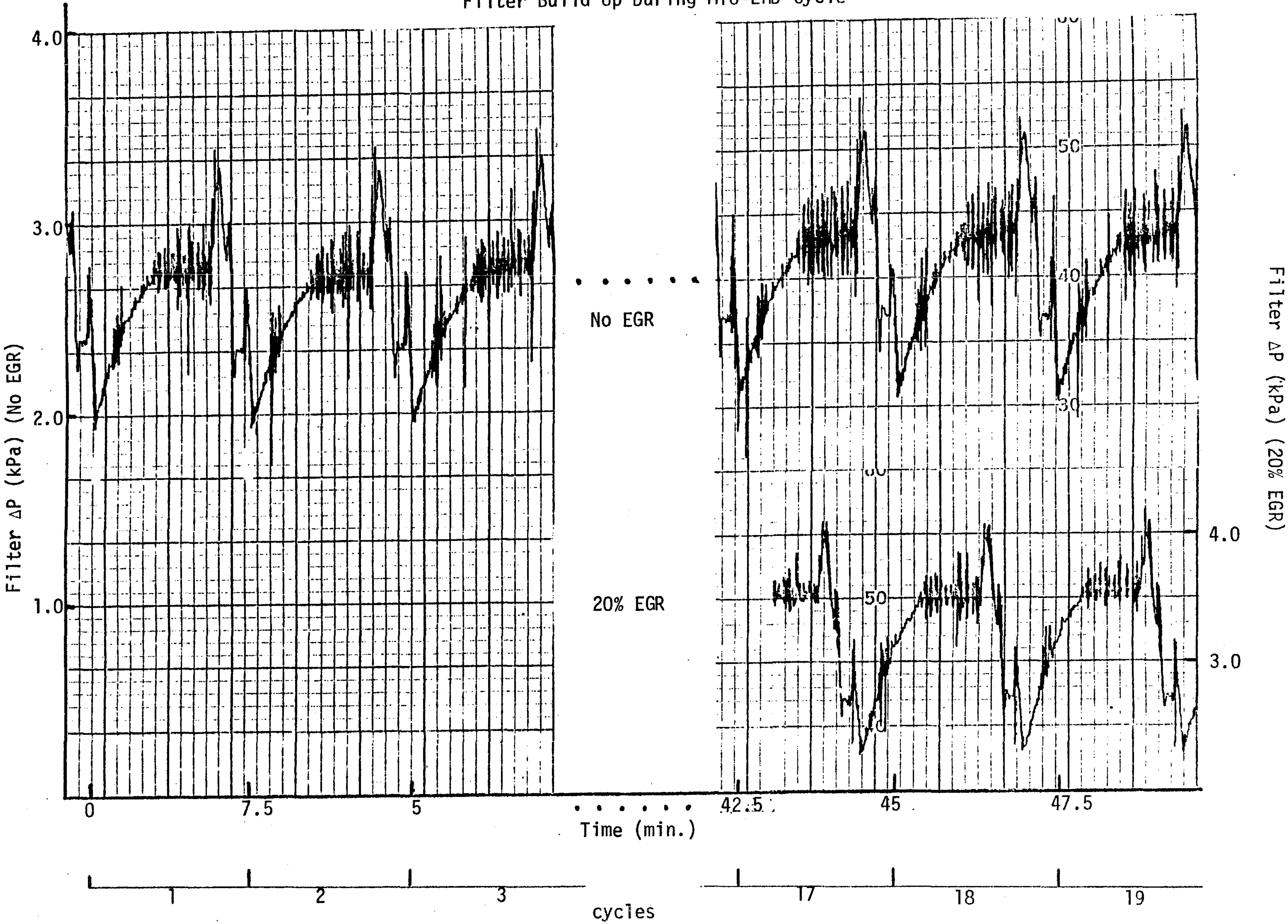


FIGURE 13.11

Exhaust Temperature Trends During MTU-LHD Cycle with 10% EGR

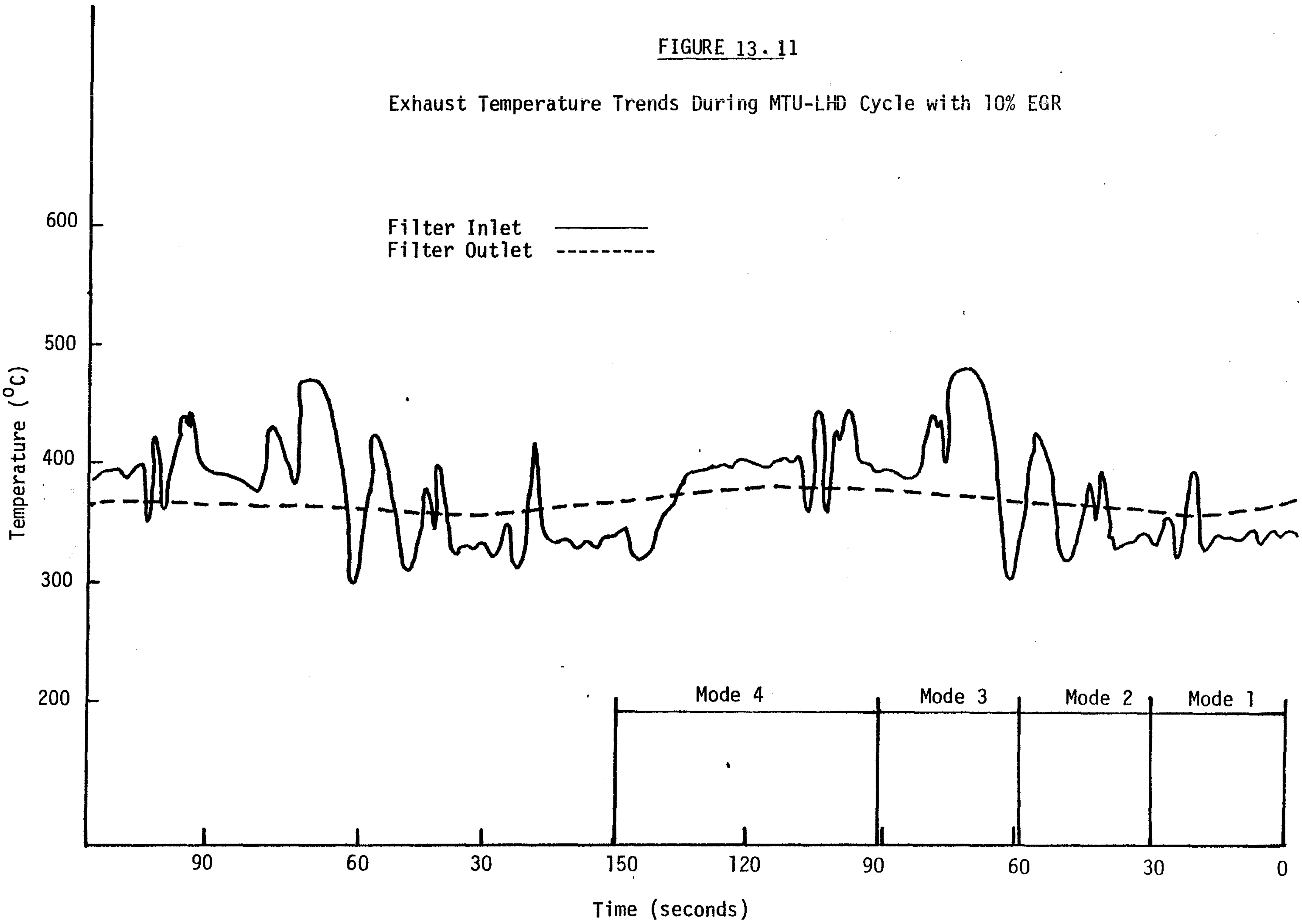
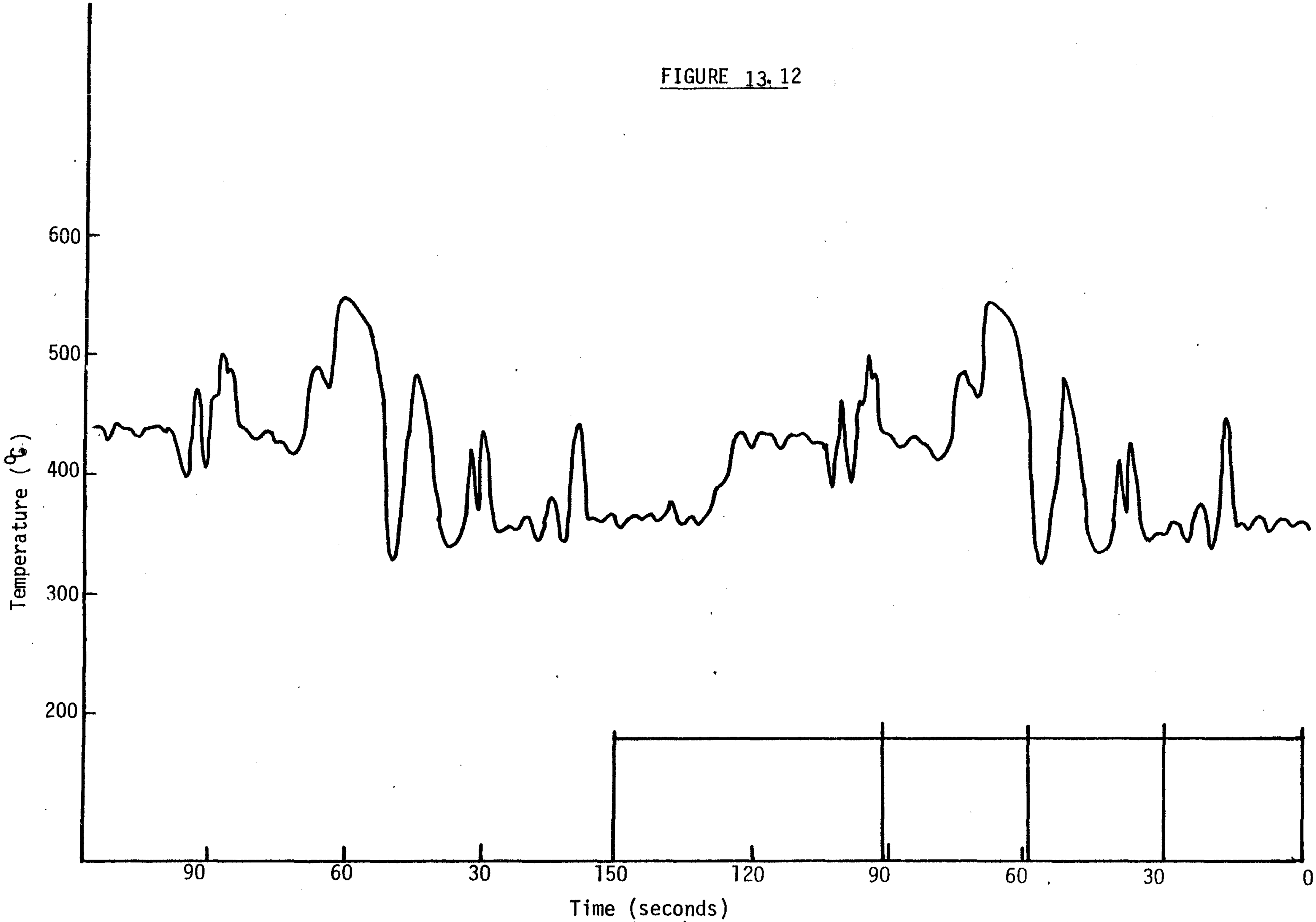
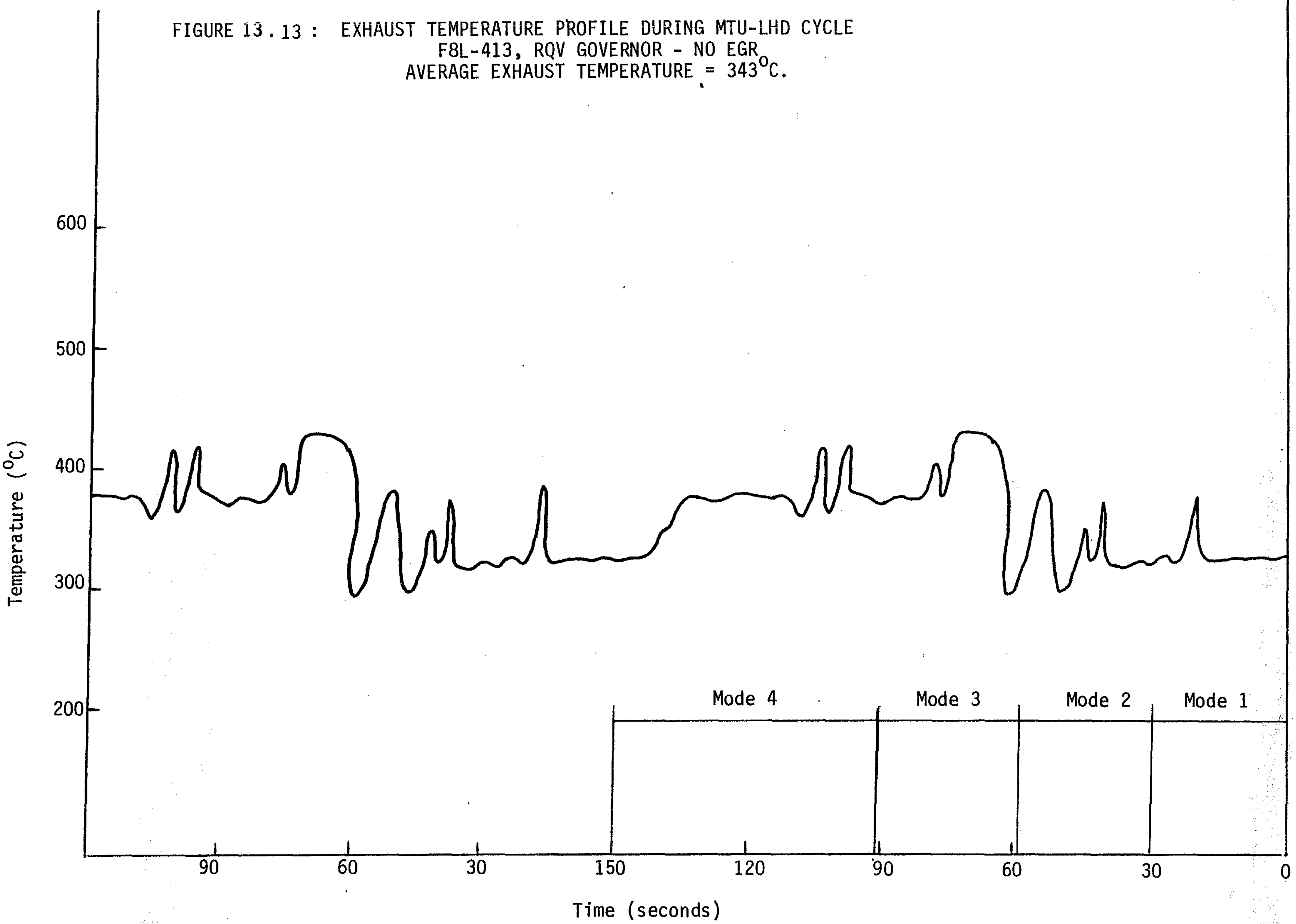


FIGURE 13.12



Exhaust Temperature Trends During MTU-LHD Cycle with 20% EGR

FIGURE 13.13 : EXHAUST TEMPERATURE PROFILE DURING MTU-LHD CYCLE
F8L-413, RQV GOVERNOR - NO EGR
AVERAGE EXHAUST TEMPERATURE = 343°C.



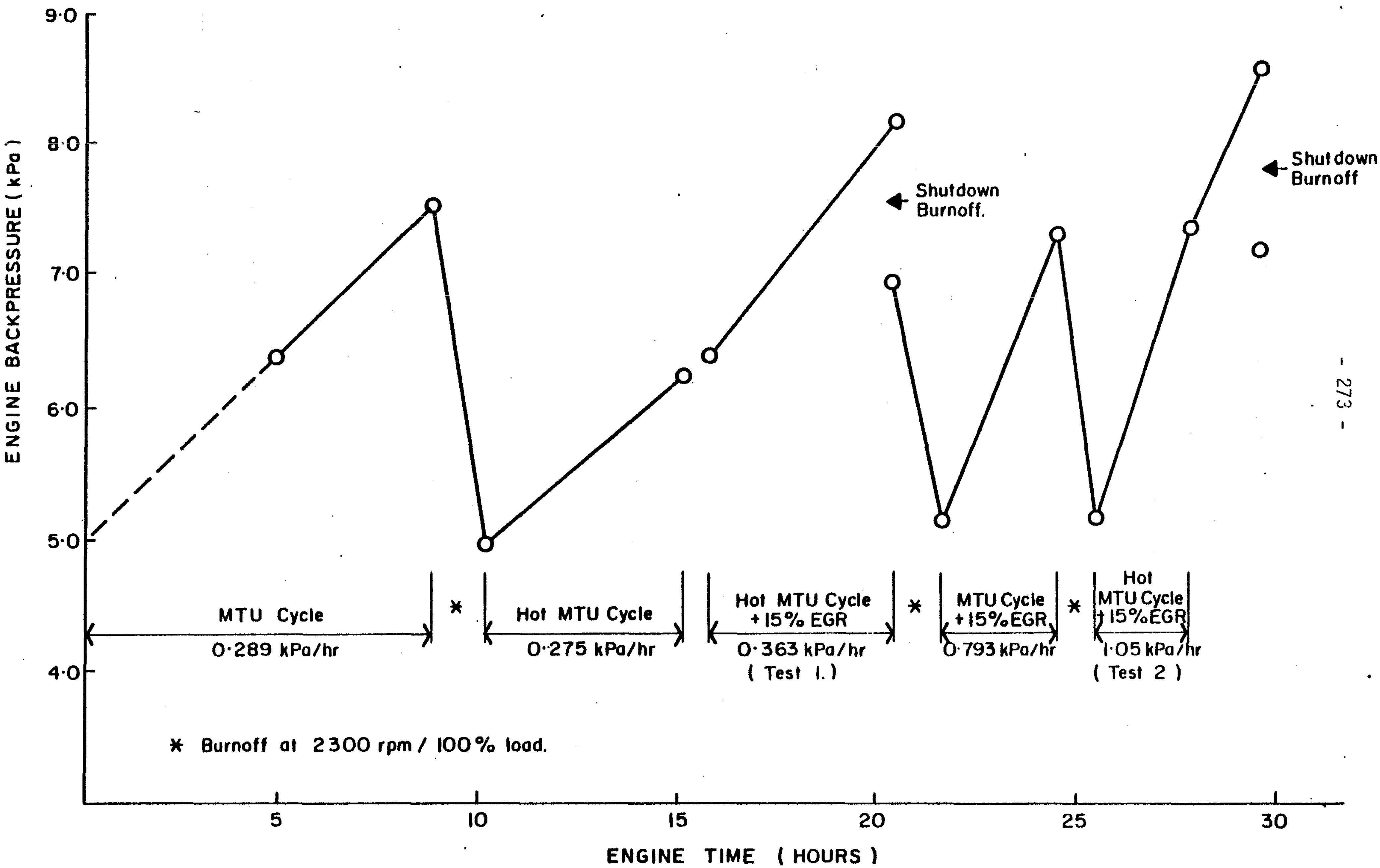


FIGURE 13.14 ENGINE BACKPRESSURE vs TIME

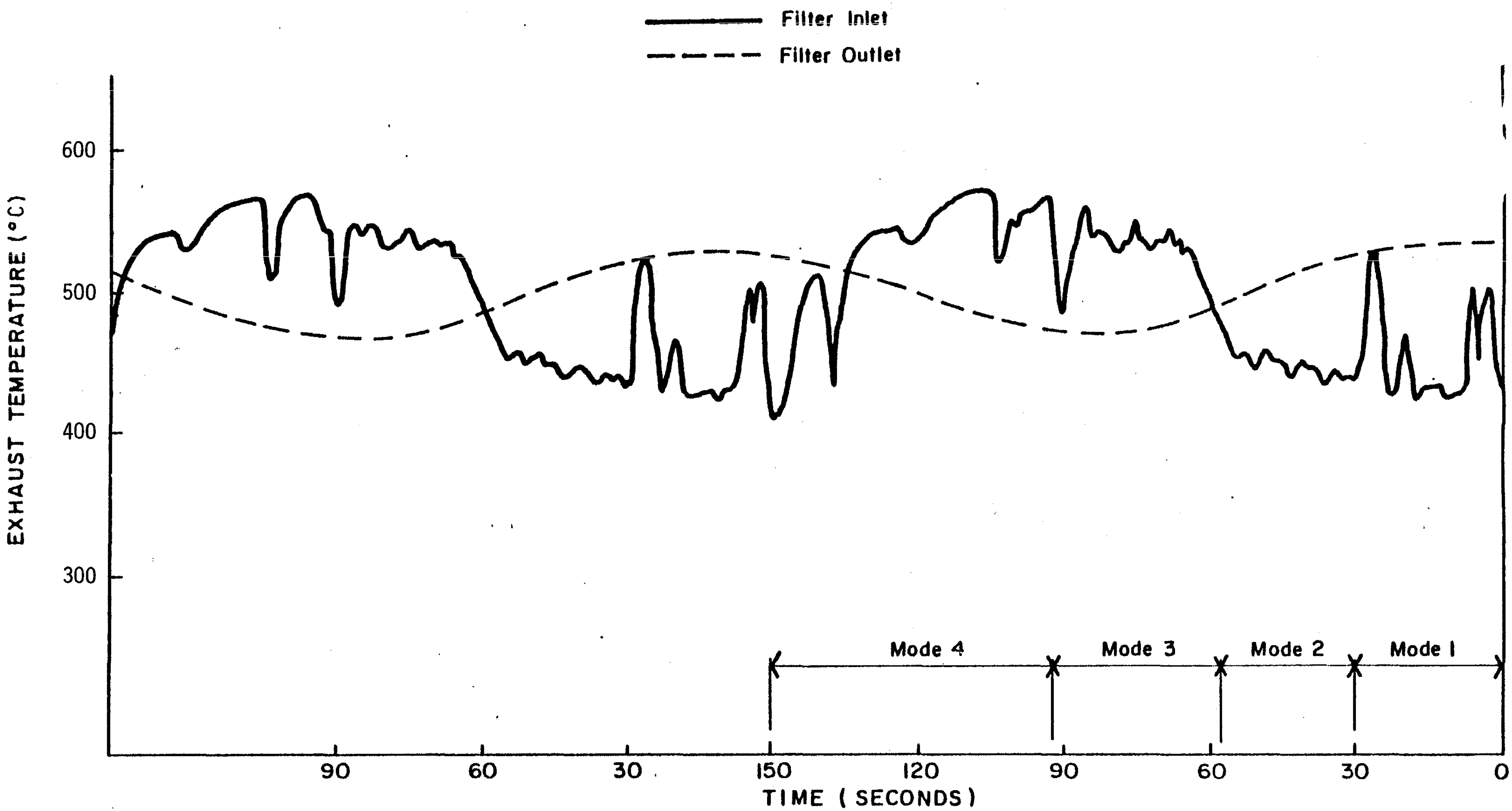


FIGURE 13.15 EXHAUST TEMPERATURE PROFILE - HOT MTU CYCLE + 15% EGR
AVERAGE EXHAUST TEMPERATURE = 496°C

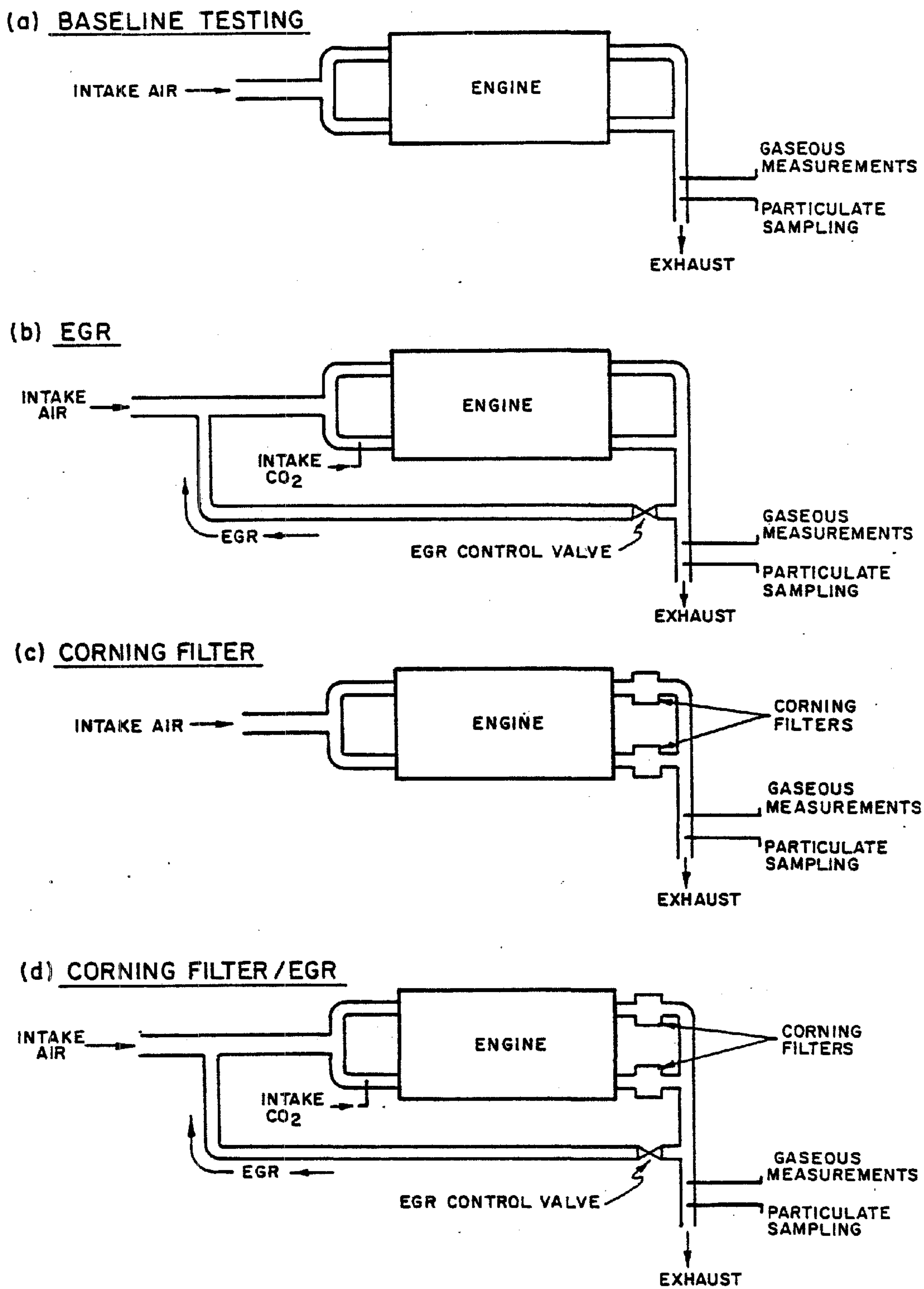


FIGURE 13.16 ENGINE TEST CONFIGURATIONS

TABLE 13.1

Effect of EGR on Steady State Emission Rates from EGR/Corning Filter

(Emission Rates in G/H)

% Full Load	Load/Speed Condition (rpm, kW)	% EGR	NO	% Change	NO_2	% Change	CO	% Change	THC	% Change
	2300/139.4	0	509	-	33	-	242	-	63	-
100	2300/130.6	10	210	-59	6	-82	817	+240	70	+11
	2300/131.9	15	136	-73	11	-66	1543	+540	47	-15
	2300/112	0	497	-	39	-	142	-	85	-
80	2300/114.6	10	263	-47	6	-84	159	+11	54	-37
	2300/114.6	15	170	-66	6	-86	276	+94	52	-39
	2300/89.2	0	399	-	31	-	110	-	62	-
60	2300/83.9	10	244	-39	12	-60	114	+4	45	-27
	2300/85.2	15	171	-57	6	-82	133	+21	35	-44
	2300/58.8	0	323	-	13	-	92	-	61	-
40	2300/56.5	10	210	-35	13	-2	102	+11	44	-29
	2300/56.8	15	160	-50	11	-14	108	+18	30	-51

