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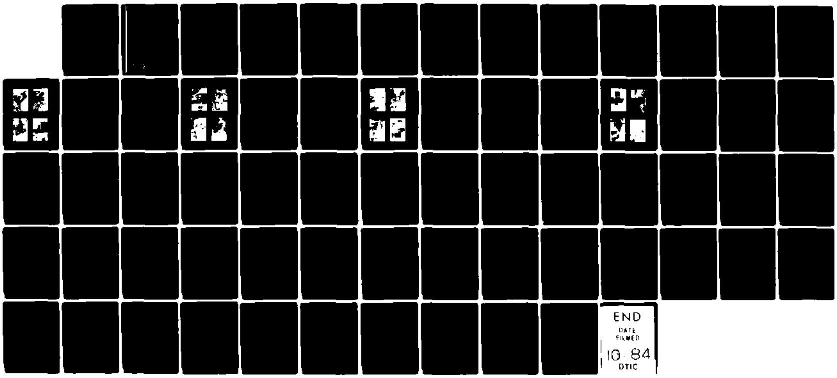

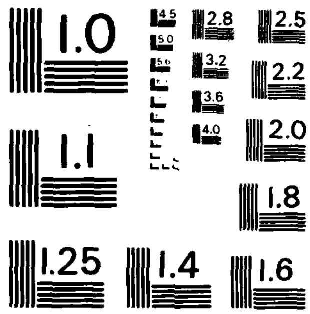


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# CLEAN-BURNING DIESEL ENGINES



## INTERIM REPORT
## AFLRL No. 169

By

**H. E. Dietzmann**
**Department of Emissions Research**
**Energy Systems Research Division**
**Southwest Research Institute**
**San Antonio, Texas**

Prepared for

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August 1983

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Gaseous and particulate emissions were measured from two diesel forklift engines under a variety of steady-state conditions. A MIL-F-46162A(MR) military referee grade fuel was used to determine CO, $CO_2$, $NO_x$, HC, particulate, sulfate, organic sulfides, phenols, DOAS odor, sulfur dioxide and aldehyde emission rates from a Deutz F3L 912W and a Perkins 4.203.2 diesel engine. Emission rates were reported in g/hp-hr, g/hr, and observed concentration, i.e., ppm, percent, or $g/m^3$.

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## FOREWORD

Work Directive 18, "Clean Burning Diesel Engines," was issued on September 13, 1982 under Contract DAAK70-82-C-0001 to the U. S. Army Mobility Equipment Research and Development Command (MERADCOM; currently the Belvoir Research and Development Center). The engineering and analytical efforts of this program were conducted by the Department of Emissions Research of Southwest Research Institute, 6220 Culebra Road, San Antonio, Texas 78284. This program was identified within Southwest Research Institute as Project 02-6800-175.

This project was under the overall supervision of Harry E. Dietzmann, manager of the Chemical Analysis Section. He was assisted by Dr. Lawrence R. Smith (chemical analysis) and Mr. Orville J. Davis (engine gaseous and particulate emissions). Emission testing was initiated in January 1983 and was completed in April 1983. Mr. Tim Lee of Belvoir Research and Development Center, STRBE-GMW, was the project technical officer, Mr. James Stephens served as the overall program manager, and Mr. M. E. LePera, Belvoir Research and Development Center, STRBE-VF, served as project coordinator.

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# I. INTRODUCTION

The U. S. Army currently uses electric forklifts in handling hazardous materials. Although these electric forklifts have certain inherent desirable characteristics, i.e., no pollution or noise, the logistics involved in field operations using electric forklifts has prompted the U. S. Army to investigate possible alternatives. One alternative is the diesel engine. The diesel engine has many advantages, i.e., mobility, cost, maintenance, but there is a major concern when these vehicles are used in areas with limited ventilation.

## A. Objective

The objective of this program was to obtain exhaust emission rates from two diesel engines used in forklift trucks. This emissions characterization was accomplished on engines provided by MERADCOM and included gaseous and particulate emissions of potential concern when these diesel forklift trucks are operated in confined areas such as ammunition storage igloos. The method used to evaluate these engines was the modal steady-state procedure used in the 13-mode Federal Test Procedure.(1)*

This project is the first step in defining the limits of acceptability for using diesel forklift trucks in areas of limited ventilation. The end use of these data will allow comparisons between engines; allow the Army to evaluate the emission rates versus Threshold Limit Values (TLV) from OSHA standards for the selected contaminants; identify and rank order contaminants from the engine in terms of priority of importance in worker health and well-being; and provide a data base from which a procurement specification for forklift diesel engines can be established.

## B. Scope

The two diesel forklift engines provided by MERADCOM for this study were a Deutz F3L 912W and a Perkins 4.203.2. The test fuel was a MIL-F-46162A(MR) provided

*Underscored numbers in parentheses designate references at the end of this report.

by the U. S. Army Fuels and Lubricants Research Laboratory (AFLRL) at Southwest Research Institute. Emissions characterization was accomplished on both engines over the test matrix presented in Table 1. Emission rates are reported in g/hp-hr, g/hr and observed concentrations, i.e., ppm, percent, or $\mu g/m^3$.