TABLE 13.2

Effect of EGR on Steady State Emission Rates from EGR/Corning Filter

(Emission Rates in G/H)

% Full Load	Load/Speed Condition (rpm, kW)	% EGR	NO	% Change	NO_2	% Change	CO	% Change	THC	% Change
	2100/131.5	0	487	-	31	-	207	-	56	-
100	2100/130.9	10	209	-57	0	-100	959	+360	67	+19
	2100/127	15	138	-72	5	-83	1397	+580	57	+1
	2100/100.8	0	450	-	38	-	104	-	54	-
80	2100/102.9	10	238	-47	6	-85	128	+23	45	-16
	2100/101.1	15	162	-64	5	-86	173	+67	42	-22
	2100/76.6	0	378	-	25	-	87	-	46	-
60	2100/78.1	10	219	-42	6	-76	97	+11	40	-13
	2100/77.2	15	162	-57	6	-78	118	+35	34	-26
	2100/50.4	0	273	-	25	-	85	-	46	-
40	2100/50.1	10	169	-38	12	-54	97	+14	36	-23
	2100/50.1	15	145	-47	5	-79	100	+18	28	-39

TABLE 13.3

Effect of EGR on Steady State Emission Rates from EGR/Corning Filter

(Emission Rates in G/H)

% Full Load	Load/Speed Condition (rpm, kW)	% EGR	NO	% Change	NO_2	% Change	CO	% Change	THC	% Change
	1900/127.6	0	466	-	17	-	228	-	46	-
100	1900/122.2	10	198	-56	0	-100	1231	+440	49	+5
	1900/118.4	15	129	-71	5	-64	1747	+670	56	+22
	1900/101.4	0	439	-	40	-	106	-	52	-
80	1900/100.1	10	218	-50	5	-87	103	-3	36	-30
	1900/99	15	157	-64	10	-76	179	+69	39	-25
	1900/74.7	0	340	-	35	-	87	-	51	-
60	1900/75.5	10	210	-38	11	-69	78	-10	32	-37
	1900/76.1	15	151	-56	15	-56	101	+16	31	-38
	1900/50.2	0	281	-	24	-	79	-	43	-
40	1900/48.6	10	182	-35	11	-55	72	-8	33	-23
	1900/48	15	137	-51	5	-79	109	+39	28	-34

TABLE 13.4

Effect of EGR on Steady State Emission Rates from EGR/Corning Filter

(Emission Rates in G/H)

% Full Load	Load/Speed Condition (rpm, kW)	% EGR	NO	% Change	NO_2	% Change	CO	% Change	THC	% Change
	1700/117.3	0	496	-	34	-	180	-	39	-
100	1700/118.5	10	254	-49	5	-85	304	+69	40	+1
	1700/115.9	15	165	-67	5	-86	539	+200	38	+5
	1700/94.9	0	477	-	46	-	69	-	47	-
80	1700/96.1	10	259	-46	10	-79	71	+6	33	-30
	1700/96.1	15	167	-65	14	-69	88	+31	20	-57
	1700/71.7	0	404	-	23	-	56	-	44	-
60	1700/71.7	10	237	-41	20	-10	55	-2	33	-26
	1700/71.9	15	180	-55	14	-36	61	-9	20	-56
	1700/47.8	0	297	-	40	-	60	-	42	-
40	1700/47.8	10	195	-35	11	-74	54	-9	30	-30
	1700/47.9	15	157	-47	10	-76	59	-2	20	-53

TABLE 13.5

Effect of EGR on Steady State Emission Rates from EGR/Corning Filter

(Emission Rates in G/H)

% Full Load	Load/Speed Condition (rpm, kW)	% EGR	NO	% Change	NO_2	% Change	CO	% Change	THC	% Change
	1500/107.6	0	419	-	30	-	90	-	34	-
100	1500/103.9	10	199	-53	8	-71	258	+190	26	-25
	1500/101.8	15	109	-74	8	-73	486	+440	28	-19
	1500/88.6	0	394	-	29	-	55	-	46	-
80	1500/88.4	10	197	-50	7	-71	52	-4	18	-61
	1500/88.4	15	139	-65	8	-73	73	+34	12	-74
	1500/66.2	0	355	-	40	-	49	-	49	-
60	1500/66.7	10	191	-46	9	-79	45	-9	24	-51
	1500/66.9	15	155	-56	8	-79	52	+5	15	-69
	1500/44.5	0	280	-	21	-	51	-	37	-
40	1500/44.7	10	165	-41	13	-37	46	-10	18	-53
	1500/44.5	15	130	-54	13	-39	54	+6	16	-58

TABLE 13.6

Effect of EGR on Steady State Emission Rates from EGR/Corning Filter

(Emission Rates in G/H)

% Full Load	Load/Speed Condition (rpm, kW)	% EGR	NO	% Change	NO_2	% Change	CO	% Change	THC	% Change
	1300/91.4	0	351	-	22	-	65	-	29	-
100	1300/91.6	10	157	-55	7	-65	90	+39	17	-42
	1300/89	15	109	-69	7	-68	148	+130	19	-35
	1300/72.7	0	338	-	26	-	41	-	40	-
80	1300/72.7	10	205	-40	12	-54	45	+9	15	-62
	1300/68.8	15	117	-65	7	-74	49	+17	14	-65
	1300/54.8	0	284	-	30	-	39	-	28	-
60	1300/54.8	10	176	-38	15	-50	37	-6	13	-51
	1300/51.3	15	123	-57	3	-88	45	+15	15	-46
	1300/36.5	0	232	-	26	-	42	-	28	-
40	1300/36	10	158	-32	19	-78	34	-19	13	-53
	1300/34.9	15	111	-52	15	-43	58	+38	17	-40

TABLE 13.7 : EGR/CORNING FILTER TESTS, ENGINE CONDITIONS

Engine Speed rpm	Engine Load N.m.	% of Max. Torque	Fuel Consumption g/s	BSFC g/kWs	% EGR	Exhaust Backpressure kPa	Temperatures ^oC			
							Comb. Air Pre-EGR	Comb. Air Post-EGR	Left Exhaust Pre-Filter	Right Exhaust Pre-Filter
2300	579	100	10.6	.0740	0	4.20	12	-	557	552
2300	542	100	10.8	.0813	10	3.93	17	53	637	632
2300	548	100	10.9	.0823	15	3.86	-4	56	641	641
2300	465	80	8.55	.0762	0	3.24	11	-	449	448
2300	476	80	8.77	.0776	10	3.66	-3	22	461	464
2300	476	80	9.06	.0820	15	4.75	-3	48	509	508
2300	370	60	6.78	.0828	0	3.11	7	-	353	351
2300	348	60	7.09	.0813	10	3.24	9	25	371	378
2300	354	60	7.27	.0847	15	4.47	4	43	402	404
2300	244	40	5.52	.0946	0	2.69	8	-	286	281
2300	234	40	5.49	.0946	10	3.04	7	20	287	288
2300	236	40	5.64	.0989	15	3.93	6	35	305	305

TABLE 13.8 : EGR/CORNING FILTER TESTS, ENGINE CONDITIONS

Engine Speed rpm	Engine Load N.m.	% of Max. Torque	Fuel Consumption g/s	BSFC g/kWs	% EGR	Exhaust Backpressure kPa	Temperatures °C			
							Comb. Air Pre-EGR	Comb. Air Post-EGR	Left Exhaust Pre-Filter	Right Exhaust Pre-Filter
2100	598	100	9.74	.0701	0	3.66	8	-	553	548
2100	595	100	10.20	.0774	10	3.11	11	42	607	604
2100	578	100	10.00	.0786	15	3.53	-4	51	623	621
2100	458	80	7.50	.0745	0	2.76	11	-	403	399
2100	468	80	7.53	.0735	10	3.17	10	28	423	422
2100	460	80	7.67	.0754	15	3.73	-2	41	447	444
2100	348	60	5.92	.0764	0	2.62	13	-	327	325
2100	355	60	6.14	.0803	10	2.90	9	25	339	343
2100	351	60	6.16	.0801	15	3.46	-1	34	348	353
2100	229	40	4.70	.0957	0	2.35	12	-	264	257
2100	228	40	4.81	.0935	10	2.48	5	14	258	261
2100	228	40	4.81	.0950	15	3.17	-1	28	269	274

TABLE 13.9 : EGR/CORNING FILTER TESTS, ENGINE CONDITIONS

Engine Speed rpm	Engine Load N.m.	% of Max. Torque	Fuel Consumption g/s	BSFC g/kWs	% EGR	Exhaust Backpressure kPa	Temperatures °C Comb. Air Pre-EGR	Comb. Air Post-EGR	Left Exhaust Pre-Filter	Right Exhaust Pre-Filter
1900	641	100	9.08	.0679	0	3.17	9	-	548	551
1900	615	100	9.29	.0757	10	3.10	14	44	554	609
1900	595	100	9.42	.0772	15	3.17	-4	49	606	617
1900	510	80	6.96	.0691	0	2.41	8	-	395	391
1900	503	80	7.04	.0670	10	2.48	7	23	403	407
1900	498	80	7.59	.0757	15	3.59	25	58	472	481
1900	376	60	5.47	.0739	0	2.28	5	-	316	315
1900	380	60	5.61	.0745	10	2.41	17	27	324	329
1900	382	60	5.61	.0732	15	2.90	-2	31	334	337
1900	252	40	4.23	.0853	0	2.00	5	-	243	242
1900	244	40	4.32	.0879	10	2.21	20	27	254	257
1900	241	40	4.23	.0877	15	2.41	-3	23	243	247

TABLE 13.10 : EGR/CORNING FILTER TESTS, ENGINE CONDITIONS

Engine Speed rpm	Engine Load N.m.	% of Max. Torque	Fuel Consumption g/s	BSFC g/kWs	% EGR	Exhaust Backpressure kPa	Temperatures °C: Comb. Air Pre-EGR	Temperatures °C: Comb. Air Post-EGR	Temperatures °C: Left Exhaust Pre-Filter	Temperatures °C: Right Exhaust Pre-Filter
1700	659	100	8.18	.0676	0	2.91	7	-	508	519
1700	666	100	8.40	.0706	10	2.62	14	34	542	551
1700	651	100	8.39	.0720	15	3.03	-4	42	545	555
1700	533	80	6.48	.0676	0	2.28	8	-	381	389
1700	540	80	6.72	.0703	10	2.69	23	37	-	422
1700	540	80	6.78	.0705	15	3.03	19	51	434	434
1700	403	60	5.14	.0703	0	2.14	8	-	313	318
1700	403	60	5.27	.0733	10	2.41	16	32	327	331
1700	404	60	5.32	.0737	15	2.76	22	46	337	342
1700	268	40	3.86	.0799	0	1.93	7	-	241	246
1700	268	40	3.97	.0837	10	2.14	12	23	241	244
1700	268	40	3.98	.0838	15	2.55	21	38	252	256

TABLE 13.11 : EGR/CORNING FILTER TESTS, ENGINE CONDITIONS

Engine Speed rpm	Engine Load N.m.	% of Max. Torque	Fuel Consumption g/s	BSFC g/kWs	% EGR	Exhaust Backpressure kPa	Temperatures °C			
							Comb. Air Pre-EGR	Comb. Air Post-EGR	Left Exhaust Pre-Filter	Right Exhaust Pre-Filter
1500	685	100	7.04	.0641	0	2.21	7	-	473	478
1500	662	100	7.14	.0684	10	2.28	24	42	517	531
1500	648	100	7.13	.0700	15	2.90	9	49	527	534
1500	564	80	5.67	.0646	0	1.86	4	-	356	360
1500	563	80	5.85	.0662	10	2.35	14	31	-	406
1500	563	80	5.96	.0668	15	2.41	19	50	441	454
1500	423	60	4.45	.0676	0	1.73	5	-	283	284
1500	424	60	4.51	.0678	10	1.86	12	28	281	305
1500	425	60	4.59	.0681	15	2.07	18	38	309	314
1500	283	40	3.38	.0754	0	1.24	6	-	215	216
1500	285	40	3.36	.0762	10	1.59	18	26	223	223
1500	283	40	3.38	.0757	15	1.79	15	27	219	222

TABLE 13.12 : EGR/CORNING FILTER TESTS, ENGINE CONDITIONS

Engine Speed rpm	Engine Load N.m.	% of Max. Torque	Fuel Consumption g/s	BSFC g/kWs	% EGR	Exhaust Backpressure kPa	Temperatures °C			
							Comb. Air Pre-EGR	Comb. Air Post-EGR	Left Exhaust Pre-Filter	Right Exhaust Pre-Filter
1300	671	100	5.73	.0620	0	1.73	6	-	436	450
1300	672	100	5.83	.0637	10	2.14	8	23	445	462
1300	653	100	5.81	.0651	15	2.35	8	38	463	479
1300	534	80	4.49	.0619	0	1.31	7	-	314	321
1300	534	80	4.59	.0632	10	1.73	21	29	-	352
1300	506	80	4.32	.0635	15	1.52	7	32	325	333
1300	403	60	3.53	.0641	0	1.17	7	-	259	267
1300	403	60	3.57	.0657	10	1.24	19	26	267	273
1300	377	60	3.33	.0646	15	1.24	6	24	246	250
1300	268	40	2.66	.0723	0	1.03	6	-	199	206
1300	264	40	2.58	.0720	10	1.31	19	-	199	207
1300	256	40	2.57	.0739	15	1.03	5	16	181	186

TABLE 13.13

Effect of Fixed Position EGR on Duty Cycle Emission Rates from EGR/Corning Filter (MTU Cycle)

% EGR indicated is set at 2200 rpm, 80% full load steady state
Average load/speed condition over cycle = 2177 rpm, 71.9 kW (52% full load)

% EGR	% Change in Emission Rates with EGR, based on G/H					
	NO	NO_2	NO_x	CO	THC	CO_2
10	-26	-47	-27	+3	+5	-0.2
15	-41	-41	-41	+12	-3	-0.2

Effect of Fixed Position EGR on Duty Cycle Emission Rates from EGR/Corning Filter

% EGR indicated is set at 2200 rpm, 80% full load
Average load/speed condition over cycle = 2177 rpm, 71.9 kW

% EGR	Emission Rates in G/H					
	NO	NO_2	NO_x	CO	THC	CO_2
0	328	23	526	115	37	76188
10	242	12	383	118	39	24827
15	194	13	311	129	36	74837

TABLE 13.14

Hot MTU Cycle Gaseous Emissions

Test Condition (Corning Filters Installed)	Carbon Monoxide				Total Hydrocarbons				Total Oxides of Nitrogen (as NO_2)				Percent NO_x Reduction
	ppm	g/h	g/kW.h	g/kg Fuel	ppm	g/h	g/kW.h	g/kg Fuel	ppm	g/h	g/kW.h	g/kg Fuel	
MTU Cycle	133	115	1.60	4.94	72.4	36.9	0.51	1.59	371	526	7.32	22.6	
MTU Cycle +15% EGR	190	128	1.79	5.58	88.7	35.7	0.50	1.50	279	311	4.32	13.5	41%
Hot MTU Cycle	157	122	0.97	4.48	68.6	31.6	0.25	1.16	582	741	5.92	27.3	
Hot MTU Cycle +15% EGR (Test 1)	465	282	2.26	10.3	89.8	32.3	0.26	1.18	338	337	2.70	12.3	55%
Hot MTU Cycle +15% EGR (Test 2) Before Corning Filter	458	278	2.95	10.2	107	41.1	0.44	1.50					
After Corning Filter	550	334	3.54	12.2	80.5	31.0	0.33	1.13					

TABLE 13.15

Particulate Emissions and Control System Efficiencies

Test Condition	Fuel	Solubles				System Efficiency	Insolubles				System Efficiency	Total Particulate				System Efficiency
		mg/m^3	g/h	g/kW.h	g/kg Fuel		mg/m^3	g/h	g/kW.h	g/kg Fuel		mg/m^3	g/h	g/kW.h	g/kg Fuel	
MTU Cycle	Phillips D-2	25.4	16.8	0.228	0.746		27.9	18.45	0.251	0.821		53.3	35.2	0.479	1.57	
MTU Cycle with Corning Filters	Phillips D-2	4.04	2.65	0.0361	0.118	84%	1.29	0.845	0.0118	0.0375	95%	5.34	3.48	0.0478	0.156	90%
MTU Cycle with Corning Filters + 15% EGR	Phillips D-2	1.04	0.565	0.0071	0.0223	97%	2.27	1.22	0.0170	0.0525	94%	3.31	1.80	0.0245	0.0765	94%
Hot MTU Cycle	Gulf Diesel 40	18.6	12.2	0.129	0.447		28.4	18.7	30.9	0.684		47.0	30.4	0.328	1.11	
Hot MTU Cycle with Corning Filters	Gulf Diesel 40	1.10	0.720	0.0076	0.0265	94%	0.603	0.393	0.0043	0.0143	98%	1.70	1.10	0.0117	0.0407	96%
Hot MTU Cycle with Corning Filters + 15% EGR	Gulf Diesel 40	0.475	0.250	0.00265	0.0090	98%	2.28	1.20	0.0013	0.0430	94%	2.76	1.45	0.0155	0.0525	94%

TABLE 13.16

Duty Cycle - Temperature Profiles

Cycle	Average Exhaust Temperature	% Time Temp. Exceeds 950°F
100 - 250 meter flat grade haul (LHD) ST8 - F8L-714 RSV	373°C (357-385)	16%
100 meter flat grade haul 5% upgrade loading LHD ST8 - F8L-714 RSV	423°C (413-441)	34%
250 meter flat grade haul LHD ST8 - F8L-714 RSV	385°C (371-399)	10%
215 meter flat grade haul 6 Phase LHD F6L-714	414°C	7%
89 meter haul LHD ST8 (Swedish data)	396°C (371-427)	0%
MTU cycle computer simulated LHD F8L-413 - RQV/2300, Av. Load 69% (Simulated from MTU F8L-714-RSV/2300, Av. Load 59%) (150 seconds)	338°C	0%
MTU as above plus 20% EGR	391°C	5%
Modified Falconbridge Cycle LHD F8L-413 - RQV/2300, Av. Load 87% (Modified from Falconbridge simulated 413-RSV/2000, Av. Load 77%) (Simulated from Falconbridge 413-RSV/2000, Av. Load 67%) (257 seconds)	532°C	77%
MTU MOD 1 = MTU + 10% Load	359°C	0%
MTU MOD 2 = MTU + 20% Load	390°C	0%
MTU MOD 3 = MTU + 30% Load	407°C	0%
MTU MOD 4 = MTU + 30% Load + 10% rpm mucking	429°C	5%

14. DIESEL PARTICULATE FILTER REGENERATION OPTIONS

Diesel Particulate Filter (DPF) technology has been steadily edging into the underground mining industry. One of the major problems that plague trap development for underground use is DPF regeneration. DPF regeneration is the process of oxidizing or burning trapped diesel particulates on the ceramic material of the filters. This regeneration is necessary to maintain an acceptable engine exhaust backpressure during engine operation. The regeneration of the DPF should be a controlled regeneration to prevent temperature stress fracturing of the DPF ceramic material.

DPF regeneration may occur if the diesel exhaust gas temperature is equal to or exceeds the ignition temperature of the trapped particulate matter for a specified period of time. The ignition temperature of the diesel particulate matter (carbon) has been found to be in excess of 550^{o}C, depending upon the chemical nature of the diesel exhaust stream. Diesel Particulate Filter regeneration can be accomplished by using each of the following methods, or, in some cases, a combination of two or more.

1. Face Heater.
2. Burner Assembly.
3. Engine Throttling.
4. High Temperature Soak.
5. Catalyzed DPF.
6. Fuel Additive in Diesel Fuel.
7. Exhaust Gas Recirculation.

The fuel additive/EGR and catalyzed DPF/EGR approaches to filter regeneration will be described in detail in the following subsections. A general overview of the first four methods of filter regeneration is presented as follows. These techniques were not addressed in this program but are included for background information.

14.1 Face Heater.

Research has been completed on variations of electrical assistance of DPF regeneration. One such type of electrical resistance heater was a dual element self-limiting glowplug installed in a manner that the tip of the plug just contacted the trap material (26). The other exposed-element ignitors which have been evaluated for DPF regeneration aids are stranded-wire grids, spiral coil elements (cigarcoils) (26) and a calrod type electrical face heater (27)

The glowplug ignitor regeneration tests indicated that heavily soot-ladened DPFs were necessary for filter regeneration but on regeneration the filters frequently failed or partial regeneration occurred.

A Calrod "face heater" combined with a low flow of bleed air was successful in initiating DPF regeneration. This regeneration method was completed successfully with and without fuel additives in the engine diesel fuel supply. This type of DPF regeneration creates high radial temperature gradients and thermal stresses within the ceramic filter medium. Cumulative regenerations may reduce the working life of the DPF with this type of regeneration mode.

14.2. Burner Assembly

The application of an in-line diesel-oil burner as an initiator of DPF regeneration has been experimentally tested. Major problems of burner nozzle clogging, ignition reliability and trap durability have been reported (28 and 29). A limit on DPF inlet temperature and filter loadings would be required to avoid excessive thermal stress within the DPF. The present complexity and expense of burner control systems makes this system unfavourable.

14.3. Throttling

The exhaust gas temperature of a diesel engine can be increased by throttling the intake air supply to the engine. On reducing the combustion air supply to the engine the air-fuel ratio of the engine is decreased from normal, thereby increasing the combustion gas temperature and subsequently increasing exhaust gas temperature. The major problem with throttling is that carbon monoxide, hydrocarbon, and particulate emissions increase. DPF failure is imminent if overthrottling is followed by low exhaust gas flows and high oxygen content, particularly with a highly loaded filter.

14.4. High Temperature Soak - Off Board System

DPF regeneration can occur by placing the filters in an oven at a temperature above the ignition temperature of carbon for a period of time. Regeneration can be controlled by limiting the amount of oxygen available for regeneration. An onboard regeneration system is, however, a more practical approach.

14.5 Catalyzed Diesel Particulate Filter (DPF)

14.5.1 Particulate Ignition Temperature

Particulate ignition temperature test results shown in Figure 14.1 reveal that the catalyzed DPF reduced the particulate ignition temperature by 149^{o}C to a value of 349^{o}C.

This brought the diesel particulate ignition temperature into the range of the average exhaust temperature experienced during the MTU LHD cycle. The exhaust temperature from a diesel engine is influenced by the temperature of the combustion air supply; lower combustion air temperatures result in lower exhaust temperatures. By varying the intake combustion air temperature and by applying EGR, it was possible to vary the average exhaust temperatures over the standard MTU cycle from 322^{o}C to 362^{o}C which bracketed the threshold ignition temperature found from Figure 14.1. Figure 14.2 shows that with average exhaust temperatures of 322^{o}C and 338^{o}C, resulting from a combustion air intake of 3^{o}C and 25^{o}C respectively, catalyzed DPF auto-regeneration did not occur (plots 1 and 2). However, with an average exhaust temperature of 354^{o}C resulting from 37.5^{o}C intake air, auto regeneration of the catalyzed trap was achieved (plots 3 and 4). Using 10% EGR, it was possible to achieve 36.5^{o}C combustion air using pre-EGR intake air of 15^{o}C. Again, auto regeneration of the catalyzed trap was achieved. Varying the temperature of the intake combustion air was used as a convenient way to alter the MTU cycle exhaust temperature over a narrow margin in order to investigate the effect on DPF auto regeneration. A more effective method of increasing the diesel engine exhaust gas temperature was to operate the engine over the Modified MTU cycle (MTU MOD 4). An average cycle exhaust gas temperature of approximately 395^{o}C is experienced. This is an average exhaust gas temperature increase of 70^{o}C above the average exhaust gas temperature of the MTU cycle which is 325^{o}C. This increase in exhaust gas temperature allows catalyzed DPF regeneration to occur as illustrated in the MTU and MTU MOD 4 rate of engine exhaust backpressure rise shown in Figure 14.3.

14.5.2 Particulate Test Results

Particulate testing was conducted over the MTU-MOD 4 cycle with catalyzed DPFs installed. The test results presented in Table 14.1 indicate soluble particulate accounts for an average of 54% of the total particulate. These results suggest total particulate removal of approximately 93% based on baseline results from a separate test cell with an identical engine. The sulphate fraction is not included with the particulate results.

14.5.3 Gaseous Emission Results

Gaseous emissions of CO, THC, NO_x, NO and NO_2 for the MTU and MTU MOD 4, LHD cycles with catalyzed DPFs are presented in Table 14.2. Highly effective CO emission control is evident for the catalyzed DPF when the diesel engine is operated over the MTU and MTU MOD 4, LHD cycles. This is an important consideration in reducing the concern over the peak CO emissions created if EGR is applied. There appeared to be a reduction in NO_x emissions found with the catalyzed trap over the MTU LHD cycle. This could be a result of carbon combustion producing CO which reduces some of the NO_x to NO_2 in an oxygen deficient zone close to the catalyst surface. The NO_2 content of the exhaust appears to be increased.

14.5.4 Sulphate Emission Results

Tests were performed to determine emissions of sulphur dioxide (SO_2) and sulphate ($SO_4^=$) with the use of catalyzed Corning DPFs. Tests were conducted at steady-state engine conditions and also over two versions of the MTU-LHD cycle.

The average engine conditions for the first series of sulphate tests are given in Table 14.3.

A series of tests were conducted at steady-state engine load/speed conditions to determine the sulphate production characteristics of the catalyzed DPFs. Table 14.4 shows that 69% of the fuel sulphur is as $SO_4^=$ for high engine load conditions (high exhaust gas temperature 545^oC). Since the accountability of the fuel sulphur is good (90% analyzed) it is clear that there is very little storage of $SO_4^=$ on the DPF. When engine conditions are changed to obtain an exhaust temperature (250^oC), below the threshold of particulate regeneration, there is very little production of sulphate (10%). Again, the accountability of fuel sulphur is very good (100%) and the catalyst does not change the engine SO_2 emissions. It can be assumed, therefore, that the catalyst activity on sulphur is negligible at these low load engine conditions.

When catalyzed DPFs are used on the Deutz F8L 413 F/W engine operating over the MTU-LHD cycle there is increased production of $SO_4^=$ and some storage of $SO_4^=$ on the DPF. Since there is an 84% accountability of fuel sulphur it can be assumed that some of the fuel sulphur is stored on the DPF as $SO_4^=$. With the application of a nominal 15% EGR over the MTU-LHD cycle there is an increased production of sulphate due to an increase in the engine fuelling rate (brake specific) and an increase in the exhaust gas temperature. Sulphate storage is also evident when EGR is applied over this cycle.

Table 14.5 gives additional $SO_2/SO_4^=$ emission results for engine operation over the MTU-LHD cycle. Three tests were conducted to establish MTU-LHD cycle baseline (without catalyzed DPFs) emissions for SO_2 and $SO_4^=$. For baseline conditions, 11% of the total sulphur is as $SO_4^=$. When catalyzed DPFs are employed over the MTU-LHD cycle the $SO_4^=$ portion of the total sulphur increases to 31%.

Figure 14.4 shows the relationship of SO_2 to $SO_4^=$ conversion versus exhaust temperature for an Engelhard PTX-623D catalyst and the catalyzed DPFs. The PTX data was obtained in a previous phase of this study and is given in ORF Final Report No. 2828 for Phases I and II. Conversions of SO_2 to $SO_4^=$ for the catalyzed DPFs follows a similar trend as was determined for the PTX catalyst. These data indicate that the catalyst activity for sulphur compounds is somewhat similar for both emission control devices. Figure 14.5 gives the relationship SO_2 and $SO_4^=$ emission rates versus exhaust gas temperature for the PTX catalyst and the catalyzed DPFs. It should be noted that this data applies to the catalyst formulations tested. Current information on later catalyst formulations for DPFs show very low conversion to $SO_4^=$. The information in this figure is based on emissions from a Deutz F8L 413 F/W engine with a known fuel sulphur content.

Three tests were conducted to determine emissions of SO_2 and $SO_4^{=}$ over the MTU MOD 4 with application of catalyzed DPFs. The MOD 4 version of the MTU-LHD cycle gives a higher average load (91 kW) than the standard MTU-LHD cycle (approximately 72 kW). Since the load is increased with the MTU-MOD 4 cycle, the exhaust temperatures are increased, and increased catalyst activity can be expected compared to the standard MTU-LHD cycle.

Table 14.6 gives results of the $SO_2/SO_4^{=}$ tests carried out over the MTU MOD 4 cycle. These tests were carried out under a parallel program sponsored by the Ontario Ministry of Labour. An average of 72% of the total sulphur analyzed is as $SO_4^{=}$ for the three tests conducted.

14.6 Fuel Additives

One of the options for reducing the ignition threshold of diesel engine particulate matter is through the use of fuel additive. Organo-metallic fuel additives result in metal dispersion in the particulate matter collection in the ceramic filter. This catalyzes the combustion of the particulate at significantly reduced ignition temperatures. Studies have shown manganese and manganese/copper to be an effective fuel additive in this respect. Diesel particulate ignition temperatures of 370^{o}C for manganese and 345^{o}C manganese/copper fuel additive have been achieved. The manganese and manganese/copper fuel additives are manufactured by Lubrizol

Corporation and are identified as 8220 and OS65135 respectively. Preliminary trials of manganese/copper fuel additive at a concentration of 80 mg of additive per litre of diesel fuel were completed over the MTU cycle to compare the effects with those found for the catalyzed DPF.

14.6.1 Fuel Additive Test Results

Figure 14.6 shows the results of operating over the MTU cycle with different combustion air temperatures and with 80 mg/L fuel additive. With 10% EGR, at an average exhaust temperature of 343^{o}C and 362^{o}C, no trap auto-regeneration was evident. Auto-regeneration of the DPF over the MTU cycle with fuel additive could only be obtained by increasing the combustion air intake to 39^{o}C. This resulted in an average exhaust temperature of 369^{o}C as indicated in Figure 14.6 plot 3. It appears that the particulate ignition temperature is slightly higher than that found for the catalyzed DPF.

14.6.2 Gaseous Emission Test Results

Average gaseous emissions obtained over the MTU cycle while the ceramic DPF was operating in a regenerative mode are shown in Table 14.7. In contrast to the catalyzed DPF a small increase in CO and THC emissions is evident using the fuel additive technique while NO_x emissions are essentially unchanged.

14.7 Conclusions

Both the catalyzed DPF and Fuel Additive/DPF approaches showed good potential for auto-regeneration, particularly if the hotter MTU MOD 4 cycle was used. Emissions with the catalyzed DPF were excellent except for a potential problem of SO_2 to $SO_4^=$ conversion. Fuel additive/DPF had no detrimental effect on gaseous emissions.

TABLE 14.1

Particulate Emissions for MTU-MOD 4
LHD Cycle with Catalyzed DPF's

Test No.	Particulate Concentration (mg/m^3)			
	Insoluble	Soluble	Total*	% Soluble of Total
1	1.44	1.78	3.22	55
2	1.63	1.44	3.07	47
3	1.73	2.16	3.89	56
4	1.06	1.44	2.50	58
Average	1.47	1.71	3.17	54

* Note: Total particulate results exclude sulfate fraction. Total is comprised of soluble and insoluble particulate.

GASEOUS EMISSIONS OVER MTU CYCLE USING

CERAMIC DPF REGENERATIVE APPROACH

TABLE 14.2

Engine Conditions rpm/kW	Test Conditions	Nitric Oxide ppm	Nitric Oxide g/hr	Nitric Oxide g.kW.h	Nitric Oxide g/kg Fuel	% Change	Nitrogen Dioxide ppm	Nitrogen Dioxide g/hr	Nitrogen Dioxide g/kW.h	Nitrogen Dioxide g/kg Fuel	% Change	Total Oxides of Nitrogen ppm	Total Oxides of Nitrogen g/hr	Total Oxides of Nitrogen g/kW.h	Total Oxides of Nitrogen g/kg Fuel	% Change
2164/69.7 (MTU Cycle)	Catalyzed Ceramic (Before) (Filter)	417	331	4.75	15.5		43.1	52.5	0.752	2.45		460	560	8.03	26.2	
2164/69.7 (MTU Cycle)	Catalyzed Ceramic (After) (Filter)	326	258	3.71	12.1	- 22	77.3	94.1	1.35	4.40	+ 79	403	490	7.03	22.9	- 12
2164/92.4 MTU MOD 4 CYCLE	Catalyzed Ceramic (After) (Filter)	348	272	3.03	9.8		153	183.4	2.04	7.36		501	601	6.68	24.1	

Engine Conditions rpm/kW	Test Conditions	Carbon Monoxide ppm	Carbon Monoxide g/hr	Carbon Monoxide g.kW.h	Carbon Monoxide g/kg Fuel	% Change	Total Hydrocarbons ppm	Total Hydrocarbons g/hr	Total Hydrocarbons g/kW/h	Total Hydrocarbons g/kg Fuel	% Change
2164/69.7 (MTU Cycle)	Catalyzed Ceramic (Before) (Filter)	113	84.0	1.20	3.43		84.0	35.6	0.51	1.66	
2164/69.7 (MTU Cycle)	Catalyzed Ceramic (After) (Filter)	5.0	3.7	0.05	0.17	- 96	40.1	17.0	0.34	0.79	- 52
2164/92.4 (MTU MOD 4) CYCLE	Catalyzed Ceramic (After) (Filter)	5.4	4.0	0.04	0.16		16.0	6.7	0.08	0.27	

TABLE 14.3

Engine and Sulphate Test Conditions

Catalyzed Ceramic Trap

Speed (RPM)	Load kW	Load %	Test Condition	Fuel Consumption g/s	Fuel Consumption g/kWh	Engine Flow (dry) m^3/min	Exhaust Temp. °C Left	Exhaust Temp. °C Right	Combustion Air °C	Dilution Tunnel Temp. °C
2200	135	100	Baseline	10.4	277	11.3	520	531	16	140
2200	133	100	Catalyzed Corning	10.3	279	11.2	547	542	21	135
2200	42	31	Catalyzed Corning	4.67	400	12.0	252	249	19	70
*2167	67	57	Catalyzed Corning	6.17	332	12.3	325	317	20	∿65-100
*2167	66	57	Catalyzed Corning + 15% EGR	6.21	339	10.1	337	331	35	∿65-100

* Average Conditions for MTU, LHD Cycle

TABLE 14.4

$SO_4^=$, SO_2 Mass Emissions

Catalyzed Ceramic Trap

Engine Conditions (RPM/% Load)	Test Conditions	SO_2				$SO_4^=$				Total Sulphur				% $SO_4^=$	% Total Sulphur of Theoretical
		ppm	g/hr	g/kWh	g/kg Fuel	ppm	g/hr	g/kWh	g/kg Fuel	ppm	g/hr	g/kWh	g/hg Fuel		
2200/100	Baseline									60.2	109*	0.807	2.91	2	96
"	Baseline									52.0**	94.1*	0.697	2.52	2	83
2200/100	Baseline									61.5	111*	0.822	2.97	2	98
	Average									60.8	110	0.814	2.94	2	97
2200/100	Catalyzed Corning	11.9	21.4	0.159	0.572	35.0	94.2	0.698	2.52	46.4**	116	0.857	3.09	75	74
"	Catalyzed Corning	19.6	35.1	0.260	0.951	38.0	101	0.748	2.74	57.6	136	1.01	3.69	66	92
2200/100	Catalyzed Corning	11.9	21.3	0.158	0.579	43.8	116	0.859	3.15	55.7	137	1.02	3.73	79	89
	Average	14.5	25.9	0.192	0.702	38.9	104	0.768	2.80	56.6	136	1.02	3.71	73	90
2200/31	Catalyzed Corning	24.2	45.5	1.08	2.71	2.5	7.0	0.167	0.417	26.7	52.5	1.25	3.13	9	100
2167/57	Catalyzed Corning	18.3	35.9	0.536	1.62	8.1	23.8	0.355	1.07	26.4	59.7	0.891	2.69	31	78
MTU Cycle	Catalyzed Corning	21.3	41.8	0.624	1.88	9.2	27.1	0.404	1.22	30.5	68.9	1.03	3.10	30	90
	Catalyzed Corning	20.6	40.4	0.603	1.82	8.2	24.1	0.360	1.09	28.8	64.5	0.963	2.91	28	85
	Average	20.1	39.4	0.587	1.78	8.5	25.0	0.373	1.13	28.6	64.4	0.961	2.90	30	84
2167/57	Catalyzed Corning	20.7	33.2	0.503	1.48	9.2	22.1	0.335	0.988	29.9	55.3	0.838	2.47	31	72
MTU Cycle	+ 15% EGR	22.8	36.6	0.555	1.64	11.9	28.6	0.433	1.28	34.7	65.2	0.988	2.92	34	83
"	Catalyzed Corning	22.1	35.4	0.536	1.58	11.5	27.7	0.420	1.24	33.6	63.1	0.956	2.82	34	80
+15% EGR	Average	21.9	35.1	0.531	1.57	10.9	26.1	0.396	1.17	32.7	61.2	0.927	2.74	33	78

* Assumed 2% $SO_4^=$

** Suspect data not used in averages

TABLE 14.5

Catalyzed DPF's

$SO_2/SO_4^{=}$ Emissions During MTU Cycle and Burn-Off

Test No. and Test Description	Total Conc. ppm SO_2 + $SO_4^{=}$	Conc. in Raw Exhaust SO_2 ppm	Conc. in Raw Exhaust $SO_4^{=}$ ppm	Emission Rates for SO_2 mg/m^3	Emission Rates for SO_2 g/h	Emission Rates for SO_2 g/kW.h	Emission Rates for SO_2 g/kg Fuel	Emission Rates for $SO_4^{=}$ mg/m^3	Emission Rates for $SO_4^{=}$ g/h	Emission Rates for $SO_4^{=}$ g/kW.h	Emission Rates for $SO_4^{=}$ g/kg Fuel
#1 MTU Cycle with Catalyzed DPF's	39.6	26.8	12.9	71.1	45.5	0.65	2.14	51.2	32.8	0.47	1.54
#2 MTU Cycle with Catalyzed DPF's	47.3	33.4	13.9	88.7	56.8	0.81	2.67	55.4	35.5	0.51	1.67
Average	43.5	30.1	13.4	79.9	51.2	0.73	2.40	53.3	34.2	0.49	1.61
#1 Burn-off with Catalyzed DPF's	58.8	19.9	38.6	52.9	36.5	0.27	0.98	153.7	106.1	0.80	2.84
#2 Burn-off with Catalyzed DPF's	62.1	14.3	47.8	38.1	26.3	0.20	0.71	190.2	131.3	0.98	3.53
Average	60.3	17.1	43.2	45.5	31.4	0.24	0.84	172.0	118.7	0.89	3.18
#1 Baseline Cycle * MTV	38.7	34.2	4.5	90.8	58.8	0.84	2.74	18.0	11.7	0.17	0.55
#2 Baseline Cycle MTV	42.3	37.7	4.6	100.0	64.8	0.93	3.06	18.4	11.9	0.17	0.56
#3 Baseline Cycle MTV	36.4	32.2	4.3	85.4	55.3	0.79	2.61	17.0	11.0	0.16	0.52
Average	39.2	34.7	4.3	92.1	59.6	0.85	2.82	17.8	11.5	0.17	0.54

TABLE 14.6

Catalyzed Corning DPF
$SO_2/SO_4^{=}$ Emissions Summary
MTU MOD 4 Cycle

Test No.	Concentration in Raw Exhaust		Emission Rates SO_2			Emission Rates $SO_4^{=}$			Measured $SO_2/SO_4^{=}$ ppm	Theoretical $SO_2/SO_4^{=}$ ppm
	ppm SO_2	ppm $SO_4^{=}$	g/h	g/kW.h	g/kg Fuel	g/h	g/kW.h	g/kg Fuel		
1	10.6	25.3	17.7	0.192	0.708	63.5	0.689	2.54	35.9	38.9
2	9.23	16.1	15.4	0.167	0.617	40.3	0.437	1.61	25.3	38.9
3	8.69	30.5	14.5	0.158	0.581	76.5	0.830	3.06	39.2	38.9
Average	9.51	24.0	15.9	0.172	0.635	60.1	0.652	2.40	33.5	38.9

Note: 1. Fuel sulfur content = 0.13% (w/w).

2. No. 1 diesel fuel used.

3. Approximately 6% of the total fuel sulphur is as $SO_4^{=}$ in uncontrolled diesel exhaust.

TABLE 14.7

Gaseous Emissions Over MTU Cycle Using Fuel Additive/ Ceramic Trap Regenerative Approaches

Engine Conditions rpm/kW	Test Conditions	Carbon Monoxide				% Change	Total Hydrocarbons				% Change
		ppm	g/hr	g/kW.h	g/kg Fuel		ppm	g/hr	g/kW.h	g/kg Fuel	
2163/70.0 (MTU Cycle)	Fuel Additives & Ceramic Filter (Before) (Filter)	132	95.9	1.37	4.48		81.4	33.8	0.48	1.58	
2163/70.0 (MTU Cycle)	Fuel Additives & Ceramic Filter (After) (Filter)	155	113	1.61	5.27	+ 15	96.6	40.1	0.57	1.87	+ 19

Engine Conditions rpm/kW	Test Conditions	Nitric Oxide				% Change	Nitrogen Dioxide				% Change	Total Oxides of Nitrogen				% Change
		ppm	g/hr	g/kW.h	g/kg Fuel		ppm	g/hr	g/kW.h	g/kg Fuel		ppm	g/hr	g/kW.h	g/kg Fuel	
2163/70.0 (MTU Cycle)	Fuel Additives (Before) (Filter)	382	297	4.25	13.9		51.2	61.1	0.873	2.86		433	517	7.38	24.2	
2163/70.0 (MTU Cycle)	Fuel Additives (After) (Filter)	373	290	4.14	13.6	- 2.0	48.6	57.9	0.827	2.71	- 5.0	422	503	7.18	23.2	- 2.7

FIGURE 14.1

FILTER IGNITION TEMPERATURE TEST

(Catalyzed Filter)

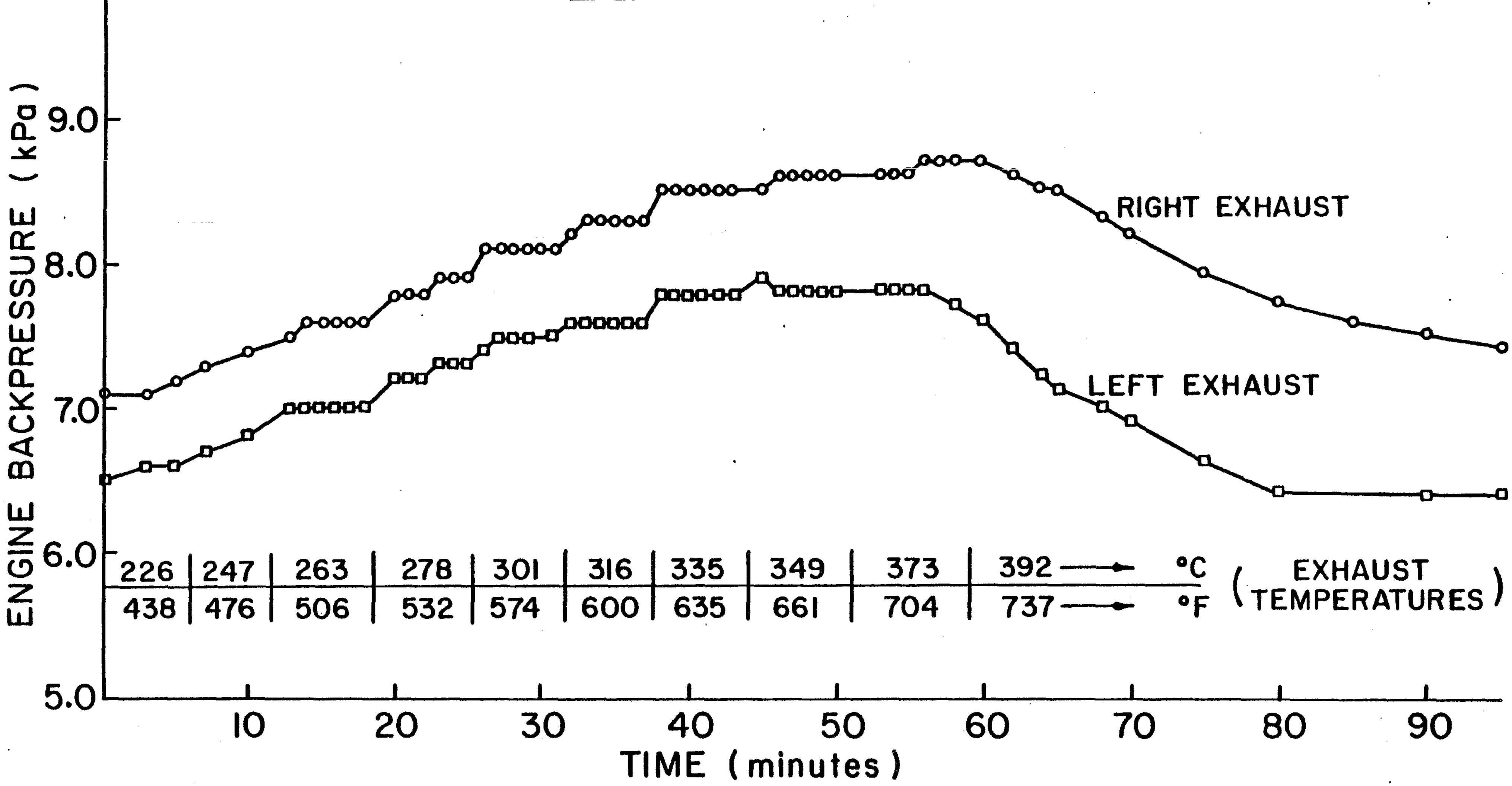
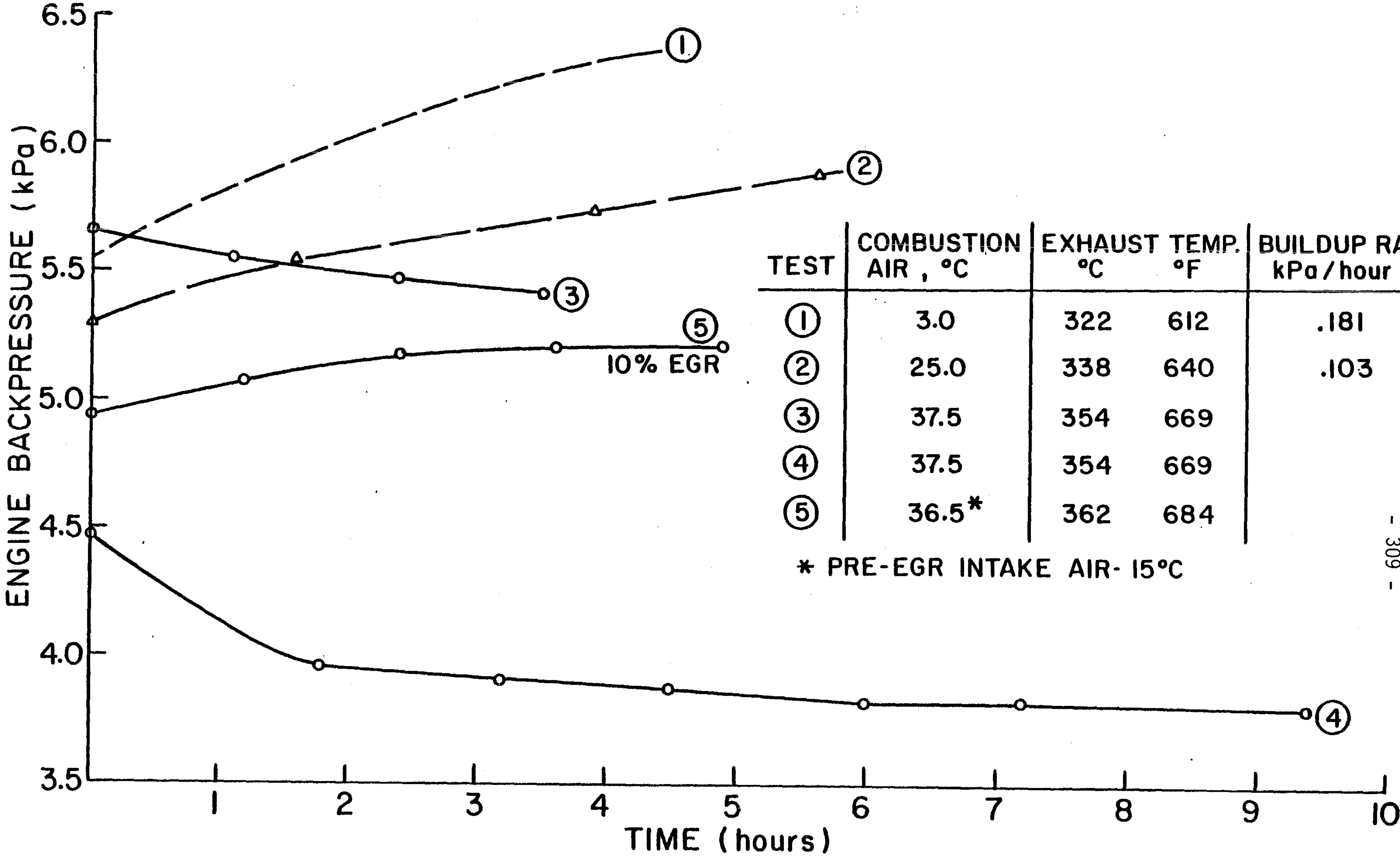


FIGURE 14.2

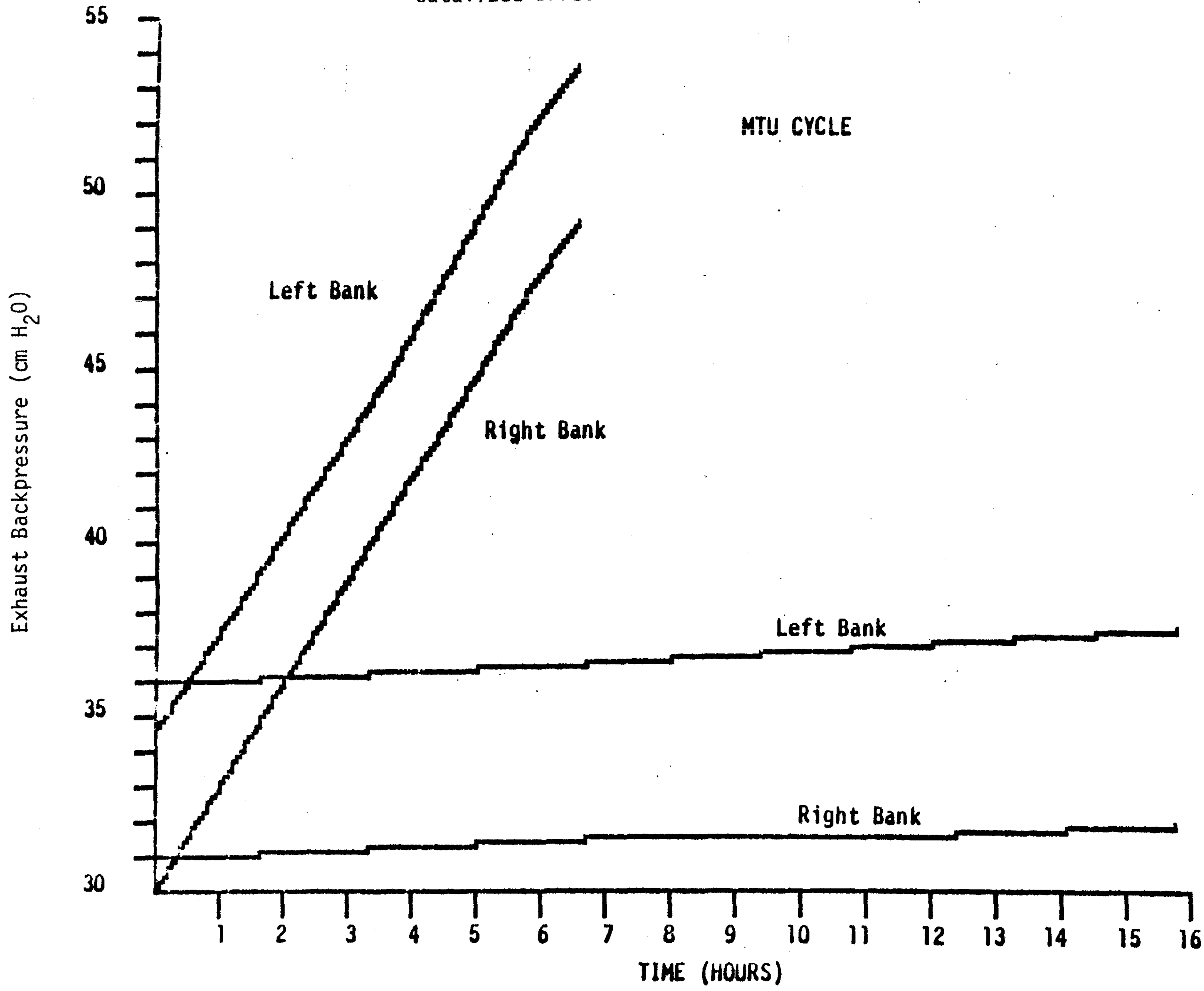
COMPARISON OF FILTER BUILDUP WITH MTU CYCLE, AT VARIOUS COMBUSTION AIR TEMPERATURES. (Catalyzed Filter)



TEST	COMBUSTION AIR, °C	EXHAUST TEMP. °C	EXHAUST TEMP. °F	BUILDUP RATE kPa/hour
①	3.0	322	612	.181
②	25.0	338	640	.103
③	37.5	354	669	
④	37.5	354	669	
⑤	36.5*	362	684	

* PRE-EGR INTAKE AIR- 15°C

FIGURE 14.3: Comparison of Engine Back-Pressure Profiles for Standard MTU Cycle and MTU-MOD 4 Cycle With Application of Catalyzed DPFs.