TABLE 1. TEST MATRIX FOR DEUTZ F3L 912W AND PERKINS 4.203.2 EMISSION RESULTS AND PROCEDURES

| Power, % Max hp at Speed | Engine Speed, rpm | | | |
|---|---|---|---|---|
| | Curb Idle | Intermediate | Peak Torque | Rated hp |
| 2 | I II III | I II III | I II III | I II III |
| 7 | NR | I | I | I |
| 12-1/2 | NR | I | I | I |
| 25 | I II | I II | I II | I II |
| 37-1/2 | NR | I | I | I |
| 50 | NR | I II III | I II III | I II III |
| 75 | NR | I | I | I |
| 100 | NR | I II III | I II III | I II III |

| Group | Emissions Measured/Included |
|---|---|
| I | HC, CO, $CO_2$, $NO_x(NO + NO_2)$, Smoke, 12 Test Conditions Group I alone |
| II | Particulates, Sulfates, and $SO_2$, 4 Test Conditions for Groups I and II |
| III | Aldehydes (includes Acrolein), Odor TIA by DOAS, Phenols, Organic Sulfides, 6 Test Conditions for Groups I, II, and III |

NR denotes Not Required

## II. DESCRIPTION OF FACILITIES, ENGINES, PROCEDURES

### A. Engine Description

This program involved emission mapping for gaseous, particulate, and unregulated emissions from two diesel engines that are candidates for use in forklift trucks to be used in handling hazardous materials. The two engines were made available for the entire duration of the program and were provided in new condition.

#### 1. Deutz Engine Description

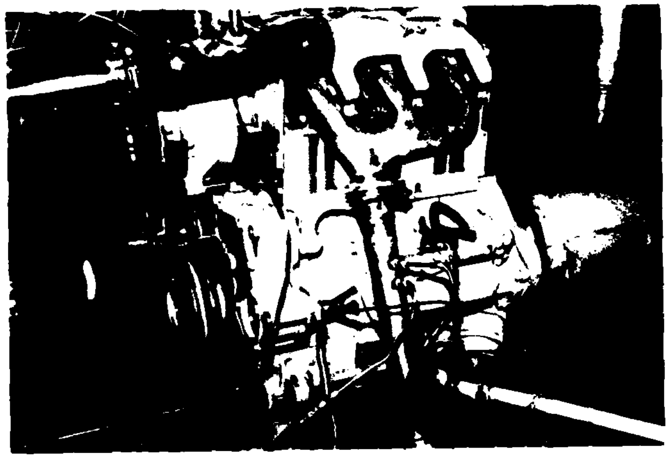
The first engine tested in this research effort was a three-cylinder, air-cooled Deutz F3L 912W. This engine is rated at 48 hp at 2650 rpm. A new test engine supplied by MERADCOM was delivered to Southwest Research Institute in December 1982. The engine was installed on the test stand, and an engine performance map was obtained. Results of the performance map indicated that there were apparent problems with the engine. Concerns over testing the engine were relayed to MERADCOM and Deutz technical and field service representatives. Deutz representatives concurred that the engine was not in satisfactory operation condition and that it was not appropriate to test that engine. The engine was shipped to Deutz (Atlanta) for diagnostics, and the results of the engine inspection were reported to the MERADCOM Project Officer.

A new replacement engine was provided by Deutz and was installed on the test stand. Results from the performance map on the replacement Deutz F3L 912W were satisfactory, although the engine produced 44 hp instead of the 48 hp at 2650 rpm. The 80-hour engine break-in and emission test program proceeded without incident until program completion. The engine "break-in" schedule is presented in Table 2. Several views of the Deutz F3L 912W on the test stand are illustrated in Figure 1. The engine performance data for the Deutz F3L 912W are presented in Table 3.

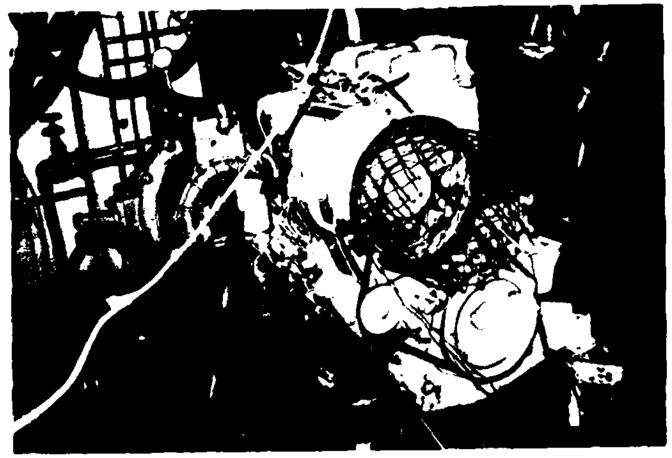
TABLE 2. ENGINE BREAK-IN SCHEDULE USED FOR DEUTZ F3L 912W AND PERKINS 4.203.2 (40-HOUR ENGINE SCHEDULE)