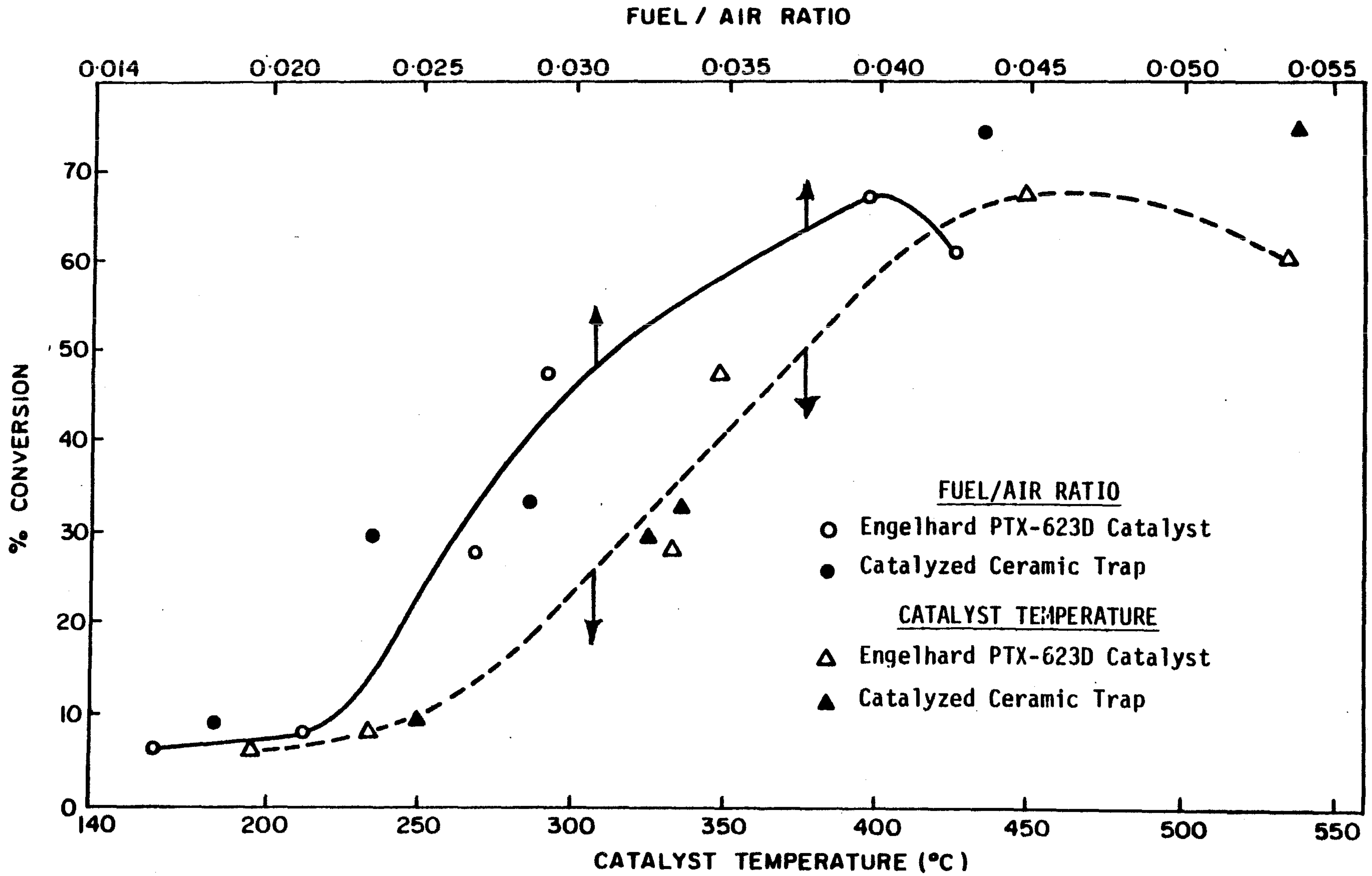


FIGURE 14.4:% Conversion SO_2 to $SO_4^=$ vs Catalyst Temperature and Fuel/Air Ratio (Deutz F8L 413 F/W)

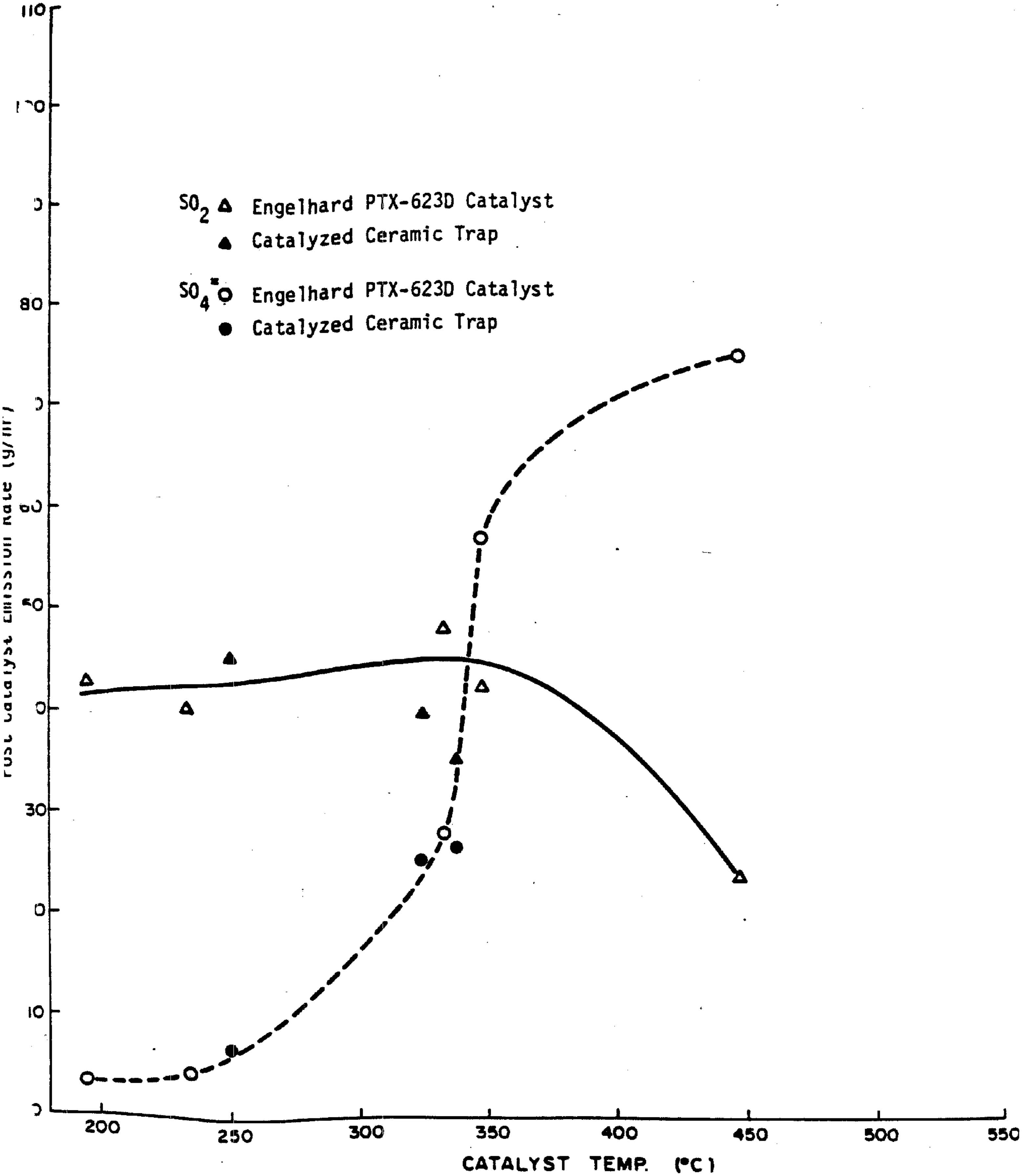
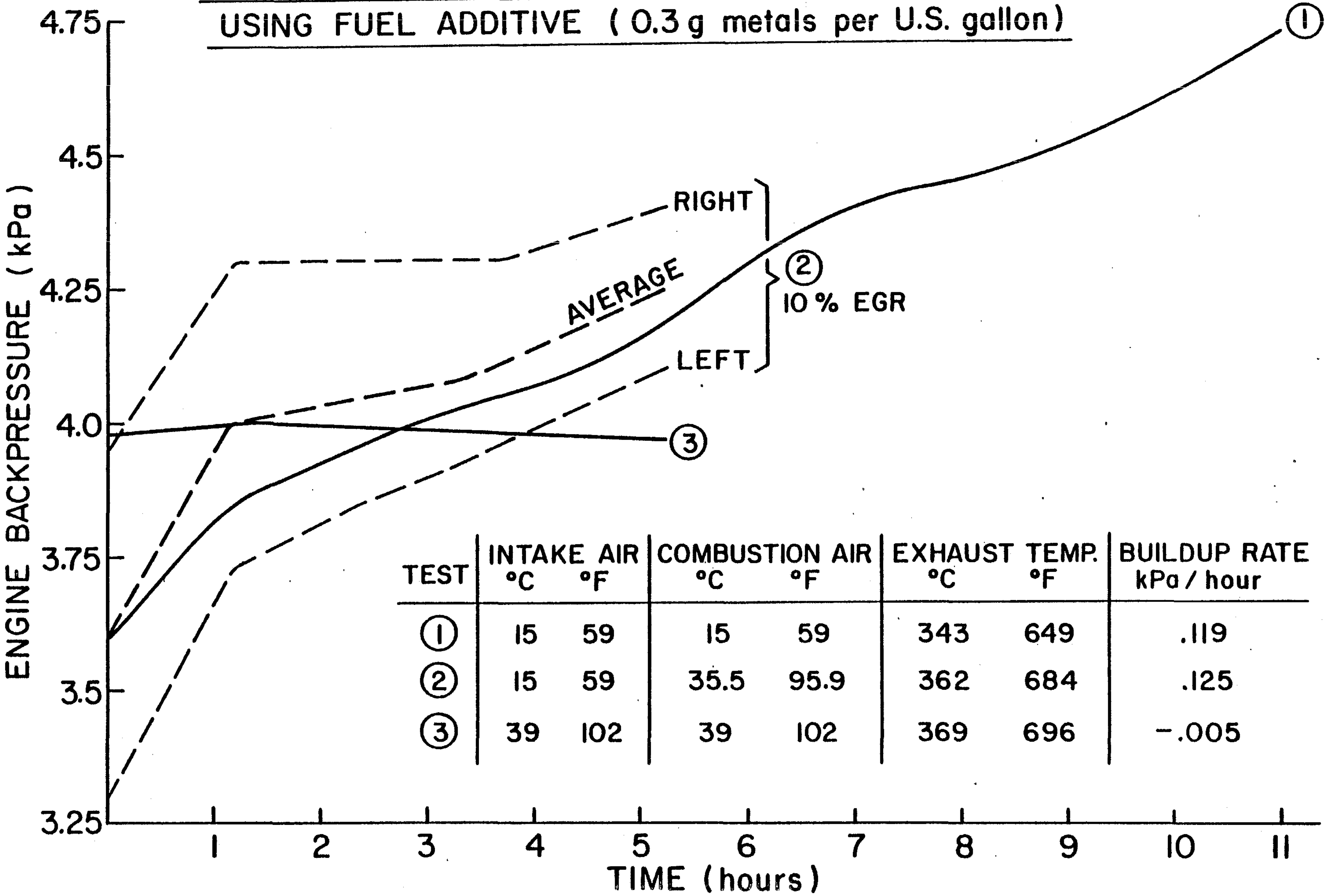


FIGURE 14.5: Post Catalyst Sulphate & Sulphur Dioxide Emission Rate (gm/hr) vs Catalyst Temperature (Deutz F8L 413 F/W)

FIGURE 14.6

COMPARISON OF FILTER BUILDUP WITH MTU CYCLE USING FUEL ADDITIVE (0.3 g metals per U.S. gallon)



TEST	INTAKE AIR °C	INTAKE AIR °F	COMBUSTION AIR °C	COMBUSTION AIR °F	EXHAUST TEMP. °C	EXHAUST TEMP. °F	BUILDUP RATE kPa/hour
①	15	59	15	59	343	649	.119
②	15	59	35.5	95.9	362	684	.125
③	39	102	39	102	369	696	-.005

15. FIELD TESTS

Field testing was carried out to evaluate mine durability and emission control effectiveness. It was felt that laboratory testing of the DPF ceramic filtrate was not an adequate substitute for real world conditions. In conjunction with DPF durability testing it was perceived that the monitoring of mine air during this demonstration may provide information on the improvement of mine air quality with the DPF technology. Two approaches of DPF regenerative assistance were considered for this project; catalyzed DPFs and fuel additive. A standard ceramic DPF was not tested because it would not be expected to self-regenerate and hence, would plug very quickly.

In choosing a location for this DPF demonstration a series of test pre-requisites needed to be fulfilled. These were:

1. The LHD vehicle exhaust gas temperature during LHD operation had to be sufficient to allow successful filter regeneration.

2. The DPFs had to be readily adapted to the engine.

3. The LHD vehicle had to be operated by the same operator in an area for a minimum of 3 weeks, where no other vehicle exhaust would interfere with the air quality in the test zone.

4. A management that was willing to participate and supply the necessary auxillary equipment and manpower necessary in performing these emissions and endurance trials.

15.1 Mine Selection

Two mines were considered for the DPF mine demonstration; St. Joe Resources Mine in Balmat, N.Y., U.S.A. and Kidd Creek Mine in

Timmins, Ontario, Canada. Ontario Research Foundation (ORF) and USBM personnel visited each mine site and discussed program requirements with mining personnel.

St. Joe mine's personnel recommended that the tests be carried out in an area being cleared for an underground maintenance bay. Discussions held with production supervisory personnel revealed that this operation would only involve periodic LHD operation, and it was not possible for the mine to extend the time of the duty cycle.

Kidd Creek Mine indicated a willingness to participate in this DPF demonstration and met all the test pre-requisites.

15.2 Mine Test Area

Copper and zinc are the primary metals mined at this operation with lesser amounts of silver and cadmium. In 1981 the mine produced an ore tonnage of 4,076,400 for subsequent milling at its refinery.

The mine management was cooperative during the planning stages and actively participated in the program itself. Mine personnel provided the necessary maintenance staff and facilities which allowed for the installation of the emission control hardware on the LHD. In addition, the necessary electrical power supplies and fuel storage facilities were provided by the mine.

It was decided to use the 915 metre level of the No. 2 mine as the location for the tests. Mine personnel were cooperative in ensuring that no other diesel powered machines operated in the vicinity of the LHD under test. This was necessary to minimize changing background air quality during mine air sampling. Figure 15.1 shows the layout of the 915 metre level of the mine.

The test site area of the 915 metre level is illustrated in Figure 15.2. Approximately 22 m^3/s of ventilation air was supplied in the main drift of the test site. Also, an axial fan supplied some ventilation air via a duct to the mucking area (771 stope). The LHD travelled between the muck pile and the ore pass, a distance of approximately 67 metres. There were no significant gradients between the ore pass and the muck pile.

15.3 Equipment Selection and Set-Up

USBM provided all the necessary test equipment and instrumentation to allow ORF personnel to collect samples of the mine air. It was originally envisaged that collection of air samples both upstream and downstream of the test LHD would allow for an adequate comparison of air quality. Mine air monitoring stations were located at the ventilation air supply to the test site (Location "A") and downstram of the test site (Location "B") as indicated in Figure 15.2. One high volume air sampler, three permissible samplers (personnel samplers) for particulate sampling and one CO_2 bag sampler were located at each monitoring station.

Strip chart recorders used for measuring RPM and exhaust gas temperature were mounted on the test LHD along with three personnel samplers and a CO_2 sampling system. Figure 15.3 and Figure 15.4 illustrate the mine air sampling equipment. A detailed description of the emission test equipment is located in Appendix II.

15.4 DPF Installation

The LHD machine (No. 502) used in this underground demonstration was a 4 m^3 ST5 "scooptram" powered by a Deutz F8L 714 air-cooled engine rated at 133 kW at 2300 RPM. As indicated in Table 15.1, a rebuilt engine had been installed in the LHD on November 1, 1983 and a total of 2092 hours of engine operation had been accumulated prior to this demonstration.

The original exhaust system employed on the LHD vehicle included an Engelhard 6 DM PTX catalyst in conjunction with a muffler on each exhaust bank. This machine was primarily chosen for the field testing due to the ease of replacing the current exhaust system with the DPFs and for its high engine exhaust temperature (400 degrees C+) necessary for successful DPF regeneration.

In previous lab tests DPFs were installed in the horizontal position, however, due to vehicle exhaust configuration and limited space, the DPFs were mounted vertically on the LHD. DPFs were attached solidly to the LHD mainframe by bolting the DPF flange directly to the vehicle floor. In this installation the exhaust, after passing through the DPF, encounters a deflection plate and is deflected towards the rear of the machine. A convoluted section of flexible tubing complete with mating flanges was mounted between the engine manifold and the DPF inlet. The flexible tubing acted as a shock absorber reducing the stress between the engine manifold and DPF inlet. Easy removal of the DPF from the LHD was accomplished through the use of 4 hole mating flanges on the DPF exhaust inlet and outlet. DPFs could be removed from the LHD vehicle in approximately 10 minutes by the simple removal of sixteen 6 mm. bolts. The total length of time for initial retrofitting of the LHD with DPFs was a total of 2 working shifts (16 hours).

Upon installation of each DPF demonstration system the LHD vehicle would be driven from the 853 metre mine level to the 1036 metre mine level and back again. This procedure produces high engine exhaust temperatures inducing DPF regeneration which ensured a "clean" DPF before air monitoring tests.

15.5 Vehicle Operation Results

The engine exhaust manifold temperatures and RPM were constantly monitored using a Soltec strip chart recorder set to a chart speed of 0.5 cm/min. This chart speed was selected to reduce the chance of chart paper jamming in the recorder. A typical chart tracing is given in Figure 15.5. In order to differentiate between LHD cycles, the chart speed was increased from 0.5 cm/min to 8 cm/min. for a number of LHD cycles one of which is shown in Figure 15.6. During this accelerated cycle trace the LHD operation was timed using a Hewer digital stopwatch. This was completed to determine the four (4) LHD cycle modes.

These modes were identified as the following:

1.	Travel to stope	The LHD vehicle travels from the ore pass to the mucking face at the stope.
2.	Mucking	The LHD vehicle fills the bucket with ore.
3.	Travel to ore pass	The LHD vehicle travels from the stope to the ore pass with a load of ore.

4.	Dump	The LHD vehicle dumps the bucket of ore down the mill hole (ore pass).

The chart recording of the LHD vehicle was segmented into 1 second increments. Engine exhaust temperature and RPM data was obtained for each of these 1 second increments. The result a digital version of the LHD vehicle cycle is given in Table 13.2 and resultant temperature and RPM graphs of these tables are shown in Figures 15.7 and 15.8. The average RPM and temperature for the four modes is given in Table 15.4.

On completion of each day's testing the LHD vehicle would climb an access ramp from the 915 metre level to the maintenance bay on the 853 metre level. During one of these ramp ascents the engine exhaust temperature and RPM were monitored using strip chart recorders. The engine exhaust backpressure was also noted. The graphs of RPM and temperature during this ascent are shown in Figures 15.9 and 15.10 respectively. A digital version of ramp ascent RPM and temperature is located in Table 15.3.

The LHD average engine exhaust temperature was 439^{o}C as indicated in Table 15.4. This is a much hotter cycle than the MTU cycle's average exhaust temperature of 340^{o}C. DPF regeneration temperatures of 420^{o}C and 370^{o}C with respective fuel additive concentrations of 80 mg and 40 mg Manganese per litre of diesel fuel have been recorded in ORF fuel additive test programs. Therefore using a concentration of 80 mg/L of fuel additive ensured DPF regeneration during mine air emission tests.

Catalyzed DPF regeneration temperature of 349°C measured at ORF test facility ensured that regeneration would occur over the Kidd Creek LHD cycle.

The engine exhaust backpressures (Tables 15.5 - 15.6) indicate no significant increase in engine exhaust backpressures during catalyzed and fuel additive DPF mine emission trials. The exhaust backpressures for both DPF systems were significantly lower than the original exhaust system (PTX + muffler) as indicated in Tables 15.5-15.7. The maximum high idle exhaust backpressure for the DPF units was approximately 3.5 kPa compared to 8.0 kPa for the PTX + muffler system. Both DPF systems appear to exhibit auto-regeneration as predicted.

A significant aid in the regeneration of the DPFs was the daily ramp ascent from the mine 915 metre level to the 853 metre level. The average engine exhaust temperature was 510°C with extreme temperatures of 550°C. Auto-regeneration of the DPFs without any assistance would likely occur during this 3 minute period of time. It would be interesting to observe an LHD vehicle with similar exhaust control devices in a mine without an access ramp.

15.6 Mine Air Monitoring Test Results

To calculate the net effect of the different exhaust conditioning systems the pollutant concentrations of the upstream air were subtracted from the pollutant concentrations of the downstream air (Table 15.8) and illustrated in Table 15.9. A negative (-) sign in Table 15.9 columns (except combustible particulate matter concentration) indicates that the downstream air was "cleaner" than the upstream air.

The personnel filter mass gains and concentrations are located in Tables 15.10-15.12. Insufficient particulate mass did not allow for conclusive results.

Analysis of combustible particulate matter test results were complicated by positive mass gains on some of the test filters. A mass loss of particulate matter (carbon) on the high volume filter was expected. However, a mass gain occurred on most of the filters and is suspected to have been due to oxidation of mine dust on the filter. The combustible particulate matter results, therefore, cannot be accepted as reliable.

The soluble particulate matter in mine air is not entirely due to diesel engine exhaust. Soluble particulate material may originate from oil leakage from the LHD. One of the major problems encountered with the Deutz engine used in this project was leakage of oil from the valve cover seals. This oil would impinge on the hot exhaust creating a high soluble particulate content in the mine air. The soluble particulate matter concentration has been recorded for the mine air as shown in Table 15.8 but is suspect. The organic fraction of the mine air may have originated from the diesel engine exhaust as well as other sources.

The sulphate $SO_4^{=}$ pollutant concentrations as shown in Table 15.8 and Table 15.9 suggest that the catalyzed DPF is producing less sulphate than the standard DPF and fuel additive. This data conflicts with earlier laboratory catalyst DPF tests completed at ORF engine test facility.

The sulphate ion results were obtained from the analysis of the high volume filter isopropyl alcohol extract.

The nitrate (NO_3^-) results were obtained using the same method as for the sulphate ion; a method not normally used in nitrate determination in air.

The mine air sampling methodology and sample analysis are located in Appendix II.

15.7 Durability Tests

15.7.1 Catalyzed DPF Durability Test

The catalyzed DPFs were operated for a total of 251.2 hours at Kidd Creek Mine. In conjunction with those hours, 186 hours of operation were accumulated at ORF's research facility for a total of 437.2 operating hours. Test details can be found in Appendix III.

No catalyzed ceramic DPF failure was evident during the mine demonstration.

The engine exhaust backpressures during the endurance testing phase of the mining demonstration showed a decrease of approximately 0.85 kPa at high idle. This, however, could be the accuracy difference between the magnehelic gage and the diaphragm type differential pressure gage. From the standpoint of auto-regeneration and durability the mine demonstration was a success.

15.7.2 Corning DPFs with Fuel Additive

During the fuel additive phase of the endurance demonstration three injectors on the right engine bank were found to be leaking unburnt fuel into the engine exhaust. This diesel fuel coated the right DPF increasing the engine exhaust backpressure and created a "smoking" problem as described in Appendix III. Once the injectors were replaced and the DPFs regenerated with an access ramp climb the right engine exhaust backpressure decreased to initial idle endurance test conditions. The high idle condition was slightly higher than initial test conditions. The right DPF ceased smoking after the access ramp climb indicating the unburnt fuel had been cleared off the filter.

The standard DPFs with fuel additives were operated for a total of 194 hours. No physical damage to the DPFs was observed and the DPFs successfully auto-regenerated.

15.8 Conclusions

The major success of this demonstration was the fact that both the catalyzed DPF and the standard DPF with fuel additive withstood the rigors of a mine environment while auto-regenerating. Although the mine air monitoring results were inconclusive, visual inspection of the DPFs indicated they were removing diesel exhaust particulates.

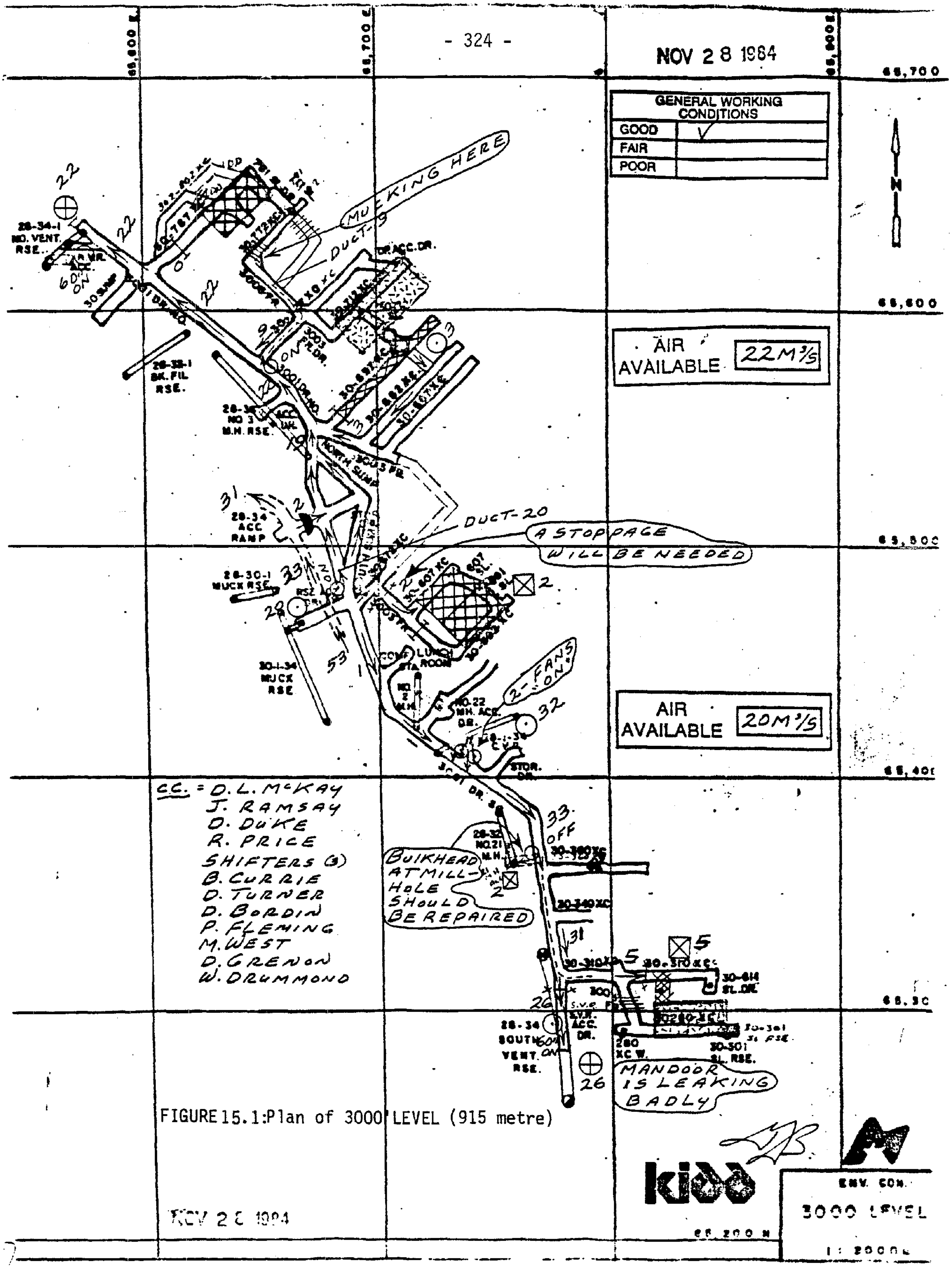


FIGURE 15.1: Plan of 3000' LEVEL (915 metre)

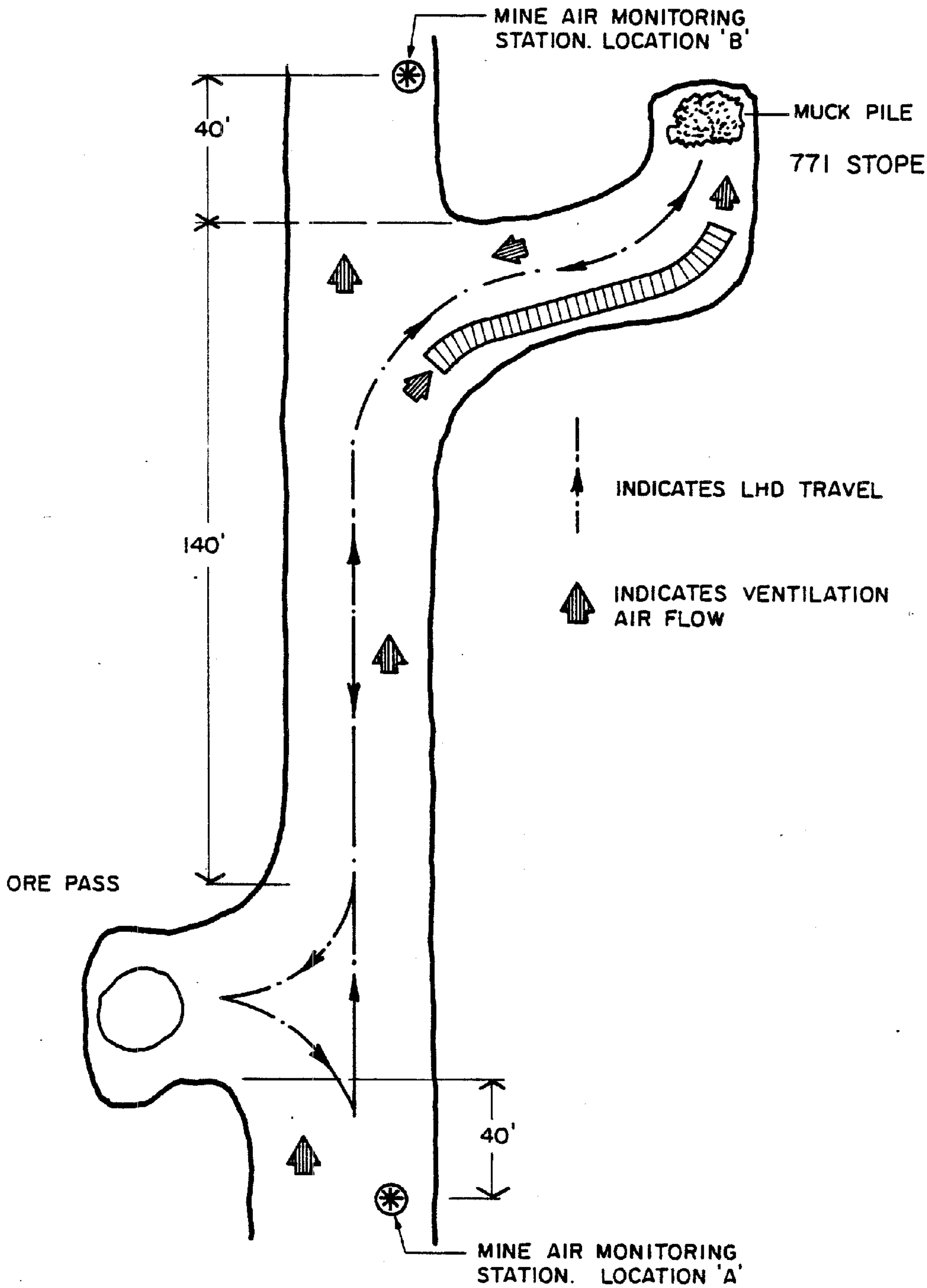


FIGURE 15.2: TEST SITE LAYOUT.

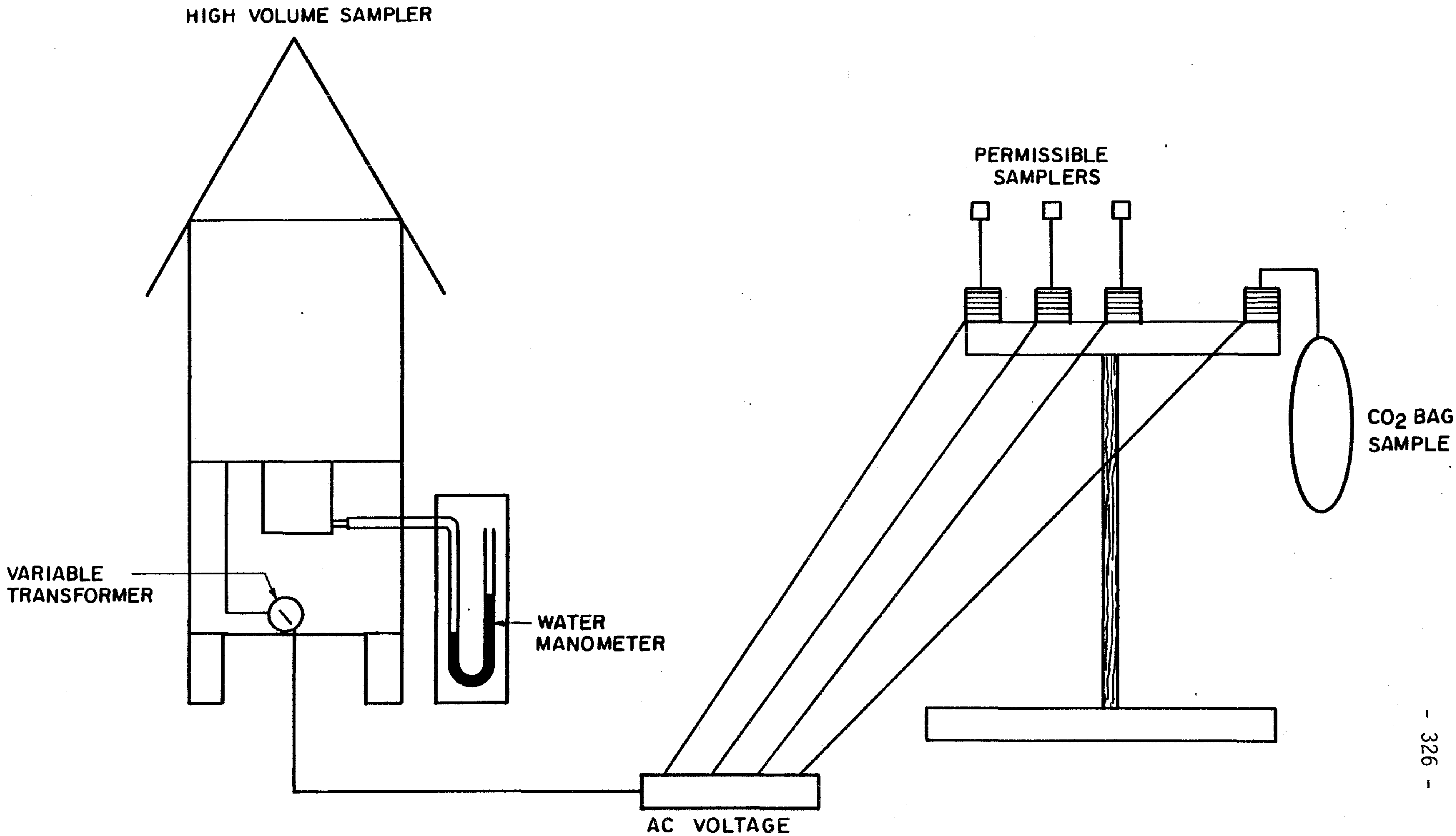


FIGURE 15.3: LAYOUT OF MINE AIR MONITORING EQUIPMENT.

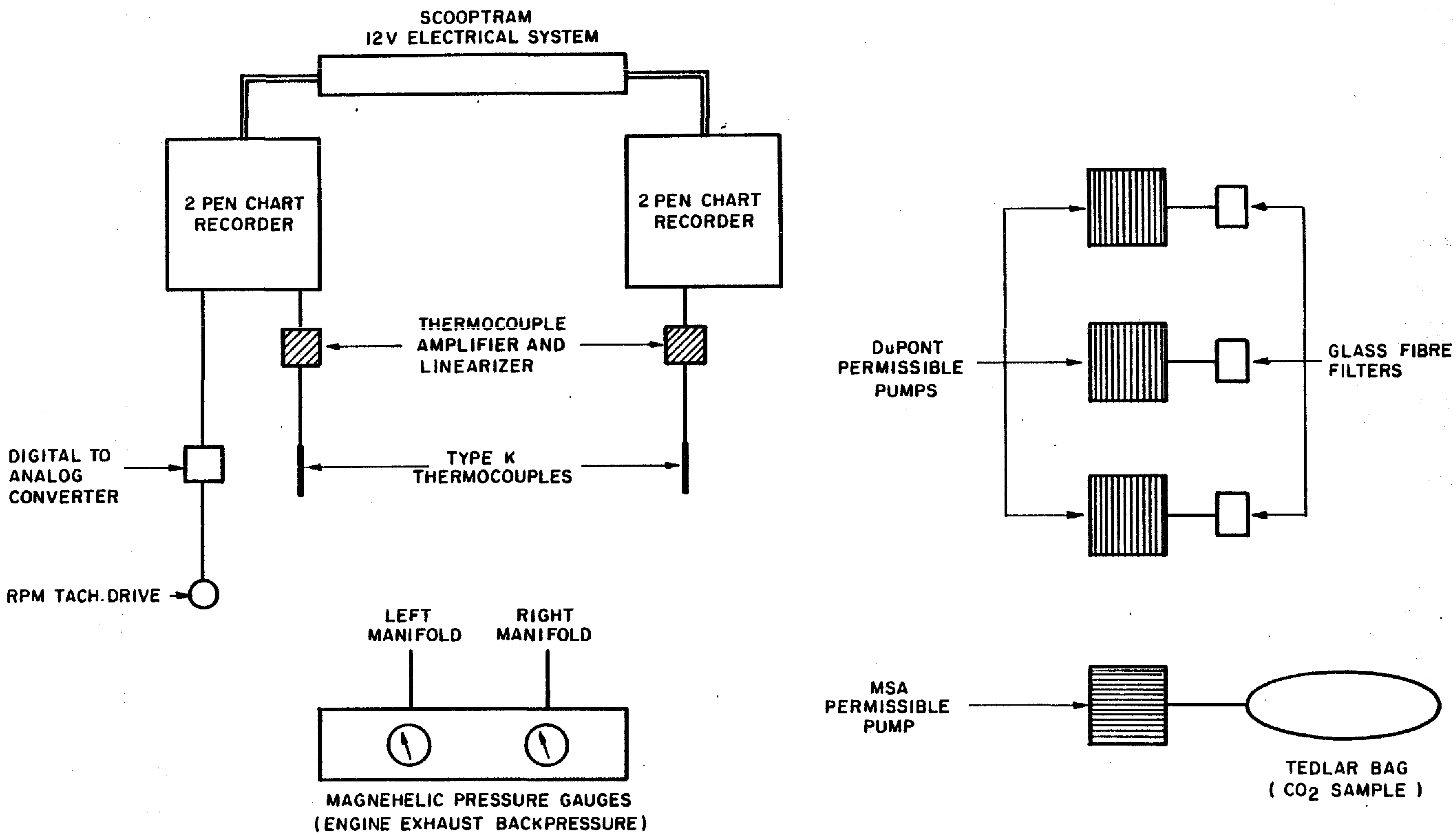
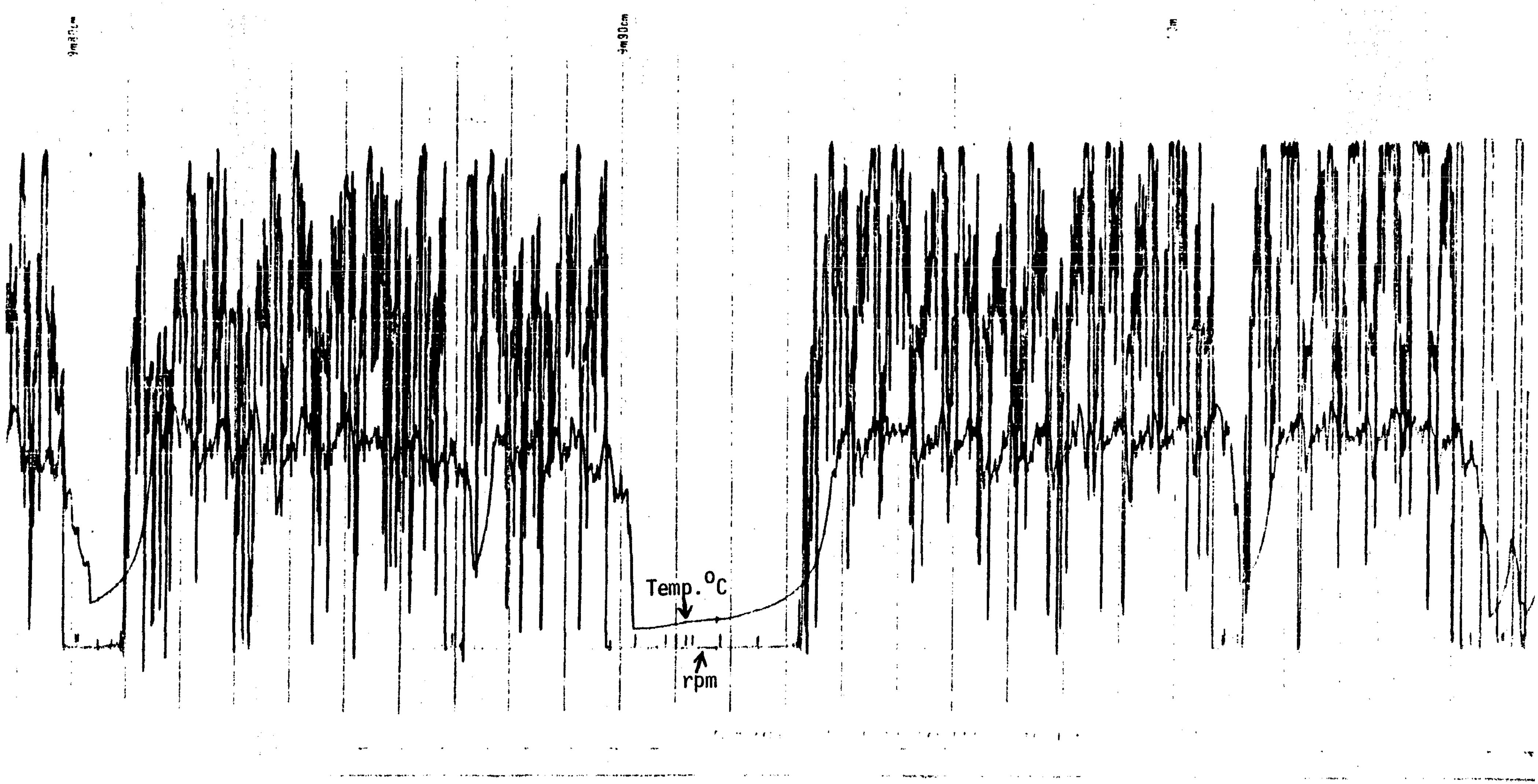
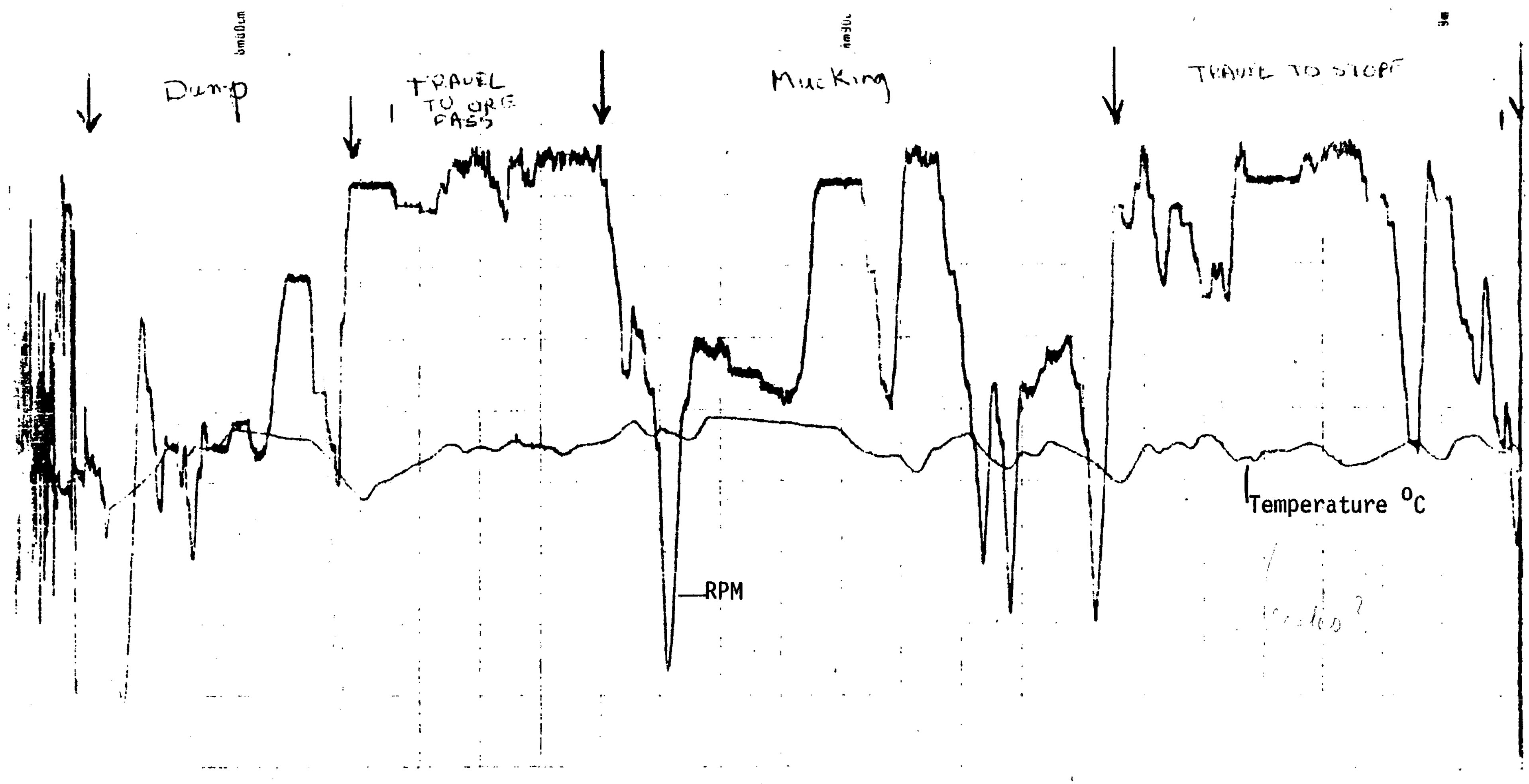


FIGURE 15.4: INSTRUMENTATION AND SAMPLERS INSTALLED ON THE LHD.



SOLTEC CHART RECORDING
OF LHD CYCLE RPM AND RIGHT EXHAUST BANK TEMPERATURE
CHART SPEED .5 cm/min.

FIGURE 15.5

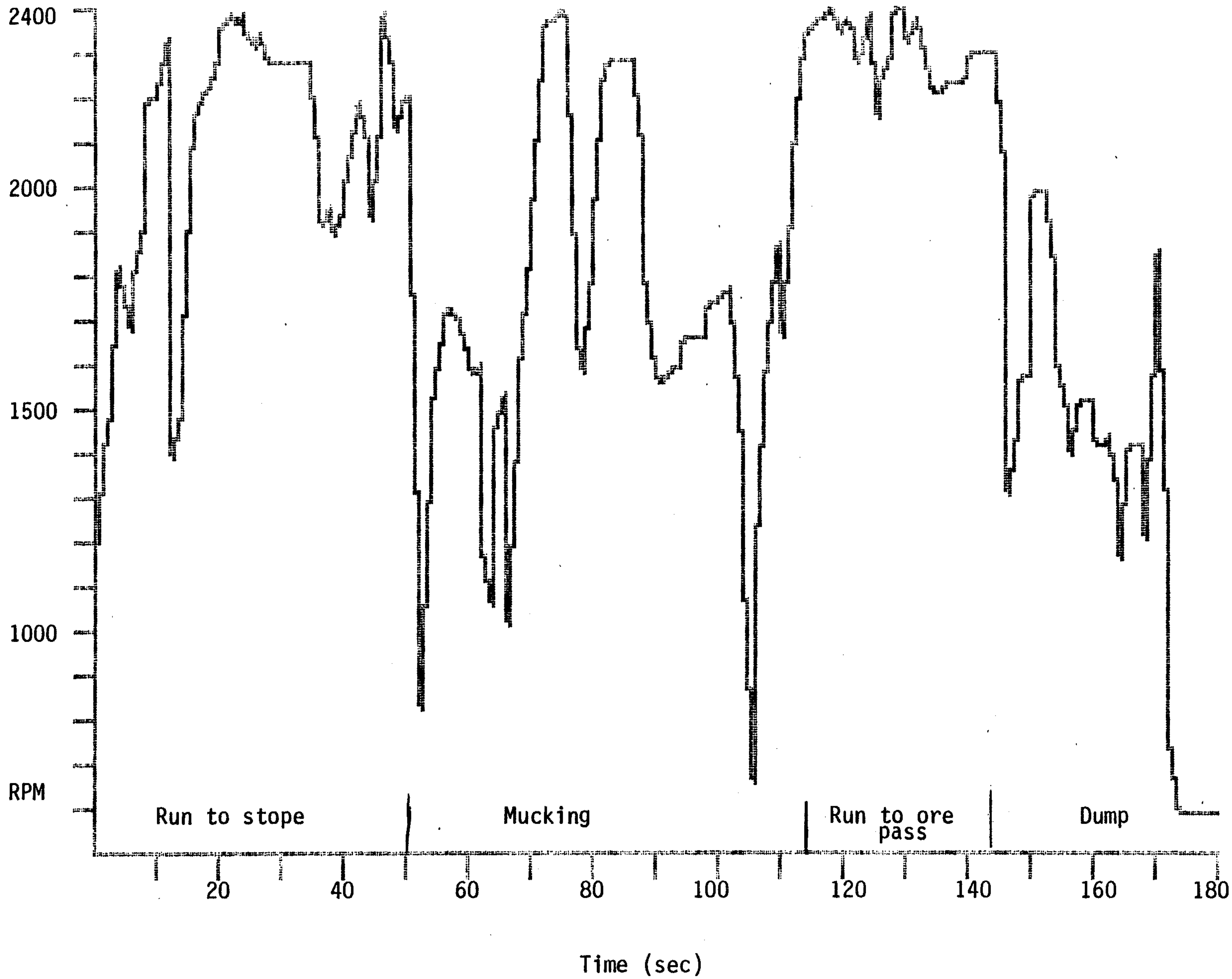


SOLTEC CHART RECORDING
OF LHD CYCLE RPM AND RIGHT EXHAUST BANK TEMPERATURE
CHART SPEED 8 cm/min.