| Step | Time per Step | Total Time, hr | Deutz F3L 912W RPM | Deutz F3L 912W Load, lb | Perkins 4.203.2 RPM | Perkins 4.203.2 Load, lb |
|---|---|---|---|---|---|---|
| 1 | 0:30 | 0:30 | 800 | 15 | 800 | 18 |
| 2 | 0:30 | 1:00 | 1200 | 25 | 1200 | 30 |
| 3 | 1:00 | 2:00 | 1400 | 25 | 1400 | 30 |
| 4 | 1:00 | 3:00 | 1600 | 25 | 1600 | 30 |
| 5 | 1:00 | 4:00 | 1800 | 40 | 1800 | 48 |
| 6 | 1:00 | 5:00 | 2000 | 38 | 2000 | 45 |
| 7 | 7 hours cycling | 0:05 | 800 | 0 | -- | -- |
| | (Total time: | 0:25 | 1200 | 33 | 1200 | 40 |
| | 12:00 hours) | 0:05 | 800 | 0 | -- | -- |
| | | 0:25 | 1600 | 33 | 1600 | 40 |
| 8 | 8 hours cycling | 0:05 | 1200 | 0 | -- | -- |
| | (Total time: | 0:25 | 1800 | 48 | 1800 | 57 |
| | 20:00 hours) | 0:05 | 1200 | 0 | -- | -- |
| | | 0:25 | 2200 | 45 | 2200 | 54 |
| 9 | 10 hours cycling | 0:15 | 1200 | 41 | 1200 | 50 |
| | (Total time: | 0:15 | 1600 | 42 | 1600 | 50 |
| | 30:00 hours) | 0:15 | 1400 | 42 | 1400 | 52 |
| | | 0:15 | 1800 | 40 | 1800 | 48 |
| 10 | 10 hours cycling | 0:15 | 1600 | 50 | 1600 | 60 |
| | (Total time: | 0:15 | 2200 | 37 | 2200 | 45 |
| | 40:00 hours) | 0:15 | 2000 | 39 | 2000 | 45 |
| | | 0:15 | 2600 | 41 | 2400 | 53 |

General Comments: A Gulf 2D fuel (EM-409-F, tank 6) was used for engine break-in; Mobil Del Vac was the engine oil used. The 40-hour break-in was run twice on both engines to give 80 hours on each engine. Engine was stopped every 8 hours for oil check, belt tension check, etc. Engine oil was changed at 40 and 80 hours. Engine data recorded included air, fuel and oil temperatures, fuel rate, beam load, engine rpm, and time of day.

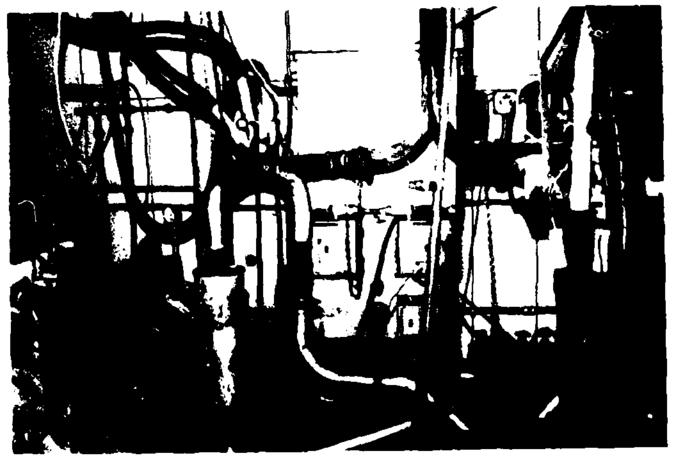


Port View of Deutz F3L 912W



Starboard View Deutz F3L 913

Control Console



Exhaust System

FIGURE 1. SEVERAL VIEWS OF THE DEUTZ F3L 912W ON THE TEST STAND

TABLE 3. DEUTZ F2L 912W ENGINE PERFORMANCE DATA

| Engine RPM | Dyno Load, lb | Engine, hp | Fuel Rate, lb/hr | Exhaust Temperature, °F(°C) |
|---|---|---|---|---|
| 1200 | 82.0 | 25.01 | 10.91 | 911(533) |
| 1400 | 83.0 | 29.05 | 11.92 | 1015(546) |
| 1600 | 83.5 | 33.40 | 14.00 | 1033(556) |
| 1800 | 80.0 | 36.00 | 14.60 | 1023(551) |
| 2000 | 77.7 | 38.85 | 15.96 | 1016(547) |
| 2200 | 74.2 | 40.81 | 17.17 | 1015(546) |
| 2400 | 71.4 | 42.84 | 18.30 | 1030(554) |
| 2600 | 67.5 | 43.88 | 19.93 | 1045(563) |
| 2650 | 64.8 | 42.93 | 20.01 | 1017(547) |

Idle Speed = 596 rpm
High Idle Speed = 2761 rpm

General Comments: Engine was run using air cleaner supplied by MERADCOM. Engine ran very good, no vibration from idle to high idle speed. No engine crankcase blowby was observed.