FIGURE 15.6

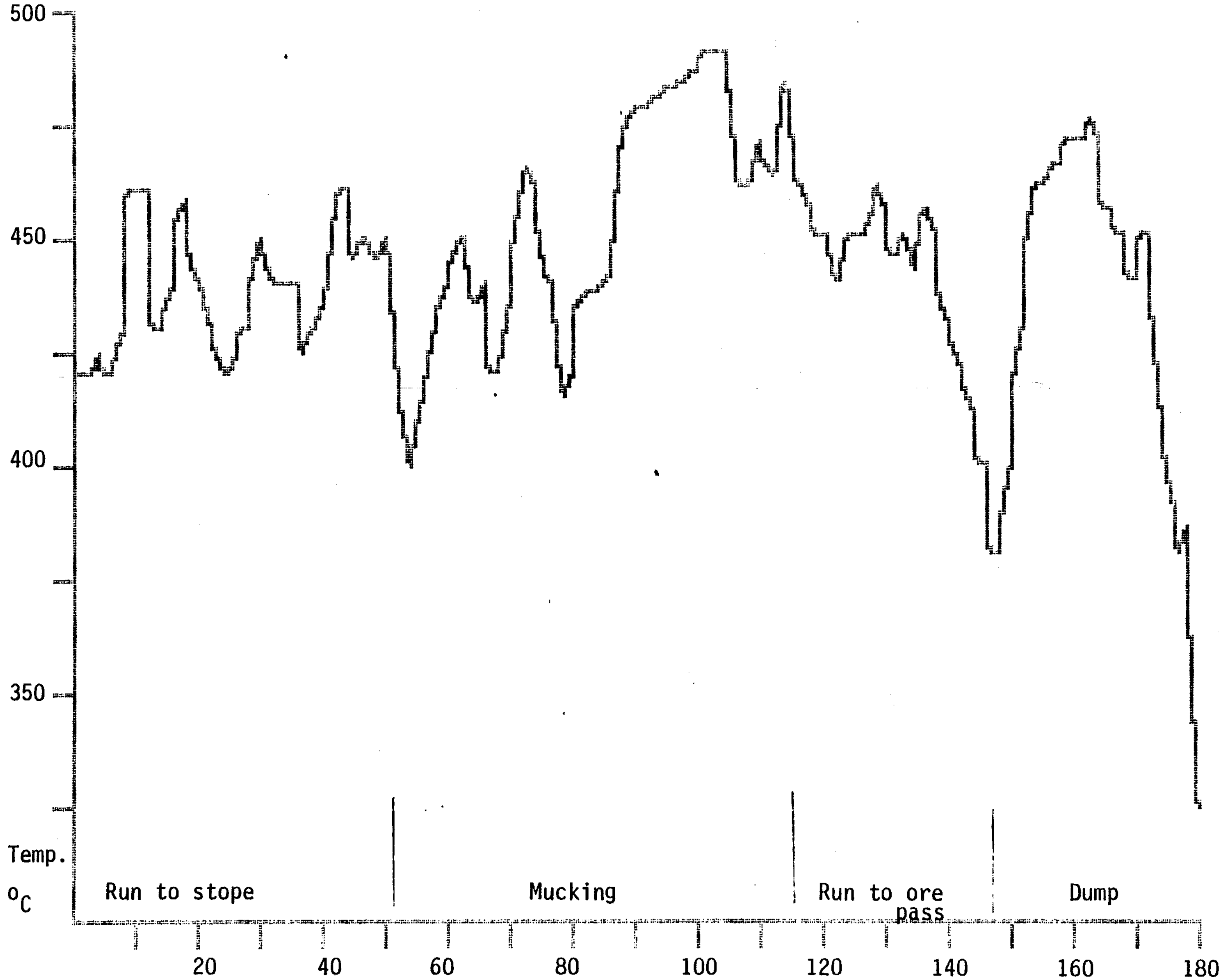
KIDD CREEK LHD CYCLE RPM

FIGURE 15.7



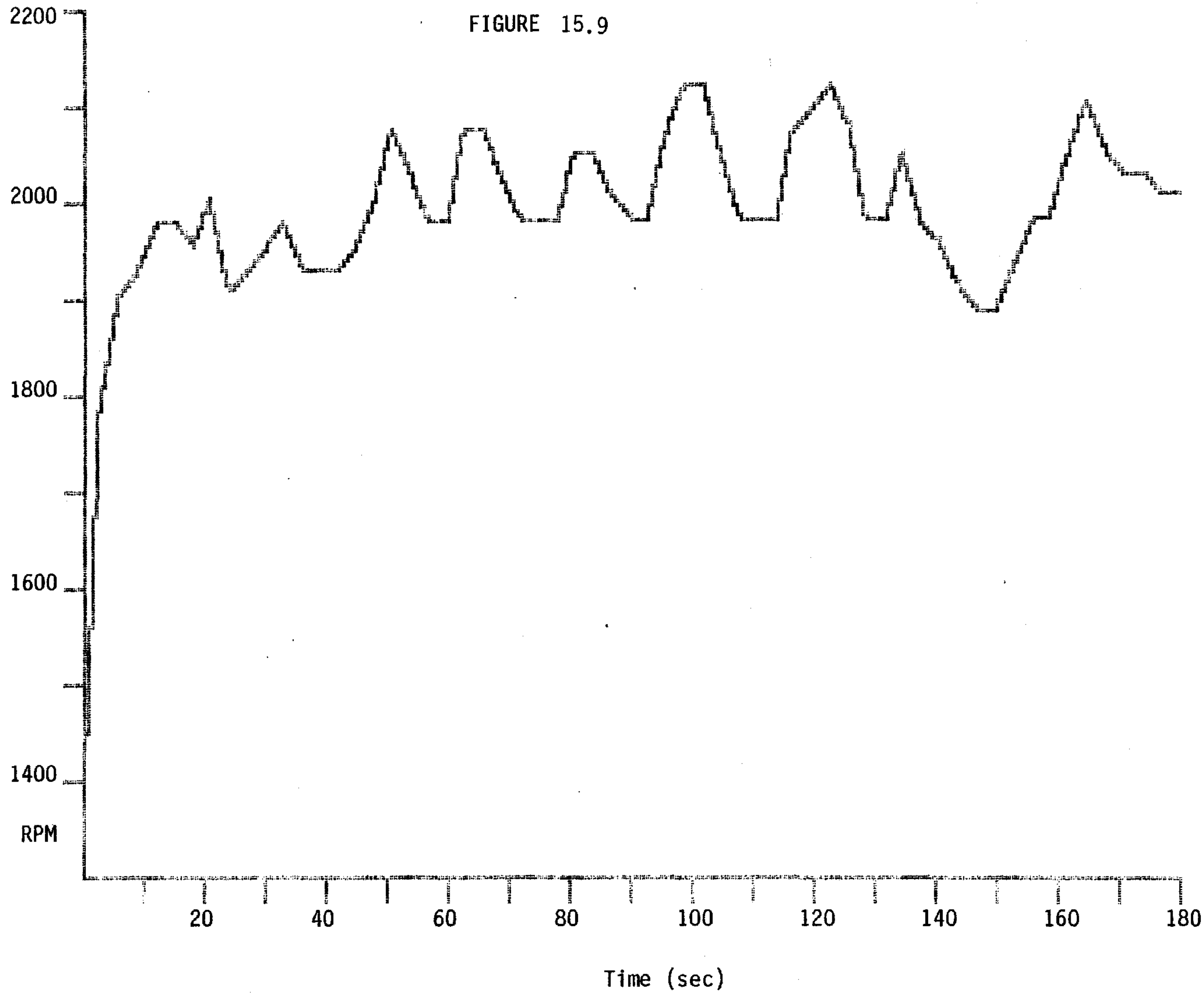
KIDD CREEK LHD CYCLE TEMPERATURE

FIGURE 15.8



KIDD CREEK RAMP ASCENT RPM

FIGURE 15.9



KIDD CREEK

LHD RAMP ASCENT

TEMPERATURE

FIGURE 15.10

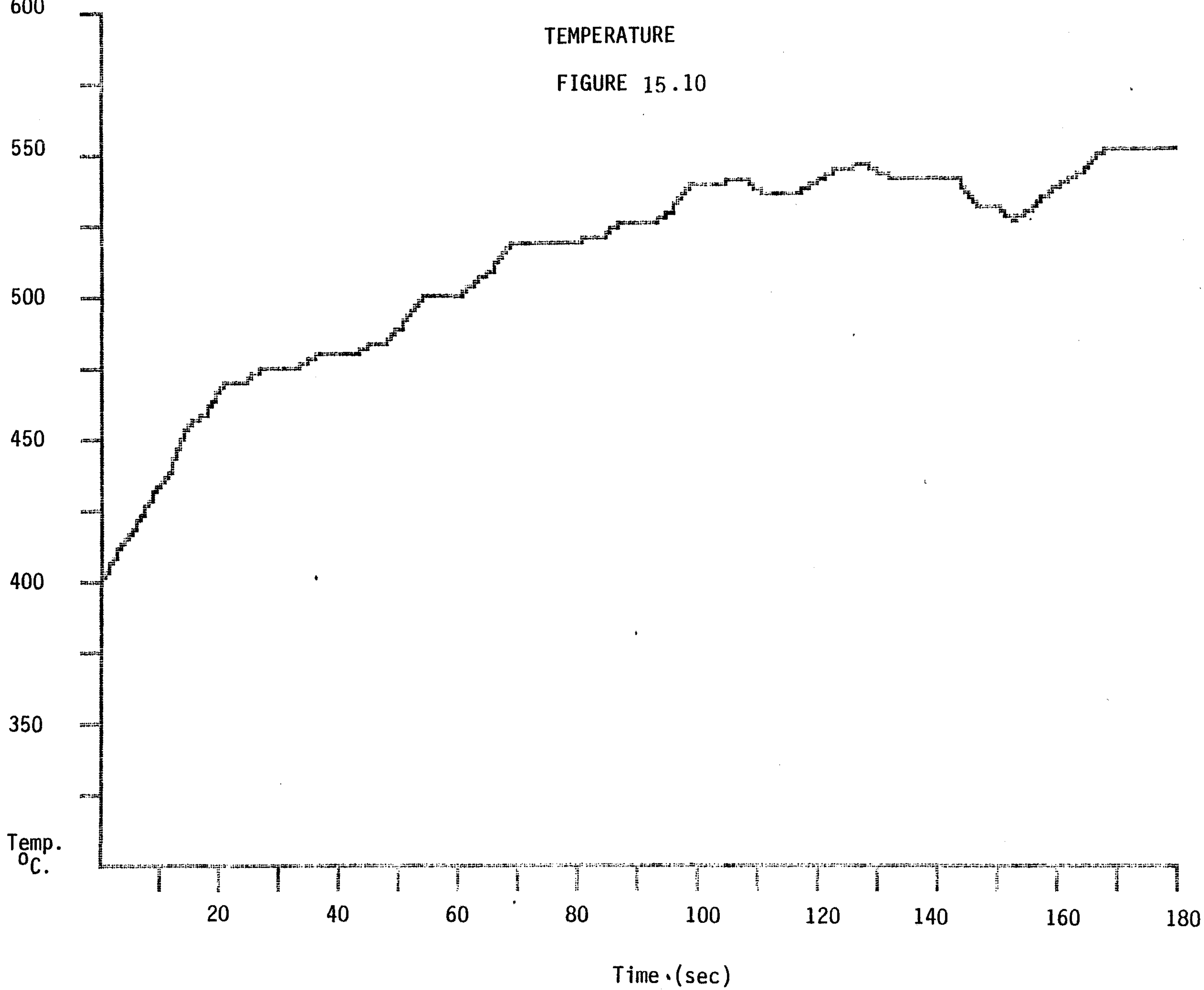


TABLE 15.1

SCOOPTRAM #502 ENGINE HISTORY

ENGINE TYPE : Deutz F8L714

ENGINE SERIAL NO. S/N 5202751

DATE	TASK	ENGINE HOURS
Nov. 1/1983	- installed rebuilt engine	0
Dec.24/1984	- Set Valves	595
May 15/1984	- Replaced leaking oil return tube	1344
June 6/1984	- Tune up - Set valves - Replaced injectors - Replaced flywheel and rear main seal	1349
Nov.22/1984	BASELINE MINE AIR MONITORING TESTS	2092

KIDD CREEK
LHD CYCLE
RPM AND TEMPERATURE
TABLE 15 .2

TRAVEL TO STOPE

TIME (SEC.)	RPM	TEMP. C
1	1196	420
2	1433	420
3	1480	420
4	1812	425
5	1764	420
6	1669	420
7	1812	425
8	1906	430
9	2200	460
10	2200	460
11	2238	460
12	2333	460
13	1385	430
14	1480	430
15	1717	435
16	2096	440
17	2167	455
18	2214	458
19	2214	445
20	2285	440
21	2356	438
22	2380	430
23	2356	425
24	2380	420
25	2333	420
26	2309	425
27	2337	430
28	2273	430
29	2273	442
30	2273	450
31	2273	445
32	2273	440
33	2273	440
34	2273	440
35	2273	440
36	2096	440
37	1906	425
38	1954	430
39	1883	430
40	1942	435
41	2013	440
42	2131	455
43	2179	460
44	2096	460
45	1918	445
46	2119	450
47	2380	450
48	2262	445
49	2119	445
50	2191	450
51	2191	445

AVERAGE RPM: 1841

VERAGE TEMP C: 443

KIDD CREEK

LHD CYCLE

RPM AND TEMPERATURE
TABLE 15.2

MUCKING

TIME (SEC.)	RPM	TEMP. C
52	1291	420
53	817	410
54	1291	400
55	1527	405
56	1646	415
57	1717	420
58	1693	430
59	1693	435
60	1622	440
61	1575	445
62	1598	450
63	1148	450
64	1054	435
65	1456	435
66	1527	440
67	1006	420
68	1385	420
69	1622	425
70	1812	435
71	1977	450
72	2238	460
73	2356	465
74	2356	460
75	2380	450
76	2356	440
77	2143	440
78	1622	420
79	1575	415
80	1788	420
81	1977	435
82	2238	438
83	2273	438
84	2273	438
85	2273	440
86	2273	442
87	2273	450
88	2096	470
89	1764	475
90	1598	478

KIDD CREEK
LHD CYCLE
RPM AND TEMPERATURE

TABLE 15 .2

MUCKING (CONT.)

TIME (SEC.)	RPM	TEMP. C
91	1551	478
92	1575	478
93	1587	480
94	1598	480
95	1646	482
96	1646	482
97	1646	483
98	1646	484
99	1729	485
100	1741	485
101	1752	490
102	1764	490
103	1669	490
104	1433	490
105	1054	490
106	651	470
107	1243	460
108	1587	460
109	1693	463
110	1859	470
111	1646	465
112	1906	462
113	2096	465
114	2285	483
115	2344	480

AVERAGE RPM: 1841

AVERAGE TEMP C: 443

KIDD CREEK
LHD CYCLE
RPM AND TEMPERATURE
TABLE 15 .2

TRAVEL TO ORE PASS

ME (SEC.)	RPM	TEMP. C
116	2356	460
117	2356	460
118	2380	455
119	2380	450
120	2333	450
121	2356	450
122	2333	440
123	2262	440
124	2333	450
125	2368	450
126	2143	450
127	2238	450
128	2285	455
129	2380	460
130	2380	455
131	2309	445
132	2356	445
133	2333	450
134	2238	445
135	2191	442
136	2191	455
137	2214	455
138	2214	450
139	2214	435
140	2238	430
141	2285	425
142	2285	420
143	2285	415
144	2285	410
145	2285	400

VERAGE RPM: 1841

AVERAGE TEMP C: 443

KIDD CREEK
LHD CYCLE
RPM AND TEMPERATURE
TABLE 15.2

DUMP

TIME (SEC.)	RPM	TEMP. C
146	2048	400
147	1291	380
148	1433	380
149	1563	390
150	1563	400
151	1977	420
152	1977	430
153	1977	450
154	1812	460
155	1575	460
156	1480	463
157	1385	465
158	1504	465
159	1504	470
160	1504	470
161	1409	470
162	1409	470
163	1433	475
164	1314	470
165	1148	455
166	1409	455
167	1409	450
168	1409	450
169	1196	440
170	1575	440
171	1835	450
172	1291	450
173	722	430
174	580	410
175	580	400
176	580	390
177	580	380
178	580	385
179	580	360
180	580	325

VERAGE RPM: 1841

VERAGE TEMP C: 443

KIDD CREEK
RAMP ASCENT
RPM AND TEMPERATURE

TABLE 15.3

RAMP ASCENT

TIME (SEC.)	RPM	TEMP. C
0	1338	400
3	1788	410
6	1906	420
9	1930	430
12	1977	440
15	1977	455
18	1954	460
21	2001	470
24	1906	470
27	1930	475
30	1954	475
33	1977	475
36	1930	480
39	1930	480
42	1930	480
45	1954	482
48	2001	485
51	2072	490
54	2025	500
57	1977	500
60	1977	500
63	2072	505
66	2072	510
69	2025	518
72	1977	518
75	1977	518
78	1977	518
81	2048	520
84	2048	520
87	2001	525
90	1977	525
93	1977	525
96	2072	530
99	2119	538
102	2119	538
105	2048	540
108	1977	540
111	1977	535
114	1977	535
117	2072	535

KIDD CREEK
RAMP ASCENT
RPM AND TEMPERATURE

TABLE 15.3

RAMP ASCENT (CONT.)

T ME (SEC.)	RPM	TEMP. C
120	2096	540
123	2119	542
126	2072	545
129	1977	542
132	1977	540
135	2048	540
138	1966	540
141	1954	540
144	1906	538
147	1883	530
150	1883	530
153	1930	525
156	1977	530
159	1977	535
162	2048	540
165	2096	542
168	2048	550
171	2025	550
174	2025	550
177	2001	550
180	2001	550

.VERAGE RPM: 1983

/ERAGE TEMP C :510

KIDD CREEK LHD

CYCLE ANALYSIS

TABLE 15.4

CONDITION	TIME (sec)	RPM	TEMPERATURE (C)
Travel to Stope	51	2071	439
Mucking	64	1841	443
Run to Ore Pass	30	2294	443
Dump	35	1320	430
CYCLE AVERAGE	180	1880	439

ENGINE EXHAUST BACKPRESSURES (KPA)

CATALYZED DPFs

TABLE 15.5

EMISSION TESTS

ENGINE HOURS	BANK	IDLE	HIGH IDLE	RAMP
770.0	RIGHT	0.8	3.4	4.0
	LEFT	0.8	3.5	4.0
777.9	RIGHT	0.8	3.2	4.0
	LEFT	0.8	3.5	4.0
791.7	RIGHT	1.0	3.5	4.0
	LEFT	1.0	3.5	4.0
803.1	End of Catalyzed DPF Emission Tests			

TOTAL HOURS: 33.1

CATALYZED DPF ENDURANCE TEST

ENGINE HOURS	BANK	IDLE	HIGH IDLE	RAMP
837.6	RIGHT	1.0	3.4	****
	LEFT	1.0	3.4	****
920.3	RIGHT	0.4	2.5	****
	LEFT	0.4	2.5	****
1055.7	RIGHT	0.3	2.5	****
	LEFT	0.3	2.6	****

TOTAL HOURS: 218.1

TOTAL HOURS EMISSIONS + ENDURANCE : 251.2

ENGINE EXHAUST BACKPRESSURES (KPA)

STANDARD DIESEL PARTICULATE FILTER

WITH FUEL ADDITIVE

TABLE 15.6

Fuel Additive DPF

EMISSION TEST ENGINE HOURS	BANK	IDLE	HIGH IDLE	RAMP
803.1	OPERATED ON PREVIOUS SHIFT			
814.1	RIGHT	0.8	0.8	1.5
	LEFT	0.8	0.8	1.5
818.3	RIGHT	0.4	2.4	2.0
	LEFT	0.4	0.8	2.0
828.6	RIGHT	0.3	2.5	2.5
	LEFT	0.3	0.8	2.5
837.6	End of Emission Tests.			

TOTAL HOURS: 34.5

FUEL ADDITIVE DPF ENDURANCE TESTS

ENGINE HOURS	BANK	IDLE	HIGH IDLE	RAMP
1055.7	RIGHT	0.3	2.5	****
	LEFT	0.3	2.5	****
1215.0	RIGHT	2.0	3.4	****
	LEFT	0.3	3.0	****
1215.0	RIGHT	0.4	3.0	****
	LEFT	0.3	3.0	****

TOTAL HOURS: 159.3

TOTAL HOURS EMISSIONS + ENDURANCE: 193.8

NOTE: The first pressure taken at 1215 was before ramp ascent
(The filter was coated with DIESEL FUEL)
The second time was after ramp ascent.

ENGINE EXHAUST BACKPRESSURES (KPA)

6DM PTX CATALYST + MUFFLER

TABLE 15 .7

TEST	BANK	IDLE	HIGH IDLE	RAMP
1	RIGHT	4.0	6.0	7.0-8.0
	LEFT	4.5	6.5	7.0-8.0
2	RIGHT	4.0	6.0	7.0-8.0
	LEFT	4.5	6.5	7.0-8.0
3	RIGHT	3.8	6.5	7.0-8.0
	LEFT	4.2	6.2	7.0-8.0

MINE AIR MONITORING TEST RESULTS

TABLE 15.8

TEST	FILTER	LOCATION	Total Particulate mg/m^3	Soluble Particulate mg/m^3	Non-Combustible Particulate mg/m^3	Combustible Particulate mg/m^3	Sulfate $SO_4^{=}$ ug/m^3	Nitrate NO_3 ug/m^3	CO_2%
1A	Baseline	Upstream	1.49	0.15	1.05	0.07	0.0	3.0	0.062
1B	"	Downstream	1.23	0.27	0.59	0.21	2.4	5.0	0.026
2A	"	Upstream	1.55	0.54	0.90	-0.10	0.0	3.5	0.040
2B	"	Downstream	1.57	0.45	0.70	0.26	2.7	6.5	0.091
3A	"	Upstream	1.46	0.21	1.20	-0.23	0.4	3.0	0.052
3B	"	Downstream	1.54	0.30	0.97	0.01	3.5	3.6	0.062
4A	Catalyzed								
4A	DPF	Upstream	0.88	0.35	0.65	-0.73	1.0	20.0	.070
4B	"	Downstream	1.12	0.28	0.70	-0.57	0.0	2.6	.048
5A	"	Upstream	0.60	0.18	0.25	0.00	0.0	4.9	.051
5B	"	Downstream	0.81	0.19	0.43	-0.02	0.0	4.1	.058
6A	"	Upstream	0.86	0.20	0.55	-0.13	0.0	1.7	.053
6B	"	Downstream	1.57	0.26	1.01	0.12	0.4	2.2	.072
7A	Fuel Add.+								
7A	Std. DPF	Upstream	0.85	0.21	0.43	-0.06	0.0	4.2	.051
7B	"	Downstream	1.51	0.29	1.17	-0.14	1.9	4.5	.081
8A	"	Upstream	1.42	0.28	0.89	0.02	0.0	5.7	.065
8B	"	Downstream	1.45	0.40	0.93	-0.05	4.7	2.9	.090
9A	"	Upstream	1.00	0.25	0.63	-0.22	0.0	3.8	.092
9B	"	Downstream	1.40	0.35	1.00	-0.18	3.4	2.6	.083

Note: a (-) sign indicates a weight gain.

POLLUTANT CONCENTRATIONS

(DOWNSTREAM - UPSTREAM) VENTILATION AIR

TABLE 15.9

TEST	FILTER	Total Particulate mg/m^3	Soluble Particulate mg/m^3	Non-Combustible Particulate mg/m^3	Combustible Particulate mg/m^3	Sulfate $SO_4^=$ ug/m^3	Nitrate NO_3 ug/m^3	CO_2%	Loads per Hour
1	Baseline	- 0.26	0.12	- 0.46	0.14	2.4	2.0	-0.036	14.3
2	"	0.02	-0.02	- 0.20	0.36	2.7	3.0	0.051	16.0
3	"	0.08	0.09	- 0.23	0.24	3.1	0.6	0.010	17.5
4	Catalyzed DPF	0.24	-0.07	0.05	0.16	-1.0	0.6	-0.022	19.0
5	"	0.21	0.01	0.18	0.02	0.0	-0.8	0.007	14.6
6	"	0.71	0.06	0.46	0.25	0.4	0.5	0.019	19.7
7	Fuel Add.+Std.								
7	DPF	0.66	-0.08	0.74	-0.08	1.9	0.3	0.030	15.2
8	"	0.03	0.12	0.04	-0.07	4.7	-2.8	0.025	20.4
9	"	0.40	0.10	0.37	0.04	3.4	-1.2	-0.009	18.6

Note: a (-) sign generally indicates pollutant concentration in upstream air is greater than downstream air.

PERMISSIBLE PUMP

Filter Mass Gains and Mine Air Particulate Concentrations

BASELINE MINE AIR QUALITY TESTS
TABLE 15.10

TEST	UPSTREAM		DOWNSTREAM		LHD VEHICLE	
	Filter Mass gain mg	Concentration mg/m^3	Filter Mass gain mg	Concentration mg/m^3	Filter Mass gain mg	Concentration mg/m^3
1	0.4	0.8	0.3	0.8	0.5	1.0
	0.8	1.6	0.5	1.6	0.3	0.6
	0.7	1.4	0.6	1.4	0.5	1.0
2	0.9	2.0	0.4	0.9	0.6	2.0
	0.5	1.2	0.3	0.6	0.7	2.4
	0.5	1.1	0.2	0.4	1.4	3.4
3	0.6	2.3	0.3	1.1	0.4	1.3
	0.3	1.2	0.1	0.4	0.4	1.3
	0.3	1.2	0.3	1.4	0.5	1.7

PERMISSIBLE PUMP

Filter Mass Gains and Mine Air Particulate Concentrations

CATALYZED DPF MINE AIR QUALITY TESTS

TABLE 15.11

TEST	UPSTREAM		DOWNSTREAM		LHD VEHICLE	
	Filter Mass gain mg	Concentration mg/m^3	Filter Mass gain mg	Concentration mg/m^3	Filter Mass gain mg	Concentration mg/m^3
4	0.0	0.0	0.6	4.8	0.3	2.3
	0.0	0.0	0.1	0.8	0.2	1.6
	0.0	0.0	0.1	0.8	0.2	1.6
5	0.7	1.3	0.3	0.6	0.3	0.6
	0.2	0.4	0.3	0.6	0.5	0.9
	0.2	0.4	0.3	0.6	1.0	1.9
6	0.6	1.3	0.6	1.4	0.4	0.9
	0.1	0.2	0.2	0.5	0.9	2.0
	0.2	0.5	0.6	1.4	0.7	1.6

PERMISSIBLE PUMP

Filter Mass Gains and Mine Air Particulate Concentrations

STANDARD DPF + FUEL ADDITIVE MINE AIR QUALITY TESTS

TABLE 15.12

TEST	UPSTREAM Filter Mass gain mg	UPSTREAM Concentration mg/m^3	DOWNSTREAM Filter Mass gain mg	DOWNSTREAM Concentration mg/m^3	LHD VEHICLE Filter Mass gain mg	LHD VEHICLE Concentration mg/m^3
7	- 0.07	- 1.8	0.3	0.8	0.1	0.3
	0.0	0.0	0.4	1.0	0.4	1.0
	0.9	2.3	0.4	1.0	0.4	1.0
8	0.4	0.8	0.4	0.9	0.8	1.7
	0.0	0.0	1.9	4.1	1.1	2.4
	0.4	0.8	0.7	1.6	0.9	1.9
9	0.1	0.3	0.5	1.5	0.5	1.5
	0.4	1.2	0.4	1.2	0.4	1.2
	0.2	0.6	0.2	0.6	2.2	6.6

16. SYSTEM COMPARISONS

16.1 Exhaust and Air Quality Indices

A number of methods are presently used to determine the impact of diesel exhaust emissions on underground mine air quality, and the amount of ventilation air which is considered necessary to reduce toxic component concentrations to levels for which no long term threat to the workers' health is anticipated. In Ontario, there is a defined quantity of fresh air which must be supplied per kilowatt of engine power. In the U.S.A. the requirement is that the concentration of diluted components shall not exceed their TLVs which are 2500 ppm CO_2, 50 ppm CO, 12.5 ppm NO, 5 ppm NO_2. In Canada the limits are .25% CO_2, 50 ppm CO, 12.5 ppm NO, 5 ppm NO_2, 2 ppm SO_2, 2 mg/m^3 RCD and 1 mg/m^3 H_2SO_4.

These methods, however, do not address the possible synergistic effects of one component in the presence of another and thereby increasing the toxicity of combined exposure. In recognition of this, a group of Canadian consultants, under contract to CANMET, Energy Mines and Resources Canada, examined the literature on the health effects of exposure to a mixture of toxic diesel exhaust components.[3] They were able to formulate the following expressions:

$$\text{AQI (gas)} : \frac{CO}{50} + \frac{NO}{25} + \frac{NO_2}{3}$$

$$\text{AQI (part)} : \frac{RCD}{2} + \left[\frac{SO_2}{2} + \frac{RCD}{2}\right] + \left[\frac{NO_2}{3} + \frac{RCD}{2}\right] + \frac{H_2SO_4}{1}$$

$$\text{AQI (Total)}: \text{AQI (gas)} + \text{AQI (part)}$$

Note: If the SO_2 and NO_2 concentrations are 25% or less of their TLVs the respective bracketed terms are not included in the calculation.

where

(CO)	=	carbon monoxide concentration in ppm
(NO)	=	nitric oxide concentration in ppm
(SO_2)	=	sulphur dioxide concentration in ppm
(NO_2)	=	nitrogen dioxide concentration in ppm
(RCD)	=	respirable combustible dust in mg/m^3 (considered equivalent to the particulate level of diesel exhaust) (20).
(H_2SO_4)	=	sulphuric acid concentration in mg/m^3

The expressions are split up so that toxicants with similar mechanisms of action are considered first on an individual basis and then as a whole in the total AQI. The inclusion of the SO_2/RCD and NO_2/RCD factors weight the equations towards diesel particulate. Thus recognizing the impact of diesel particulate and its synergistic effects with SO_2 and NO_2. (Sulphuric acid was collected using the controlled condensate method for this program.)

An aerosol is a particle of solid or liquid matter that can remain suspended in the air because of its small size. Both $H_2 SO_4$ and 80-95% of diesel particles (i.e. particles < 1 μm) are considered aerosols. Therefore it appears to be appropriate to consider both as particulates. However since diesel particulate do have a synergistic effect with SO_2 and NO_2 it was not considered correct to include H_2SO_4 with the RCD. Therefore in this report H_2SO_4 concentrations were recognized in a separate term from the RCD but were considered part of the EQI (part).

The AQI expressions were designed for use with ambient mine air pollutant concentrations. When undiluted exhaust is being considered as in this program, the same equations are applied but are referred to as an Exhaust Quality Index (EQI).

The AQI (gas) should not exceed 1.0 and no individual pollutant should exceed its TLV. The AQI (part) should not exceed 2.0 and again no individual component should exceed its TLV as stated by the ACGIH. The total acceptable EQI then is 3.0. Therefore the EQI/3 indicates the dilution ratio required to obtain an acceptable air quality. This dilution ratio multiplied by the dry engine exhaust flowrate results in a value for the recommended quantity of fresh ventilating air. Considerations have been made that the total AQI value of 3 is too high and that 2 may be more appropriate.

There are, however, limitations to this approach. Since the expression was designed as an air quality index, the use of tailpipe undiluted emission values creates a different impact on the EQI values. This is due to the lack of accountability for the ultimate fate of emission components which are emitted to the mine atmosphere. For example, NO emissions will be oxidized to NO_2 at a rate dependent on mine air residence time, and environment. NO_2 may subsequently be removed from the mine atmosphere by interaction with water. Similar considerations apply to H_2SO_4 emissions. An accurate assessment can only be made, therefore, by applying pollutant concentrations actually measured underground.

The original 1978 equations did not address concerns with the synergistic terms NO_2 and SO_2. It was felt that at lower levels of NO_2 and SO_2 the synergistic effects would become less prominent. Therefore the current equations now carry the rider that if the SO_2 and NO_2 concentrations are 25% or less of their TLVs the bracketed terms are not included in the calculations.

Despite these limitations, the expression is probably the best tool presently available, in order to compare the different impacts on exhaust quality of various emission control strategies. It is considered appropriate and relevant but not necessarily conclusive, therefore, to use EQI values to provide a view of the ranking of different emission control approaches, and try to assess which approaches show the greatest benefits.

16.2 Representation of Emission Control Strategies Relative to Exhaust Quality Indices.

Since the EQI equation had been changed since the Phase I and II final report all EQIs have been recalculated and included in this section.

Using the data contained in Phases I, II and III, (and data from relevant literature referenced in this report) EQI values were calculated at two engine load/speed conditions, and for two engines, the Deutz F6L-714 and the Deutz F8L-413 FW. The EQI values vary with engine type and load/speed conditions, but, for the same engine and the same load/speed condition, it is possible to compare EQI values of the controlled versus the baseline uncontrolled engine. Calculations of EQI values were also made with results from two mine duty cycles, the MTU Cycle and MTU MOD 4 Cycle. Data used in the calculations can be found in Tables 16.4 to 16.8 along with explanations of assumptions and estimates that had to be made.

Table 16.1 shows EQI values for the Deutz F6L-714 engine at two different load/speed conditions with the application of various emission control devices at 2200 rpm full load.

EGR/Catalyst, EGR/Scrubber and EGR alone applications, were the worst strategy with respect to EQI (Total). For both 10% and 21% EGR the gaseous emissions were significantly improved over the baseline. However, the particulates and sulphates were 600% higher than baseline, totally offsetting the gaseous improvements. The application of 21% EGR alone also resulted in very large particulate emissions above baseline. Emulsification/Catalyst reduced the EQI (Gaseous) to 61% of baseline but again large increases in sulphate emissions resulted in a 212% increase in EQI (Total). Emulsification alone produced good results with an EQI (Total) of 75% of baseline as did the Gaspe Scrubber at 63% of baseline. The mesh filter with exhaust gas cooled by water injection, the wet mesh filter with catalyst and the emulsion/catalyst/mesh filter (wet) produced EQI (Total) values of 48%, 37% and 32% respectively. These final three systems show excellent emission reduction. However, all require an onboard supply of water which is a disadvantage. Also the mesh filters would require frequent cleaning.

Also in Table 16.1 are EQI values for the 714 engine at 2200 rpm and three quarter full load condition. Off full load the EGR penalty is less severe as shown by the 21% EGR EQI (Total) at 108%. The 21% EGR/Catalyst/Scrubber however, is still very high due to SO_2 to $SO_4^=$ conversion. Gaspe Scrubber technology is again fairly good with a 75% EQI(Total). The 21% EGR/Catalyst/Mesh Filter (wet) was excellent with 31% EQI (total) due in part to the wet mesh filter removimg the $SO_4^=$ caused by the catalyst.

Table 16.2 shows EQI values calculated for the controlled and uncontrolled Deutz F8L-413 FW engine, at two load/speed conditions, rated speed/full load, rated speed/three-quarter load. In this case, emulsification, catalyst and EGR techniques, used alone, are unattractive at either load/speed condition. At full load/speed condition, the Corning filter and EGR/Corning filter system produce the best performance, reducing the EQI values to 47% and 44% of baseline values respectively. This result, by itself, would seem to indicate that there is no great advantage in combining EGR with the Corning filter, since the addition of EGR further reduces the EQI value by only 3 percentage points, while the complexity of the device is significantly increased. However, when the EQI values are examined at 2300 rpm/103 kW, it is apparent that there is now a significant improvement in the EQI value when the EGR is added to the Corning filter to form a combined system. This shows the significance of assessing EQI values at different load/speed conditions, and the need for performance evaluation over a typical underground vehicle duty cycle. It is to be concluded, therefore, that, for the 413 engine, the EGR/Corning filter system offers the best opportunities, in terms of effectiveness and minimum complexity, for development into field usable hardware.

EQI values from typical LHD cycles are given in Table 16.3. For both cycles the catalyzed Corning filter is unattractive due to its conversion of SO_2 to $SO_4^=$. There is a discrepancy between the effectiveness of the catalyzed Corning filter reported here and in the April 19, 1984 CIM report "Diesel Exhaust Emissions Control Using EGR and Particulate Filters". Differences in assumed fuel sulphurs are the main reason for the difference. The CIM report used a fuel sulphur of 0.1% while this report uses 0.22% fuel sulphur. This causes a significant difference in H_2SO_4 emissions and hence in the total EQI value. This device however is the simplest and most effective as far as regeneration is concerned. Therefore if the SO_2 conversion problem can be improved this device would be very practical. As in the steady state testing the Corning and particularly the EGR/Corning system results are very favourable. However, the Corning and EGR/Corning systems do not regenerate on their own. For this reason the Fuel Additive/Corning or a EGR/Fuel Additive/Corning look to be the most promising systems at the moment. One note of concern with fuel additive systems, however, is the pass-through of additive. However, recent preliminary results at ORF suggest the retention of the fuel additive is very high by the Corning Filter so may not be a concern.

Further comments are necessary at this stage regarding the relationship between EQI values and the dilution ratio with ventilation air necessary to reduce the Air Quality Index to the recommended value of three. Dilution ratios can be calculated for the EQI values for various emission control approaches. For example, for the Deutz F6L-714 engine, the dilution ratio for the uncontrolled engine at 2200 rpm/93 kW (full load/speed) amounts to 59:1, whereas if the engine is controlled with the emulsification/catalyst/mesh filter combination, the dilution ratio (D.R.) is reduced to 18:1. D.R. values are however, limited by the dilution necessary to reduce CO_2 concentrations produced by the engine to below the threshold limit value (TLV) for CO_2 which is 5000 ppm. Since the CO_2 concentration at full load/speed condition for this engine is 9.9%, then a D.R. value of 19.8 is required to maintain CO_2 concentrations below the TLV. There is, therefore, little value in applying exhaust control technology which will lower the EQI below the CO_2 limitation. For the cycle data however the limiting EQI was not reached by any system.

The system comparisons have illustrated the following conclusions:

(1) The Phase III results using transient LHD cycles, generally confirmed the results obtained using steady state engine conditions. However, in general, steady state and transient tests would not be acceptable for comparison because of the different nature of transient emissions. Another important point observed was that emission measurements must be made when the control device is in a regenerative mode due to the storage/release phenomena.

(2) EGR/Corning systems are the most efficient in the treatment of diesel exhaust emissions.

(3) The Corning filter is also the most practical system to install and operate on a vehicle.

TABLE 161: COMPOSITE EQI VALUES FOR COMPARISON OF VARIOUS EMISSION CONTROL STRATEGIES

(Steady State - Deutz F6L-714 Engine)

RPM/kW	Device	EQI (Gas)	% Baseline	EQI (Part)	% Baseline	EQI (Total)	% Baseline
	21% EGR	25	109%	489	411%	514	362%
	21% EGR/Cat/Scrubber	6	26%	501	421%	507	357%
	10% EGR/Cat/Scrubber	16	70%	479	403%	564	397%
	Emulsification/Catalyst	14	61%	287	241%	301	212%
2200/93	Baseline	23	100%	119	100%	142	100%
	Emulsification	18	78%	89	75%	107	75%
	Gaspe Scrubber	23	100%	67	56%	90	63%
	Mesh Filter (wet)	23	100%	45	38%	68	48%
	Cat/Mesh Filter (wet)	20	87%	32	27%	52	37%
	Emuls/Cat/Mesh Filter (wet)	14	61%	31	26%	45	32%
	Limiting EQI Value (CO_2 Dilution)					59	
	21% EGR/Cat/Scrubber	13	62%	261	395%	300	345%
	21% EGR	10	48%	84	127%	94	108%
2200/71	Baseline	21	100%	66	100%	87	100%
	Gaspe Scrubber	21	100%	44	67%	65	75%
	21% EGR/Cat/Mesh Filter (cooled)	7	33%	20	30%	27	31%
	Limiting EQI Value (CO_2 Dilution)					44	

TABLE 16.2 : COMPOSITE EQI VALUES FOR COMPARISON OF VARIOUS EMISSION CONTROL STRATEGIES
(Steady State - Deutz F8L-413 Engine)

RPM/kW	Device	EQI (Gas)	% Baseline	EQI (Part)	% Baseline	EQI (Total)	% Baseline
	PTX Catalyst	31	84%	401	270%	432	189%
	10% EGR	30	89%	238	124%	268	117%
	Baseline	37	100%	192	100%	229	100%
2300/138	Emulsification	32	86%	135	70%	167	73%
	Cat/Mesh Filter (Dry)	31	84%	116	69%	147	64%
	Mesh Filter (Dry)	37	100%	96	50%	133	58%
	Corning Filter	37	100%	71	37%	108	47%
	10% EGR/Corning	30	81%	70	35%	100	44%
	Limiting EQI Value (CO_2 Dilution)					56	
	Emulsification	27	90%	294	219%	321	196%
2300/103	PTX Catalyst	50	167%	277	207%	327	199%
	Baseline	30	100%	134	100%	164	100%
	10% EGR	22	73%	118	88%	140	85%
	10% EGR/Emul/Corning	35	117%	92	67%	127	77%
	Corning Filter	31	103%	62	46%	93	57%
	10% EGR/Corning	22	73%	43	32%	65	40%
	Limiting EQI Value (CO_2 Dilution)					47	

TABLE 16.3: COMPOSITE EQI VALUES FOR COMPARISON OF VARIOUS EMISSIONS CONTROL STRATEGIES (MTU CYCLES - DEUTZ F8L-413 ENGINE)

Cycle	Device	EQI (Gas)	% of Baseline	EQI (Part)	% of Baseline	EQI (Total)	% of Baseline
MTU	Baseline	24	100%	111	100%	135	100%
	Catalyzed Corning	39(22)	162% (92%)	115(96)	103% (86%)	154 (118)	114% (87%)
	Fuel Additive/Corning	34(25)	142%(104%)	48(39)	43% (35%)	82 (64)	61%
	Corning	24	100%	39	35%	63	47%
	15% EGR/Corning	18	75%	30	27%	48	36%
	Limiting EQI Value (CO_2 Dilution)					33	
MTU MOD 4	Catalyzed Corning	65 (33)	181% (92%)	254 (213)	229% (192%)	319 (246)	217% (167%
	Baseline	36	100%	111	100%	147	100%
	Corning	36	100%	44	40%	80	54%
	15% EGR/Corning	25	69%	35	32%	60	41%
	Limiting EQI Value (CO_2 Dilution)					39	

( ) - EQI calculated using estimated NO_2 values as measured values may be suspect.

TABLE 16.3A: COMPOSITE EQI VALUES FOR COMPARISON OF VARIOUS EMISSIONS CONTROL STRATEGIES
(MTU CYCLES - DEUTZ F8L-413 ENGINE)

Cycle	Device	EQI (Gas)	% of Baseline	EQI (Part)	% of Baseline	EQI (Total)	% of Baseline
MTU	Baseline	24	100%	89	100%	113	100%
	Catalyzed Corning	39 (22)	162% (92%)	40 (21)	45% (24%)	79 (43)	70% (38%)
	Fuel Additive/Corning	34 (25)	142% (104%)	26 (17)	29% (19%)	61 (41.4)	54% (37%)
	Corning	24	100%	17	19%	41	36%
	15% EGR/Corning	18	75%	12	13%	30	27%
	Limiting EQI Value (CO_2 Dilution)					33	
MTU MOD 4	Catalyzed Corning	65 (33)	181% (92%)	72 (30)	87% (36%)	137 (64)	114% (53%)
	Baseline	36	100%	83	100%	120	100%
	Corning	36	100%	15	18%	52	43%
	15% EGR/Corning	25	69%	12	14%	37	31%
	Limiting EQI Value (CO_2 Dilution)					39	

( ) - EQI calculated using estimated NO_2 values as measured values may be suspect.

* - Low fuel Sulphur of .02% assumed.

TABLE 16.4 : EQI DATA - DEUTZ F6L-714 DIESEL ENGINE - 2200 RPM/93 kW.

System	CO (ppm)	NO (ppm)	NO_2 (ppm)	SO_2 (2) (ppm)	H_2SO_4 (ppm)	RCD (mg/m^3)	H_2SO_4 (1) (mg/m^3)
21% EGR	>1000(1000)	150(118)	< 1	92.3(72.9)	4.9	452.9	
21% EGR/Cat/Scrubber	52(41.1)	150(118)	< 1	13.5(10.7)(3)	70.3(55.5)	339.2(268)	287(227)
10% EGR/Cat/Scrubber	18(16)	260(234)	20(18)	13.5(12.2)(3)	70.3(63.3)	136(122)	287(258)
Emulsification/Catalyst	9	340	< 1	36.9	55.4	43.1	226
Baseline	122	495	< 1	92.3	4.9	72.1	
Gaspe Scrubber(5)	122	495	< 1	35.6	8.5	49.0	
Emulsification	180	345	< 1	92.3	4.9	43.1	
Cat/Mesh Filter (wet)	9	495(4)	< 1(4)	29.2	1.5	11.95	5.9
Mesh Filter (wet)	122(4)	495(4)	< 1(4)	65.8(6)	.1(6)	11.95	
Emuls/Cat/Mesh Filter (wet)	9	340	< 1	29.2	1.5	10.6	5.9

(1) for non-catalyzed systems H_2SO_4 assumed to be included in RCD.

(2) Assumed .222% fuel sulphur for all tests (97.2 ppm) (total sulphur) H_2SO_4 assumed 5% of total sulphur.

(3) - From Figure 5.4 PTX Catalyst yields 60% SO_2-SO_4 conversion at this catalyst temp. (550°C)

- From Reference 8 scrubber removes 63.4% of SO_2 but ≃ 10 ppm is re-emitted as H_2SO_4

(4) Estimated from Table 9.1 Wet Mesh Filter removes 25% of SO_2 and 97.5% of SO_4

(5) Percent reductions from Reference 8 applied to baseline.

(6) Correction for reduced exhaust flow with EGR systems ⬭ - data taken from other appropriate data points in table.

( ) Correction for reduced exhaust flow with EGR systems

TABLE 16.5: EQI DATA - DEUTZ F6L-714 DIESEL ENGINE - 2200 RPM/71 kW.

System	CO (ppm)	NO (ppm)	NO_2 (ppm)	$SO_{(2)}$ [2] (ppm)	H_2SO_4 (ppm)	RCD (mg/m^3)	H_2SO_4 [1] (mg/m^3)
21% EGR	154 (122)	220 (174)	< 1	67.7(53.5)	3.6	73(58)	
Baseline	92	480	< 1	67.7	3.6	32.4	
21% EGR/Cat/Scrubber	22 (17)	220 (174)	20(16)	14.6(11.5) [3]	57.6(45.5)	53.7(42.4)	235(186)
Gaspé Scrubber [4]	92	480	< 1	41.6	8.6 [5]	22.7 [5]	
21% EGR/Cat/ Mesh Filter (Cooled)	24 (19.0)	200 (158)	< 1	17.8(14.0) [3] [6]	1.2(0.9)	12.5(9.9)	3.8(3.0)

(1) for non-catalyzed systems H_2SO_4 assumed to be included in RCD

(2) assumed .222% fuel sulphur for all tests (71.3 ppm total S), H_2SO_4 assumed 5% of total sulphur

(3) from Figure 5.4 PTX catalyst yields 65% SO_2-$SO_4^{=}$ conversion at this temperature (460°C)
from Reference 8
scrubber removes 38.5% of SO_2 but≃ 10 ppm is re-emitted as H_2SO_4

(4) Percent reductions from above report applied to baseline.

(5) Estimate.

(6) From Table 9.1 Wet Mesh Filter removes 25% SO_2 and 97.5% of $SO_4^{=}$

( ) correction made for reduced exhaust flow with EGR systems.

TABLE 16.6 : EQI DATA - DEUTZ F8L-413 DIESEL ENGINE - 2300 RPM/103 kW

System	CO (ppm)	NO (ppm)	NO_2 (ppm)	SO_2 (2) (ppm)	H_2SO_4 (1) (ppm)	RCD (mg/m^3)	H_2SO_4 (mg/m^3)
Emulsification	450	405	5	70.8	3.7	171	
PTX Catalyst (3)	6	495	90	42.5	32.0	63.7	130
Baseline	154	585	10	70.8	3.7	63.7	
10% EGR	192 (173)	462 (416)	5 (4)	70.8 (63.7)	3.7 (3.3)	62.2 (56.0)	
10% EGR/Emul/Corning	1480(1332)	184 (166)	5	70.8 (63.7)	3.7 (3.3)	43.4 (39.1)	
Corning Filter	163	610	(10)	70.8	3.7	15.8	
10% EGR/Corning	192 (173)	462 (416)	5 (4)	70.8 (63.7)	3.7 (3.3)	6.77 (6.1)	

(1) For non-catalyzed systems H_2SO_4 assumed to be included in RCD.

(2) Assumed .222% Fuel Sulphur for all tests (74.5 ppm total sulphur), H_2SO_4 assumed 5% of total sulphur.

(3) From Figure 5.4 PTX Catalyst yields 60% SO_2 - SO_4 conversion at this temperature (432^oC).

(4) Estimate

( ) correction for reduced exhaust flow with EGR systems.

◯ data taken from other appropriate data points in Table.

TABLE 16.7: EQI DATA - DEUTZ F8L-413 DIESEL ENGINE - 2300 RPM/138 kW.

System	CO (ppm)	NO (ppm)	NO_2 (ppm)	SO_2 (2) (ppm)	H_2SO_4 (ppm)	RCD (mg/m^3)	H_2SO_4 (1) (mg/m^3)
PTX Catalyst (3)	7	648	15	35.1	57.2	96.7	233
10% EGR	670(603)	445(400)	5 (4)	87.7(78.9)	4.6(3.6)	166 (131)	
Emulsification	700	450	0	87.7	4.6	91.2	
Baseline	345	665	10	87.7	4.6	96.7	
Cat/Mesh Filter (Dry)	7	648	15	61.8	7.6	32.7	31
Mesh Filter (Dry)	345	665	10	87.7	2.3	32.7	
Corning Filter	340	665	10	87.7	4.6	16.1	
10% EGR/Corning	670 (603)	445 (400)	5 (4)	87.7(78.9)	4.6 (4.1)	19.6 (17.6)	

(1) For non-catalyzed systems H_2SO_4 assumed to be included in RCD

(2) Assumed .222% fuel sulphur for all tests (92.3 ppm total S), H_2SO_4 assumed 5% of total sulphur.

(3) From Figure 5.4 PTX Catalyst yields 60% SO_2 - SO_4 conversion at this temperature (536°C).

(4) Estimated.

( ) - correction for reduced exhaust flow with EGR systems.

○ - data taken from other appropriate data points in Table.

TABLE 16.8: EQI DATA - DEUTZ F8L-413 DIESEL ENGINE - MTU CYCLES.

System	CO (ppm)	NO (ppm)	NO_2 (ppm)	SO_2 (2) (ppm)	H_2SO_4 (ppm)	RCD mg/m^3	H_2SO_4 (3) (mg/m^3)
Standard MTU							
Baseline	133	371	20 (1)	48.0	2.5	53.3	
Corning	133	371	20 (1)	48.0	2.5	5.34	
15% EGR/Corning	190 (162)	279 (237)	15 (1)	48.0 (40.8)	2.5(2.1)	3.31	
Catalyzed Corning	5	326 [371]	77 [20]	34.8	15.7	5.0 (1)	64
Fuel Additive/Corning	155	373 [371]	49 [20]	48.0	2.5	5.34 (1)	
Hot MTU MOD 4							
Baseline	157	582	30 (1)	61.8	3.2	47.0	
Corning	157 (circled)	582 (circled)	30 (circled)	61.8	3.2	1.7	
15% EGR/Corning	465 (395)	338 (287)	20 (1) (17)	61.8 (52.5)	3.2 (2.7)	2.76(2.35)	
Catalyzed Corning	5	348 [582]	153 [30]	18.2	46.8	1.7 (circled)	191

(1) Estimate

(2) Assumed .222% Fuel Sulphur for all tests (50.5 ppm total sulphur MTU Cycle, 65.0 ppm total sulphur MTU MOD 4) H_2SO_4 assumed 5% of total sulphur.

(3) For non-catalyzed systems H_2SO_4 assumed to be included in RCD.

[ ]- estimated because of suspect NO, NO_2 data.

O- data taken from other appropriate data points in Table.

( )- correction for reduced exhaust flow with EGR systems.

TABLE 16.8A: EQI DATA - DEUTZ F8L-413 DIESEL ENGINE - MTU CYCLES.

System	CO (ppm)	NO (ppm)	NO_2 (ppm)	SO_2 [2] (ppm)	H_2SO_4 (ppm)	RCD mg/m^3	H_2SO_4 [3] mg/m^3
Standard MTU							
Baseline	133	371	20[1]	4.3	.2	53.3	
Corning	133	371	20[1]	4.3	.2	5.34	
15% EGR/Corning	190 (162)	279 (237)	15[1]	4.3 (3.7)	.2 (.2)	3.31	
Catalyzed Corning	5	326 [371]	77 [20]	3.1	1.4	5.0[1]	5.7
Fuel Additive/Corning	155	373 [371]	49 [20]	4.3	.2	5.34[1]	
Hot MTU MOD 4							
Baseline	157	582	30[1]	5.6	.3	47.0	
Corning	157 (circled)	582 (circled)	30 (circled)	5.6	.3	1.7	
15% EGR/Corning	465 (395)	338 (287)	20[1] (17)	5.6 (4.8)	.3 (.3)	2.76 (2.35)	
Catalyzed Corning	5	348 [582]	153 (30)	1.7	4.2	1.7 (circled)	17.1

(1) Estimate

(2) Assumed .02% Fuel Sulphur for all tests (4.5 ppm total sulphur MTU Cycle, 5.9 ppm total sulphur MTU MOD 4). H_2SO_4 assumed 5% of total sulphur.

(3) For non-catalyzed systems H_2SO_4 assumed to be included in RCD.

[ ] - estimated because of suspect NO, NO_2 data.

(circled) - data taken from other appropriate data points in Table.

( ) - correction for reduced exhaust flow with EGR systems.

17. DISCUSSIONS AND CONCLUSIONS

As in many areas of research it has to be stressed that there are potentially significant differences between laboratory and field testing. This is particularly true with underground diesel emissions. This unique environment of cool temperature, high moisture, rock dust etc. is quite different from dilution tunnel conditions in the laboratory. Therefore there is concern over negative or positive phenomena which may affect the pollutants in the underground environment.

Sulphuric acid is a crucial pollutant because of its production by catalyzed control systems. Laboratory results show SO_2 to H_2SO_4 conversions to be a real problem. What however happens underground? One school of thought suggests that interactions of H_2SO_4 with water droplets may cause H_2SO_4 to be removed from the mine air. If this occurred to any great extent, catalyzed units would be much more viable than suggested by laboratory results. This would also impact on whether more costly low sulphur fuels would need to be used. Therefore it is critical that additional work be done in evaluating sulphur compounds in the mine environment.

Of course, there may also be factors affecting (negatively or positively) the other pollutants in the underground environment. So it is important that mine air monitoring in general be advanced, researched and understood.

In this report the AQI/EQI equations have been used to provide a means of comparing emission control systems. Although the validity of the equations can be debated it was felt that they do provide a reasonable measure for comparing relative system efficiencies.

Although not addressed in this program, the Ames Test has been used in parallel programs to clarify diesel soot's potential mutagenicity. In general, these other programs have found that the mutagenicity reduction is similar to the reduction in total particulate matter, except with precious metal catalyst coatings, where the mutagenicity reduction is significant but not as great, due to a more active soluble portion.

1. Of all the various approaches evaluated in the three phases of the program, systems utilizing Corning DPFs showed the greatest capability for improving exhaust quality. This was true for both steady state and transient engine operations. Corning DPF systems are also the least complex and most practical of all the systems for installation and operation. However, poor regeneration performance makes the systems impractical without the addition of fuel additives or the catalyzing of the DPFs.

2. The EGR/Corning DPF system was the best system as a result of its having the highest AQI improvement. This reflected the EGR benefits of reduced NO_x and reduced exhaust flow rate.

3. It was observed that some control systems can actually worsen the exhaust emissions. This is an important point in that a control system may decrease one pollutant but increase others so that the net effect is a negative control system. Applications of EGR alone is a prime example. However, it should also be re-emphasized here that potential differences exist between field testing and laboratory evaluation.

4. Mesh filters consisting of a fibreglass material knitted in a stainless steel mesh were successful in treating diesel exhaust. However they were impractical because of size, compaction problems and possible fibreglass fibre loss.

5. Water scrubbers were also effective in reducing diesel emissions. Due to complications of size and water supply however they too were considered impractical for on vehicle use.

6. It has already been established by engine test data that regeneration of the Corning DPF on the engine is possible at full load/speed condition. During a simulated mine cycle (MTU MOD 4) constant regeneration was accomplished using manganese based fuel additives and with the Engelhard catalyzed Corning DPF. These two techniques allow a Corning DPF system to operate continuously during an LHD cycle so that the system can be considered acceptable and practical for underground mines. The only drawbacks of these two regenerative systems are:

(i) the catalyzed Corning DPFs tested in this program have an SO_2-$SO_4^=$ conversion problem. Testing of improved catalyst formulations which do not seem to have this problem should be pursued as well as underground H_2SO_4 impact studies.

(ii) questions have been raised on the health effects of additives that pass through the DPFs. However recent preliminary tests have suggested the retention of fuel additive by the Corning Filter is very high.

7. Both the Corning DPF/fuel additive and catalyzed Corning DPF systems survived and regenerated successfully on board an LHD vehicle during routine operation at Kidd Creek Mine. Long term evaluations are still desirable but both systems look viable in the real world.

8. Additional work must still be done in two important areas:

   (i) improved regenerative systems must be developed for vehicles with lower exhaust temperatures. At this point only hotter running vehicles such as LHD vehicles can use the current regenerative systems.

   (ii) additional studies are a must in mine air monitoring. The correlation between laboratory and field emission results are unclear, especially for H_2SO_4.

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APPENDIX I

Analytical Instrumentation and Methodology.

1. STEADY STATE ANALYSIS

1.1 Particulate Testing

All steady state particulate tests were conducted using modified EPA Method 5 source sampling trains. With this system, a portion of the exhaust gas is drawn via a heated stainless steel sampling probe from the exhaust pipe through a pre-weighed 12.5 cm Pallflex, teflon coated filter. The filter is maintained at a temperature not less than 121^{o}C, to minimize moisture condensation on the filter. A nozzle connected to the sampling probe is directed upstream of, and parallel to the exhaust flow at a location approximately 8 exhaust duct diameters downstream of the nearest flow disturbance (i.e. elbow). After passing through the filter the sample gas is cooled in four impingers which are contained in an ice bath. The first two impingers contain approximately 125 ml of distilled water each, the third is dry and the fourth contains a known mass of silica gel. The cooled, dry sample gas is then passed through a calibrated dry gas meter for subsequent determination of the volume sampled.

Following each test the sampling equipment is disassembled and the probe rinsed with cyclohexane (cyclohexane/isopropyl alcohol 50% w/w for catalyst tests). Rinsings are collected in a jar for subsequent analysis. The filter is removed from its holder and stored in a glass petri dish and the filter holder rinsed with the appropriate solvent. All samples collected are then transferred to the laboratory for analysis.

Probe rinse solutions are filtered to remove the insoluble fraction and the filtrate evaporated to allow for the determination of the soluble fraction. Any residue remaining after evaporation is considered soluble particulate. The 12.5 cm sampling filter is allowed to condition for 24 hours and re-weighed to determine the total particulate material collected. Filters are then extracted for a minimum of 4 hours with water to remove sulphates in the case of tests performed with catalysts. With catalysts removed the cyclohexane extractions can begin immediately. Following the cyclohexane extraction which lasts for 4 hours, the filters are removed and transferred to the conditioning room where they are allowed to condition for 24 hours before re-weighing. The difference between the total weight and weight after extraction is considered to be soluble particulate material.

All pertinent data collected using the above method were used in a computer program to determine particulate soluble and insoluble concentrations (mg/m^3) and emission rates in g/kW-h, g/hr, g/kg of fuel.

1.2 Gaseous Emissions Testing

Testing for gaseous emissions included the measurement of CO, CO_2, O_2, NO, NO_2 and total hydrocarbons (THC as methane). A portion of the hot exhaust gas is drawn from the exhaust duct through a heated (180°C) stainless steel sample line. Prior to any sample gas cooling, a portion of the hot exhaust is sent to the THC analyzer. Critical components in this analyzer are maintained at approximately 190°C to minimize hydrocarbon condensation. This analyzer, therefore, displays concentrations on a 'wet' basis.

The following analyzers were used during the test program:

CO_2 - Horiba, Model A1A23, non-dispersive infra-red.

CO - Horiba, model AlA23AS, non-dispersive infra-red.

O_2 - Taylor Servomex, Model OA272, paramagnetic.

($NO + NO_2$)
NO_x - Thermo-Electron, Model 10A, chemiluminescent.

THC - Ratfisch IPM, Model RS5 heated flame ionization.

Following the THC analyzer, the sample gas is cooled in a condensing coil and the condensate removed. Sample gases are then filtered and sent to each analyzer using a stainless steel metal bellows pump. Flow rates to each analyzer are monitored and controlled using rotameters.

All analyzers are zeroed and calibrated for span prior to testing on a given day. Analyzer outputs are displayed on strip chart recorders for a hard copy of data. Following emissions testing, all pertinent information was entered into a computer program for calculation of concentrations and emission rates for each load/speed condition.

2. DYNAMIC DYNAMOMETER TEST CELL

The following sub-sections describe some of the equipment used in the facility.

2.1 Dynamometer

An Eaton Model AO-8121 eddy current dynamometer is used in test cell #5 to absorb the power generated by the engine. This dyno is a wet gap type capable of absorbing 373 kW at 5000 RPM and has an inertia of 46 lb. ft^2. Test cell #4 is equipped with a General Electric eddy current dynamometer. Torque is measured using a Lebow load cell connected to the trunnion mounted dynamometer casing. The dynamometer operation can be manually controlled in a speed or torque mode via a stand-alone dyno exitation controller. Dynamometer bearing lubrication is provided by gravity fed oil reservoirs. A Hayes-Dana driveshaft with rubber element absorption is used as a coupling between engine and dyno.

2.2 Computer Control System

The heart of the dynamic test facility lies in the computer control system. This system uses a Hewlett Packard 1000 series E computer with 128K of memory and is coupled with a HP disc drive unit. Input/output interface is performed with Computer Products I/O equipment.