## 2. Perkins Engine Description

The second engine was a four-cylinder, water-cooled Perkins 4.203.2 diesel engine rated at 59 hp at 2500 rpm. The engine was run using the inlet and exhaust restrictions provided by the Perkins representatives. The 80-hour engine break-in on the Perkins 4.203.2 is presented in Table 2, and engine performance data are presented in Table 4. The engine was received in satisfactory operating condition and underwent the 80-hour engine break-in and emission test program without incident. The test engine produced 53 hp instead of the rated 59 hp at 2500 rpm. Figure 2 illustrates the Perkins 4.203.2 on the test stand. Both engines were tested without alternators.

TABLE 4. PERKINS 4.203.2 ENGINE PERFORMANCE DATA

| Engine RPM | Dyno Load, lb | Engine, hp | Fuel Rate, lb/hr | Exhaust Temperature, °F(°C) |
|---|---|---|---|---|
| 900 | 93.8 | 21.15 | 7.75 | 849(454) |
| 1100 | 98.3 | 27.03 | 10.20 | 905(485) |
| 1300 | 101.5 | 32.99 | 11.88 | 968(520) |
| 1500 | 103.5 | 38.81 | 13.60 | 993(534) |
| 1700 | 97.0 | 41.23 | 14.60 | 981(527) |
| 1900 | 92.5 | 43.94 | 16.62 | 989(532) |
| 2100 | 91.8 | 48.20 | 17.70 | 1021(549) |
| 2400 | 88.9 | 51.12 | 19.53 | 1058(570) |
| 2500 | 85.0 | 53.13 | 22.00 | 1190(643) |

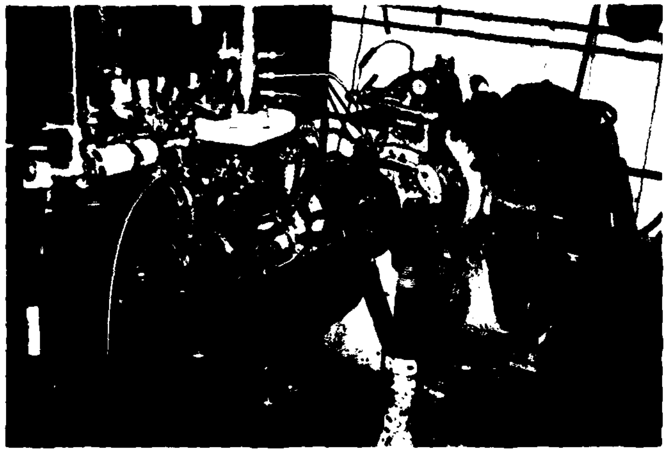
Idle Speed = 500 rpm
High Idle Speed = 2785 rpm

General Comments: No problems with engine installation, engine 80-hour break-in, or during emission testing.

B. Fuel Description

The original intent of this program provided for the emission testing to be conducted using a 1-percent sulfur MIL-F-46162B(ME) supplied by the U. S. Army Fuels and Lubricants Research Laboratory (AFLRL) at Southwest Research Institute. At the time testing was to begin, it was determined that AFLRL did not have any of the MIL-F-46162B(ME) nor were there immediate plans to obtain any. However, AFLRL did have MIL-F-46162A(MR). To have acquired the MIL-F-46162B(ME) fuel would have required several additional weeks.

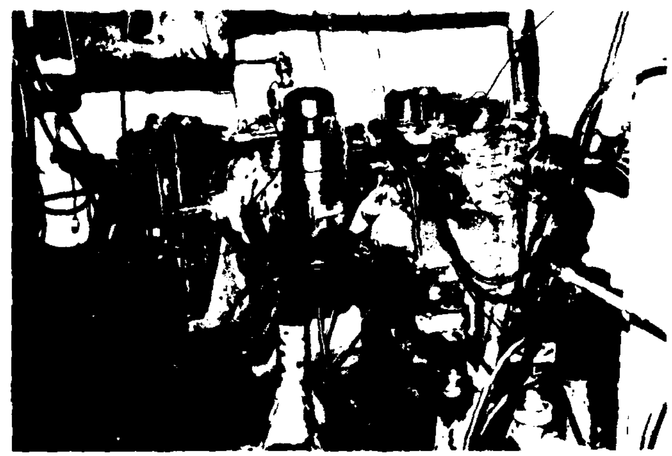
In reviewing the fuel specifications for sulfur content, it was apparent that the 1-percent sulfur level was three to four times higher than fuel sulfur in commercial or military fuels. In order to reach the 1-percent sulfur level, it would be necessary to add abnormally large amounts of tertiary butyl disulfide. With the interest in trace organic sulfides and diesel odor in the exhaust, it was recommended that



Port View of Perkins 4.203.2

Control Console

Intake Air Measurement System



Starboard View of Perkins 4.203.2

FIGURE 2. SEVERAL VIEWS OF THE PERKINS 4.203.2 ON THE TEST STAND

emission tests be conducted with a currently available referee grade fuel, namely MIL-F-46162A(MR). The MIL-F-46162A(MR) fuel specifications are similar if not identical in most aspects to the EPA D-2 emission certification fuel specifications. Table 5 summarizes the fuel specifications of MIL-F-46162A(MR), MIL-F-46162B (ME), and EPA D-2 certification fuel, as well as actual fuel analysis of the fuel used on this program.