All programs are stored on a HP 7900 disc unit with measured and calculated data displayed on the operator console. The console is also used for entering operation commands concerning the test cell. During automatic control the system reads engine speed and torque ten times per second and, if required, corrects via output signals ten times per second. The system has a programming capability for cycle testing known as the schedule builder. The schedule builder is based upon a series of steps. A step is a defined RPM, torque, ramp time, stay time, where ramp time is the length of time to change from one load speed condition to the next. Stay time is defined as the length of time to remain at a given load speed. The minimum ramp time is one second and the minimum stay time is zero seconds. Up to 198 steps are user definable, however, the system includes the capability of major and minor looping within a cycle.

3. HEAVY DUTY DIESEL EMISSIONS TEST FACILITY

The sampling and measurement of diesel exhaust emissions has presented many problems with respect to obtaining representative data that will correlate to conditions that occur in the underground mining environment. Chemical and physical reactions with certain species of diesel exhaust emissions take place after the exhaust has been released from the engine exhaust system. Specifically, particulate agglomeration in the soluble and insoluble form occur as the exhaust temperature is lowered to promote condensation of the soluble organic material. Formation of nitrogen dioxide (NO_2) from nitric acid (NO) is a characteristic reaction in diesel exhaust as often it is released from the exhaust system. These reactions have necessitated the need for a representative diesel exhaust sampling and analysis system. EPA has standardized such a system for engine certification procedures.

In an effort to keep abreast of these changes, ORF has installed and commissioned a heavy duty diesel emissions test facility. The primary purpose of this facility is the measurement of emissions from diesel engines which are part of the dynamic test facility. The facility is comprised of two major systems; the dilution tunnel system and the analytical system. The following sub-sections describe these systems.

3.1 Dilution Tunnel System

There are basically two types of dilution tunnels available for the sampling of diesel exhaust emissions. One uses a single dilution method, the other a double dilution. ORF has selected a double dilution tunnel from a flexibility and cost standpoint. With a double dilution system the primary air mover can be down-sized considerably to meet the temperature criteria necessary in designing such a system. The system comprises of three basic sections as described below.

3.1.1 Dilution Tunnel

The dilution tunnel consists of 25.4 cm inside diameter primary tunnel and a 10.2 cm inside diameter secondary tunnel. All tunnel components are fabricated of stainless steel. Engine exhaust enters the primary tunnel via an upstream facing 10.2 cm nozzle. Dilution air flows past the nozzle and the resultant counter-current flow enhances mixing of the exhaust with the air. The primary tunnel has been engineered to provide a Reynolds number of more than 4000 to provide sufficient turbulence of the diluted exhaust. A fine mesh screen prevents large foreign objects from entering the primary tunnel.

Three sample probes are located approximately 2.5 meters downstream of the exhaust inlet. The first probe is used to transfer a portion of the primary tunnel exhaust to the secondary tunnel. The second probe is used for sample transport to the heated hydrocarbon analyzer and the third probe is dedicated to the other gaseous analyzers. Maximum allowable primary tunnel gas temperature at the sample probes is 190^{o}C. A specially designed acoustic chamber was installed at the primary tunnel inlet to minimize engine exhaust and air mover noise in the vicinity of the test facility.

The secondary tunnel can be used to further dilute the sample from the primary tunnel to maintain a sample filter that will not exceed the maximum allowable 52^{o}C. Three sample filters and one bypass filter are connected to the outlet of the secondary tunnel. The filter holders accept 70 mm diameter filters (Pallflex T60A20) and produce a 60 mm diameter stain area.

Secondary, or back-up filters, are used to remove any particulate material that has passed the primary filter. Any one of the four filters can be selected manually or automatically from the particulate console. Automatic sequencing of the filter is achieved using computer activated relays or using a programmable sequence timer.

The particulate console, contains an air pump and protective filters for sampling diluted exhaust. A second pump is used to provide pre-filtered air to the secondary tunnel when further dilution is required. Mass flows of sample gas and secondary dilution air are measured and controlled using mass flow controllers (Tylan Model FC202). These controllers are state-of-the-art devices which continuously monitor and correct the mass flow to maintain a proportional sampling rate, regardless of gas temperature and pressure. Accumulated dilution and sample gas flows are displayed using integrators, one set for each of the sample filters. The particulate console also contains a temperature measuring device to allow for recording of a variety of temperature stations, especially the primary and secondary tunnel gas temperatures.

3.1.2 Heat Exchanger

According to EPA specifications, the primary tunnel gas temperature must be adjusted to 43^{o}C in order to provide constant gas density conditions to the primary air mover. In order to achieve a 147°C gas temperature drop, a tube and shell heat exchanger is located between the primary dilution tunnel and air mover. A 227 l pm water pump recirculates water through the shell side of the heat exchanger while primary tunnel exhaust gas is passed through the tube side.

During testing of duty cycles with high load factors, the primary tunnel gas temperature is well above 43°C. In these cases the heat exchanger is used solely to cool the gas and this is achieved by adding cold water to the recirculating water loop. Thermostatically controlled, air actuated, water valves allow water to enter the system and a check valve discharges an equal volume of warm water. A second heat exchanger which is steam heated can be used to raise the water temperature to 43°C (in the case of low load factor duty cycles).

3.1.3 Air Mover

The primary tunnel gas flow is normally maintained at 51.0 standard cubic meters per minute (SCMM) with a high capacity positive displacement blower. This blower is a roots type and uses a 22 kW electric motor as a drive. Excessive noise, characteristics of these blowers, is reduced using a Donaldson muffler.

3.2 Gas Analysis

The gas analysis system is comprised of a hydrocarbon console and a main analysis console. Filters, housed in the heated hydrocarbon console, are used to remove particulate matter from the sample gas stream. A Beckman, Model 402, heated hydrocarbon analyzer continuously measures gaseous hydrocarbons (as methane) at a temperature of 190^{o}C using a flame ionization detector. Background (ambient air) hydrocarbon concentrations are determined by sampling the dilution air at the primary tunnel. Concentrations of hydrocarbons in the dilution air are subtracted from the primary tunnel concentration to obtain hydrocarbon concentrations that are attributable to engine exhaust.

The main analysis console contains the NO, CO, CO_2 and heated NO_x analyzers. Four sample pumps are used to provide sample gas to the various analyzers. The following analyzers are used:

NO_x - Beckman Model 955 heated chemiluminescent analyzer

NO - Beckman Model 951A chemiluminescent analyzer

CO - Beckman Model 867 non-dispersive infra-red.

CO_2 - Beckman Model 864 non-dispersive infra-red.

CO_2 - Horiba Model AlA-21-AS non-dispersive infra-red.

Three calibration gases are used to span each analyzer for a given concentration range. These gases can be selected by push buttons on the main analysis console front panel. Strip chart recorders are used to display analyzer outputs on a continuous basis. Heated lines are used to keep the sample temperature well above the gas dewpoint to minimize losses due to condensation. A Hankinson dryer is used to remove sample gas moisture prior to the NO, CO and CO_2 analyzers. Air/water heat exchangers are used to remove sample gas moisture prior to the CO_2 analyzers.

Recent additions to the HP 1000 computer software now provide the capability of recording all gaseous emissions data for steady state and cycle testing. The computer provides a printout of gaseous pollutant mass emissions and exhaust flows and can average results over a transient engine operating cycle.

3.3 Particulate Analysis

The filters taken from the secondary dilution tunnel are conditioned for ≃ 12 hours and weighed. Then they are extracted for 8 hours using methylene chloride. After reconditioning the weight of the filter is taken. The difference between the total weight and the weight after extraction is the soluble particulate material. The remaining material is the insoluble fraction.

3.4 Sulphate Sampling and Analysis

Samples were taken using the controlled condensation method. This system allows for the quantitative collection of sulphate $SO_4^=$ and sulphur dioxide (SO_2) from hot exhaust gas streams. The sampling system withdraws diluted exhaust gas through a glass probe maintained at 250°C for raw exhaust and 100°C for diluted exhaust. Next the exhaust passes through a glass cooling coil maintained at 70°C. The sulphate fraction is removed by the coil. Sulphur dioxide is removed by a following set of impingers containing a 3% (V/V) hydrogen peroxide solution. Solutions are then reacted with barium chloride to form a barium sulphate suspension. The absorbance is measured with a spectrophotometer to determine the sulphur concentrations.

APPENDIX II

Mine Air Monitoring.

APPENDIX II

MINE AIR MONITORING

A mine air sampling station was placed in the upstream and downstream ventilation air of the LHD vehicle work area as shown in Figure 15.2. Each sampling station consisted of a Hi-volume sampler, three personnel sampling units and a CO_2 sampling system.

A GMWL-2000 high volume sampler capable of maintaining a sample flowrate of 1.75 m^3/min. was used as the primary air mover enabling collection of particulate matter on a 20 cm x 25 cm, 935 BJH glass fibre filter at each station.

Also used to collect airborne particulate samples at each station were three Dupont Constant Flow Model 2500A permissible air sampling pumps with an air flowrate of approximately 2 L/min. using a 37 cm. diameter GFC glass fibre filter as its filter medium.

An MSA portable permissible pump exhausting into a 115 L Tedlar bag at a flowrate of about 0.275 L/min. was used to collect a time weighted air sample for subsequent CO_2 analysis.

Similar Dupont permissible pumps with 37 cm diameter glass fibre filters and an MSA portable pump were installed on the LHD vehicle to collect particulate and CO_2 samples.

Portable tables were constructed at ORF on which the permissible pumps were placed. Each table consisted of two .37 m square pieces of 1.5 cm thick plywood with a 2 cm floor flange bolted in its centre. A piece of 25 cm steel pipe threaded at both ends and threaded into the two floor flanges connected the two pieces of plywood into a free standing table. Four ceiling flanges were bolted on to the top of the table and 30 cm of 1 cm threaded rod placed into these flanges. This threaded rod allowed the permissible pump to be attached to it and also allowed the personnel particulate filter to be placed (filter opening toward ground) approximately 30 cm above the permissible pump.

The CO_2 sampling pump was attached to the table similar to the permissible particulate sample pumps. A 3 mm Tygon tube connected the pump's exhaust to a Tedlar CO_2 sample bag. The sample bag hung vertically from the side of the table attached to the table with 41 mm binder clips for easy removal.

The high volume sampler orifice pressure was recorded at sampler start up and shutdown. The time was also recorded.

The mine air sampling equipment used in this project was assembled in a lunch room located on the 915 metre level. This allowed adequate AC power for daily recharging of the permissible pumps and a safe refuge for the equipment. The original test plan was to locate the equipment in the drift at the two sampling locations; upstream and downstream of the LHD vehicle work area and leave it there during the evening shifts.

Kidd Creek mining personnel recommended that the test equipment be placed in the 915 metre level lunch room on the completion of each day's testing. This would protect the instrumentation from being damaged by an unwary scooptram operator or rock blast shock wave. Their suggestion was accepted. On completion of each day's test, the equipment would be loaded into the LHD vehicle's bucket and transported to the lunchroom approximately 90 m away from the test area. All the LHD vehicle test equipment, chart recorder and personnel samplers were also disconnected from the vehicle at this time.

Each morning ORF personnel would prepare the test equipment for the day's testing. Filters would be installed in the high volume and personnel particulate samplers. New Tedlar CO_2 sample bags would be attached to their respective sampling pumps. The LHD vehicle would at this time locate itself in the drift outside the lunch room. The emission sampling equipment was loaded into its bucket to be delivered to the appropriate sampling location.

The two Soltec chart recorders, used for measuring RPM and exhaust gas temperature, were mounted on the vehicle along with personnel samplers and the CO_2 sampling system. The RPM tachometer drive and thermocouples were connected to the chart recorder.

The RPM tachometer drive was calibrated by setting the engine idle (580 RPM) to 10 chart units. This was followed by increasing the engine RPM to ensure that the RPM tachometer drive, thermocouples and chart recorders were operating properly. Upon completion of vehicle equipment checkout the LHD vehicle transported the equipment to the appropriate sampling locations in the drift.

Following completion of an initial LHD cycle the personnel and CO_2 samplers on board the LHD vehicle were started and the start time taken. The downstream station test equipment was initialized next and the start up time taken. The upstream air sampling test equipment was the last to be started and its start up time recorded.

It was originally assumed that four hours of continuous sampling time would be available for sample collection. Throughout the test problems occurred limiting the length of sample time from one hour to three hours. Surprisingly, the LHD vehicle operated without any mechanical breakdown through the three week test period. The mine mechanics had stated that an LHD vehicle could not operate for three weeks without breakdown.

The majority of the problems during testing were related to the accessibility of ore. Baseline tests were delayed for two days while ore was drilled and blasted in 7-71 stope. The size of ore was a large factor in obtaining a steady LHD cycle. With larger pieces of ore the LHD vehicle had to idle at the ore pass with a bucket load of ore waiting until the hole ram broke the ore into sizable chunks for passage down the ore pass.

During the mine air monitoring tests, engine RPM and exhaust temperature were recorded on a real time basis. A Rhul RPM digital to analog frequency converter sending unit was installed on the Wagner scooptram's Deutz F8L 714 engine's tachometer drive take off. A 3 mm diameter grounded K type thermocouple was installed in each exhaust manifold bank. The thermocouple millivolt signal was conditioned with an Omega universal thermocouple amplifier and linearizer with cold reference junction. Both RPM and temperature millivolt signals were recorded on two Soltec 2 pen strip chart recorders powered by the scooptram's 12 volt D.C. electrical system as shown in Figure 15.4.

Magnehelic pressure gauges (0-10 kPa) were installed above the scooptram driver's console and were used to monitor engine backpressure from each exhaust bank. Engine exhaust backpressures were only monitored at low and high idle RPM and with the operator's assistance while mucking.

The Soltec 2 pen strip chart recorders were mounted on the LHD vehicle with a removable plywood board with polyurethane foam as a shock absorber. Rubber tarpaulin straps connected to a dexion frame held the chart recorders firmly in place.

Permissible pumps were installed on the LHD vehicle to measure operator exposure particulate levels during vehicle operation. Three pumps were installed on a removable plywood board with foam padding as a shock absorber. Four ceiling flanges were bolted on to the plywood and 30 cm of threaded rod placed into these flanges. This threaded rod allowed the permissible pumps to be attached to the board and to allow support for the personnel particulate filters. Polyurethane foam was also used to isolate the pumps from LHD vehicle vibration.

The CO_2 Tedlar sample bag was attached onto the LHD vehicle with 41 mm binder clips. A 3 mm Tygon tube joined the exhaust of the CO_2 sample pump to the Tedlar bag inlet.

It was necessary to install all the equipment on the LHD vehicle in a way that would make it easily removeable. This was necessary because the equipment was removed from the LHD vehicle on completion of each test to allow the scooptram to be used on evening production shifts.

Sample Analysis

The Whatman 20 x 25 cm glass fibre filters were conditioned at a room temperature of 20 degrees C and relative humidity of 50% prior to weighing.

The filters were weighed on a Mettler microbalance and the total mass of particulate matter and filter recorded. The total particulate mass on the filter was determined by subtracting the total mass of the particulate matter and filter from the initial clean filter mass.

The filters were then extracted for 16 hours with dichloromethane (methylene chloride) solvent in a soxhlet extraction apparatus. The extracted dichloromethane solvent was evaporated to dryness in preweighed disposable aluminum weighing dishes. The total mass of the aluminum dish and organic residue was determined with a Mettler microbalance. The soluble organic mass can be determined by subtracting the initial mass of the preweighed aluminum dish from the aluminum dish and organic residue mass. The mass of the Hi-Volume filter after dichloromethane extraction was then determined. Filters were extracted again for 16 hours in the soxhlet extraction apparatus with isopropyl alcohol (IPA) as the solvent. This extraction removes sulphate present in the particulate matter. The masses of the filters after the IPA extraction were recorded and the volume of IPA solute used for extraction of each filter was recorded. A sample of the IPA was analyzed using a Dionex Ion chromatograph for determination of sulphate content. The NO_3 ion was also analyzed using the above procedure. Upon completion of these extractions all that remained on the filters was insoluble carbonaceous material from the diesel engine exhaust and inorganic particulate matter (ore dust).

It was decided that to determine the amount of carbon particulate matter on the glass fibre filter it would be necessary to subject them to a minimum temperature of 550 degrees C (the ignition temperature of carbon). A trial test using Test #1 Baseline high volume glass fibre filters from upstream and downstream sampling locations, plus three preweighed 20 x 25 cm blank glass fibre filters was attempted. The blank filters were necessary to determine the mass loss of an unused glass fibre filter when subjected to identical conditions.

The filters were placed inside a Limberg heavy duty Muffle furnace operated by a Pyr-O-Vane temperature controller. These filters were initially subjected to a temperature of 400 degrees C for 24 hours, removed and conditioned at 20 degrees C and 50% relative humidity (RH) for 24 hours, and the mass recorded again.

Filters were again placed in the Muffle furnace at a temperature of 550 degrees C for 24 hours, conditioned at 20 degrees C and 50% RH for a further 24 hours, and their mass recorded. The loss of carbonaceous particulate matter was calculated by subtracting the initial mass of the filter and particulate matter recorded before the 400 degrees C soak from the filter and particulate matter mass after the 550 degrees C combustion temperature and adding the average mass loss of the three blank filters.

On completion of the trial it was analyzed and a corrected insoluble carbonaceous material mass loss of 19.2 mg and 63.3 mg was recorded for the Test #1 Baseline high volume glass fibre filters from upstream and downstream emission sampling locations respectively.

The remaining high volume filters were then subjected to identical analysis procedures described since the trial test results appeared correct. Ten preweighed blank 20 x 25 cm glass fibre filters were used to determine average blank filter loss.

Particulate matter that remained on the filter following combustion was considered to be inorganic mine dust (non-combustible particulate matter). The total mass of non-combustible particulate matter was calculated by subtracting the initial filter mass before particulate matter collection from the final filter mass including non-combustible particulate matter and adding the average blank filter mass loss.

The personnel sampler filters were conditioned for 24 hours at 20 degrees C and 50% relative humidity before recording the mass of the filter and particulate matter. Total particulate matter on the filter was calculated by subtracting the initial filter mass from the mass of the filter and particulate matter. Since the mass gain was too low for further analysis to be complete (0.0 mg - 2.2 mg mass gain) only the total particulate mass was recorded.

Tedlar plastic bag samples of upstream and downstream ventilation air were analyzed for CO_2 concentrations. A Varian 2700 Gas Chromatograph using a 3.1 metre long x 3 mm diameter, stainless steel column filled with PoroPak 881-100 mesh was used for analysis. The gas chromatograph employed a 150 ma thermoconductivity detector using Helium gas as a carrier.

APPENDIX III

Durability Tests.

APPENDIX III

DURABILITY TESTS

Catalyzed DPFs

Upon completion of mine air monitoring with the DPF/fuel additive system on December 5, 1984 the diesel fuel and fuel additive was hand pumped from the LHD's fuel supply tank into the 1137L holding tank located in the 30-1 fuel bay. Purging of the LHD fuel tank insured that no fuel additive would be deposited on the catalyzed filters during their endurance trial. The LHD was then refuelled with diesel fuel and driven to the 853 metre level maintenance bay for installation of the catalyzed DPFs.

Both of the catalyzed DPFs were visually inspected for cracks in the ceramic and ceramic to metal interface. None was detected. The catalyzed DPFs were placed vertically on each exhaust bank and the engine hours (837.6) and engine backpressures recorded at engine idle (580 RPM) and engine high idle (2300 RPM) as shown in Table 15.5.

On December 20, 1984 ORF personnel arrived at Kidd Creek Mine to inspect the catalyzed DPFs and replace the two magnehelic exhaust backpressure gauges with two Orange pressure gauges. The Orange pressure gauge (0-2000 mm H_2O) is powered by a 12 volt DC source (LHD vehicle electrical system) and has the ability to illuminate a warning light when a preset engine exhaust backpressure is exceeded. The Orange pressure gauges were preset to 900 mm of water pressure; 100 mm H2O pressure below what ORF considered a safe exhaust backpressure.

ORF personnel ascertained that if an excessive engine backpressure alarm should occur the LHD vehicle could safely be operated until ORF technical staff arrived to analyze the problem.

The Orange pressure gauges were installed on the right hand side of the LHD vehicle operator. The position allowed for good visibility and also was out of the way of the LHD bucket controls.

Catalyzed DPFs were removed from the LHD vehicle and inspected for particulate breakthrough; none was detected. The engine exhaust outlet of the catalyzed DPFs contained a very small amount of light brown soot. Several Kidd Creek mining personnel were impressed by the cleanliness of the exhaust outlet. Both DPFs were reinstalled and engine hours (920.3) and engine exhaust backpressures recorded as indicated in Table 15.5.

On January 15, 1985 ORF personnel returned to the Kidd Creek Mine to remove and inspect the Catalyzed DPFs and to install standard DPFs for endurance testing with manganese fuel additive. It was decided to observe the LHD vehicle in its operation of mucking ore on the 1158 metre level and record the engine exhaust backpressures. Upon locating the scooptram it was noted that both Orange exhaust backpressure gauges were not functioning. The LHD was then returned to the 853 metre maintenance area for repair of the gauges.

On examination of the Orange pressure sensors it was noted that the left exhaust bank gauge had a large chip out of its glass face and a dent on the top of the gauge. The crack was repaired with a silicone adhesive. The right engine exhaust pressure gauge indicating needle had fallen below the metal zero rest post. Pressure exerted on this gauge would only push the needle hard against the post preventing it from indicating. This gauge was repaired by removing the front glass face and manually placing the pressure indicating dial from below the zero post to resting position above and on the post.

The left and right engine exhaust backpressure lines were disconnected and pressure applied. No pressure was indicated on the gauges. Both pressure snubbers were then removed from the Orange pressure gauges revealing significant amounts of diesel particulate matter in them. Exhaust backpressure lines were then reconnected to the Orange gauges without the snubbers and pressure again applied as before. The indicating needles moved freely with the applied pressure indicating that the snubbers were restricting the pressure lines. It was felt that cleaning the pressure snubbers was impractical so a 1.17 cm pipe coupling was inserted in the pressure lines to act as a pulsation damper.

During diagnosis of the pressure gauge problem it was also noted that when pressure in excess of the preset alarm pressure (900 mm H2O) occurred the alarm indicating light failed to illuminate. On further investigation it was discovered that the Orange pressure gauge 12 volt DC power supply was disconnected.

The power supply was repaired and pressure applied to the pressure gauges with the high pressure indicating lights illuminated for both gauges at the preset pressure of 900 mm H2O. Both exhaust backpressure lines were reconnected and the engine started.

The LHD vehicle was allowed to operate through afternoon and evening shifts allowing ORF personnel to observe the vehicle in operation the next day. On January 16, 1985 the scooptram was observed operating on the 1158 metre level with engine exhaust backpressures monitored at idle and high idle as indicated in Table 15.10.

The catalyzed DPFs were removed and visually inspected for particulate pass-through, none was detected. Mining personnel witnessed the cleanliness of the exhaust outlet of the catalyzed DPFs. The engine hours at removal were 1055.7. Both catalyzed filters were exposed to 251 hours operation in actual mining conditions at the Kidd Creek Mine.

<u>DPFs With Fuel Additive</u>

Upon completion of the catalyzed DPF endurance testing, the standard DPFs plus manganese fuel additive testing was initiated.

On January 16, 1985 the standard DPFs were visually examined for ceramic failure, none was detected. Filters were then mounted in a vertical position on each engine exhaust bank of the Wagner ST5 scooptram identical to the installation of the catalyzed DPFs. The fuel additive used in this test program was supplied by Lubrizol Corporation. Lubrizol identify the stock manganese as 8220 containing 40 mg of manganese per millilitre of stock additive. Treatment level of the diesel fuel for this endurance test was 40 mg Mn per litre of fuel. This treatment level was selected on the basis of the high duty cycle temperature and the expected ignition temperature of the soot with this treatment level.

Fuel additive was added to the LHD fuel tank at a concentration of 40 mg/L of fuel. The engine was started and engine hours (1055.7) and engine exhaust backpressures recorded at idle and high idle conditions as indicated in Table 15.6.

A 1137L fuel tank was installed at the 30-1 fuel bay for refuelling the LHD during the earlier tests. This tank was filled with diesel fuel and manganese fuel additive at a concentration of 40 mg/L of fuel added. A chart of fuel additive volume (mL) versus fuel volume (US gallons) was prepared enabling mine personnel to refill the tank and add the appropriate amount of fuel additive. The number of gallons of diesel fuel used could easily be determined by reading the electric fuel pump totalizer on the supply tank.

On February 19, 1985, Kidd Creek Mine maintenance personnel contacted ORF informing them about a problem of large amounts of black smoke being emitted from the right exhaust bank of the engine. From the conversation it was gathered that the "high" pressure indicating lights on the Orange pressure gauges had not illuminated and that the engine right exhaust backpressure was indicating zero.

ORF suggested that the LHD be driven up the access ramp from the 915 metre level to the 853 metre level to initiate filter regeneration if indeed the filters were plugged.

Kidd Creek personnel claimed that they had completed this procedure but the smoke started again after 5 minutes. ORF technical personnel questioned whether the engine was operating properly or perhaps overfuelling occurred. Kidd Creek personnel assured ORF that a tune up had just been completed with all fuel injectors having been replaced. When asked to remove the filter and observe the filter exhaust outlet it was revealed that this had been completed and the DPF exhaust outlet was black. Kidd Creek Mine personnel claimed that with the right filter removed and engine operating no smoke was observed from the right exhaust bank. However, when the filter was replaced the smoking effect continued. ORF technical personnel responded by travelling to the mine site.

The LHD vehicle was inspected in the 853 metre maintenance bay awaiting a new differential. Engine hours at this point were 1215. The engine was started resulting in emissions of white smoke from the right exhaust bank when the exhaust temperatures were increased by increasing engine RPM. The Orange pressure gauge was indicating normal engine exhaust backpressure on the left exhaust bank but 0.0 on the right bank. Once again the indicating needle on the pressure gauge had fallen below the 0 resting post. The gauge was repaired and engine exhaust backpressure monitored using both the Orange pressure gauges and a magnehelic pressure gauge. The right exhaust backpressure was slightly higher than the left and higher than the initial reading at the beginning of the endurance test. Results are shown in Table 15.6.

The right DPF was removed from the engine and the engine restarted. No smoke was observed with the DPF removed.

The DPF was visually examined for ceramic fatigue and none was observed. Exhaust outlet of the right DPF was light brown in colour; a normal appearance and not black as had been indicated. When questioned about the engine maintenance one of the mine engine mechanics explained a different sequence of events than was previously given.

The scooptram had originally undergone differential repair and it was decided that an engine tune up could be accomplished at the same time. All the fuel injectors had been replaced and it was noted that the scooptram engine exhaust was not emitting smoke at this time. The engine was placed back into service, however, a lack of communication resulted in the differential not being filled with oil. After approximately 3 hours of operation the differential malfunctioned.

The initial DPF, smoking problem was first noticed when climbing the access ramp to the maintenance bay from a lower mine level. With the scooptram in the shop it was decided that an inspection of the injectors should take place. Three injectors on the right side of the engine were found to be leaking and were replaced. ORF technical personnel diagnosed the problem to be a build-up of unburned diesel fuel in the right DPF caused from leaking injectors. It was felt that when the temperature of the DPF was increased by increasing engine speed, or by driving up the access ramp, the residual fuel would be burnt off the DPF creating white smoke. Removal of the unburned fuel from the filter required operation at increased temperatures for an extended period of time.

To remedy the problem the scooptram was driven from the 853 metre to the 792 metre level and back again. On returning to the maintenance bay it was observed that the right DPF had ceased to stop smoking. The engine exhaust backpressure was recorded at engine idle for both exhaust banks and it was noted that the right exhaust backpressure had decreased from 2.0 kPa to 0.4 kPa indicating that the particulate trap was clean. At this point it was then decided to halt the fuel additive endurance tests since 159 engine hours had been accumulated on the DPFs at the mine.

Both DPFs were found to be in good operating condition on completion of the test.