Emission tests conducted on high-sulfur fuels (i.e., 1-percent sulfur) would probably produce proportionately higher sulfur dioxide and sulfate. The amount and nature of trace organic sulfides could be influenced by the specific sulfur additive if large quantities were added to increase the fuel sulfur, although no experimental data are available for confirmation. With concurrence of the Project Officer, all emission tests were conducted with MIL-F-46162A(MR) instead of the originally proposed MIL-F-46162B(ME).

## C. Dynamometer Description

A 250-hp Midwest wet gap eddy current dynamometer determined the load on the Deutz F3L 912W, and an adjacent 175-hp Midwest dry gap eddy current dynamometer measured the engine load on the Perkins 4.203.2. Fuel was measured using a Flotron. An 8-inch stainless steel dilution tunnel was used to collect particulate samples. All equipment was calibrated prior to testing using accepted applicable procedures, i.e., Federal Register, SAE, EPA Recommended Practice, etc. Several views of the test equipment are illustrated in Figure 3.

## D. Gaseous Emissions (Group I)

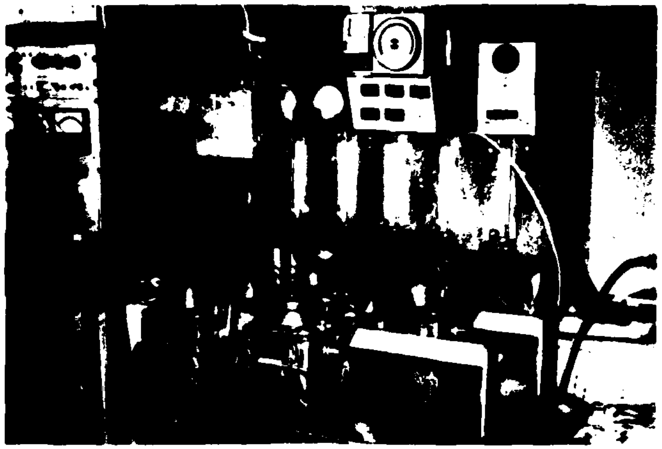
The measurement of gaseous emissions was accomplished using analytical equipment, procedures, and calculations specified in the Federal Register for 13-mode certification testing. The specific analytical instruments used in this study are listed in Table 6, and several views of this equipment are also illustrated in Figure 3. A flow schematic of the gaseous emissions instrumentation is shown in Figure 4.

One set of gaseous, particulate, and unregulated emissions instrumentation was used to obtain emissions data on this program. The proximity of the two test stands and the common exhaust allowed ready changing between the Deutz F3L 912W and the Perkins 4.203.2 engines.

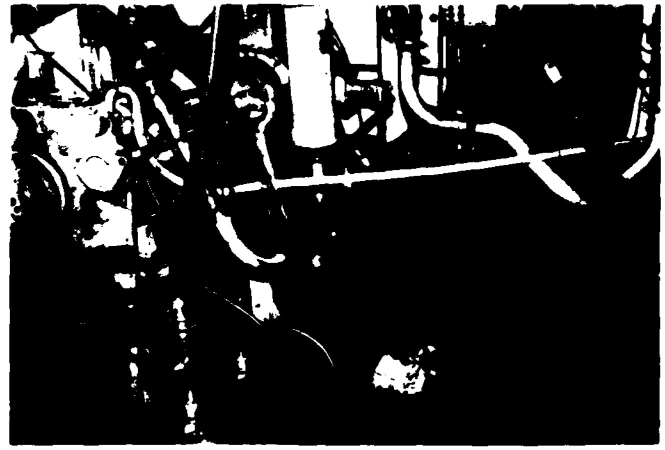
TABLE 5. COMPARISON OF TEST FUEL (AL-7225-F) to MIL-F-46162A(MR), MIL-F-46162B(ME), and EPA D-2 EMISSION SPECIFICATIONS

| | Fuel Specifications | | | Fuel Analysis |
|---|---|---|---|---|
| | MIL-F-46162A(MR) | MIL-F-46162B(ME) | EPA D-2 Emissions | AL-7225-F |
| Gravity, °API | 33-37 | NA | 33-37 | 36.1 |
| Density, g/mL | 0.84-0.85 | Report | NA | 0.844 |
| Flash Point, °C | >56 | Report | >49 | 60 |
| Cloud Point, °C | <-13 | ≤-13 | NA | -21 |
| Pour Point, °C | <-18 | ≤-18 | NA | -24 |
| Viscosity, cSt, @ 40°C | 2.2-3.2* | 1.9-4.1 | 2.0-3.2* | 2.2 |
| Distillation, °C | | | | |
| IBP | 171-204 | Report | 171-204 | 166 |
| 10% Recovered | 204-238 | Report | 204-238 | 219 |
| 50% Recovered | 243-282 | 245-285 | 243-282 | 244 |
| 90% Recovered | 288-321 | 330-357 | 288-321 | 296 |
| EBP | 304-349 | ≤385 | 304-349 | 358 |
| Carbon Residue (10% Bottom) | <0.20 | ≤0.20 | NA | 0.15 |
| Ash, wt% | <0.02 | 0.02 max | NA | 0.01 |
| Cu Strip Corrosion | Report | 1 max | NA | 1A |
| Acceleration Stability, mg/100 mL | 1.0 max | 1.5 max | NA | 0.60 |
| Neutral Number | ≤ 0.01 | < 0.2 | NA | 0.01 |
| Aromatics, vol% | ≥ 27.0 | Report | > 27.0 | 27.5 |
| Sulfur, % | 0.35-0.70 | 0.95-1.05 | 0.2-0.5 | 0.35 |
| Cetane Number | > 42 | 40-45 | 42-50 | 48 |

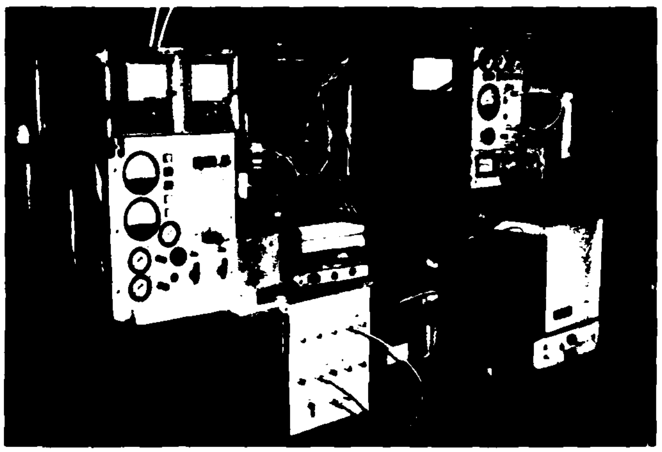
*Viscosity at 37.8°C(100°F)



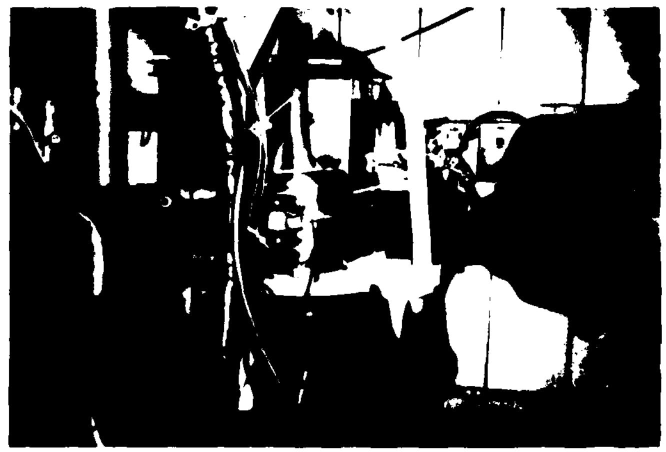
Particulate Sampling Controls



Dilution Tunnel



Gaseous Emissions Cart



Heated Interface

FIGURE 3. SEVERAL VIEWS OF GASEOUS AND PARTICULATE EMISSIONS INSTRUMENTATION

TABLE 6. LIST OF GROUP I EMISSION MEASUREMENT EQUIPMENT

| Exhaust Species | Chemical Symbol | Detection Technique | Instrument |
|---|---|---|---|
| Carbon Monoxide | CO | NDIR[a] | Beckman 315 |
| Carbon Dioxide | $CO_2$ | NDIR[a] | Beckman 315 |
| Oxides of Nitrogen | $NO_x$ | CL[b] | SwRI w/EPA Design |
| Hydrocarbons | HC | FID[c] | SwRI w/Beckman 402 Detector |
| Smoke | --- | Opacity | PHS Smokemeter |

[a]NDIR denotes nondispersive infrared

[b]CL denotes chemiluminescent analyzer

[c]FID denotes flame ionization detector

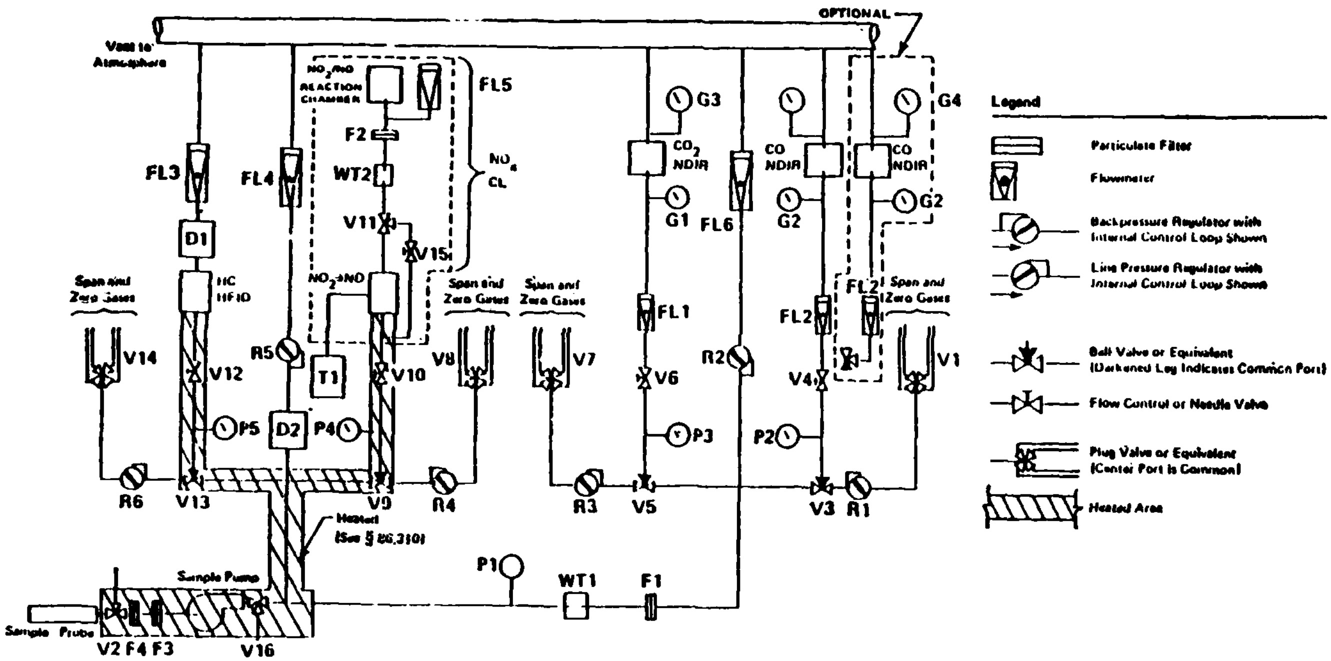



FIGURE 4. EXHAUST GAS SAMPLING AND ANALYTICAL TRAIN

## III. ANALYTICAL PROCEDURES FOR UNREGULATED EMISSIONS

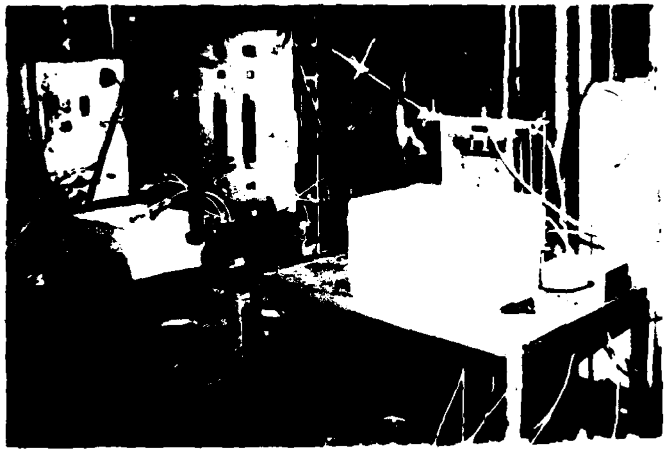
The analytical procedures used to measure the unregulated emissions are summarized in this section. Detailed descriptions of most of the procedures, along with discussions of their development, validation, and qualification, are available in Interim Report II, "Analytical Procedures for Characterizing Unregulated Pollutant Emissions From Motor Vehicles," developed in a related EPA project.(2,3) Several views of Group I, II, and III sampling systems are shown in Figure 5.

### A. Description of Analytical Procedures

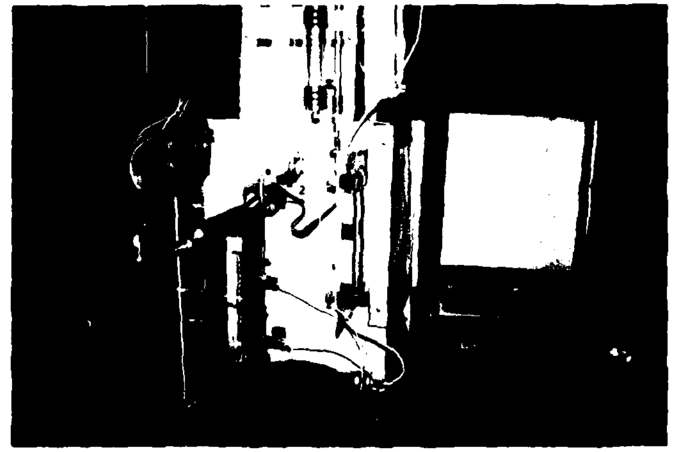
The unregulated emissions evaluated in this project, along with the methods for sampling and the procedures used in the analyses, are listed in Table 7. Aldehydes and ketones, organic sulfides, and phenols represent groups of compounds. The respective procedures separate and identify a number of individual components within each of these groups. The analytical procedures involved in this project are briefly described in the following subsections.

#### 1. Aldehydes and Ketones

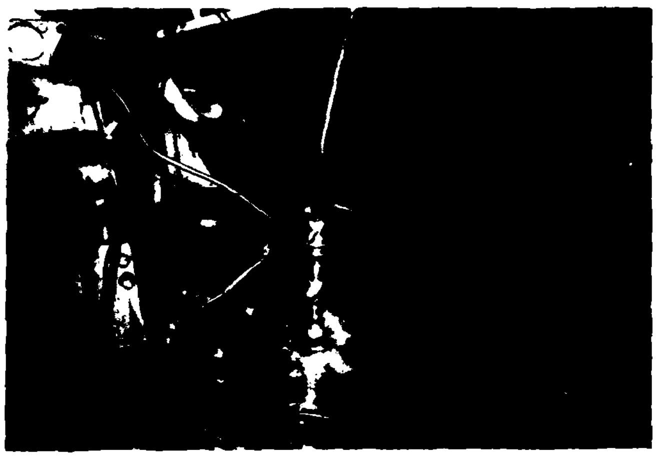
The collection of aldehydes (formaldehyde, acetaldehyde, acrolein, propionaldehyde, crotonaldehyde, isobutyraldehyde, benzaldehyde, and hexanaldehyde) and ketones (acetone and methylethylketone) is accomplished by bubbling exhaust through glass impingers containing 2,4 dinitrophenylhydrazine (DNPH) in dilute hydrochloric acid. The aldehydes and ketones (also known as carbonyl compounds) react with the DNPH to form their respective phenylhydrazone derivatives. These derivatives are insoluble or only slightly soluble in the DNPH/HCl solution and are removed by filtration followed by pentane extractions. The filtered precipitate and the pentane extracts are combined, and then the pentane is evaporated in a vacuum oven. The remaining dried extract contains the phenylhydrazone derivatives. The extract is dissolved in a quantitative volume of methanol, and a portion of this dissolved extract is injected into a liquid chromatograph and analyzed for several individual aldehydes and ketones using an ultraviolet detector.



Aldehydes and Phenols



DOAS Odor



Particulate/Sulfate

Organic Sulfides

FIGURE 5. SEVERAL VIEWS OF GROUP II AND III SAMPLING SYSTEMS
(USED WITH DEUTZ F3L 912W AND PERKINS 4.203.2)

TABLE 7. SAMPLING AND ANALYSIS METHODOLOGY FOR UNREGULATED EMISSIONS

| Compound | Sampling | Method of Analysis |
|---|---|---|
| Aldehydes and Ketones | Impinger | Dinitrophenylhydrazone derivative. Liquid chromatograph with ultraviolet detector (LC-UV) |
| Sulfur Dioxide | Impinger | Ion chromatograph |
| Carbonyl Sulfide (COS) and Organic Sulfides | Trap | Gas Chromatograph with flame photometric detector (GC-FPD) |
| Sulfate | 47-mm filter | Barium Chloranilate derivative (BCA). Liquid Chromatograph with ultraviolet detector (LC-UV) |
| Particulates | 47-mm filter | Weighed using microbalance |
| Phenols | Impinger | Gas Chromatograph with flame ionization detector (GC-FID) |
| DOAS | Trap | Liquid Chromatograph with ultraviolet detector (LC-UV) |

2. Sulfur Dioxide

The concentration of sulfur dioxide in exhaust is determined as sulfate using an ion chromatograph. Sulfur dioxide is collected and converted to sulfate by bubbling dilute exhaust through two glass impingers containing 3-percent hydrogen peroxide absorbing solution. The samples are analyzed on the ion chromatograph and compared to standards of known sulfate concentrations.

3. Carbonyl Sulfide and Organic Sulfides

The collection of carbonyl sulfide (COS) and the organic sulfides, methyl sulfide [dimethylsulfide $(CH_3)_2S$], ethyl sulfide [diethylsulfide $(C_2H_5)_2S$] and methyl disulfide [dimethyl disulfide $(CH_3)_2S_2$], is accomplished by passing exhaust through Tenax GC traps at -76°C. At this temperature, the traps remove the organic sulfides from the exhaust. The organic sulfides are thermally desorbed from the traps into a gas chromatograph sampling system and injected into a gas chromatograph equipped with a flame photometric detector for analysis. External organic sulfide standards generated from permeation tubes are used to quantify the results.

4. Sulfate

The exhaust is vented into a dilution tunnel where it is mixed with a stream of filtered room air. In the tunnel, the $SO_3$ reacts rapidly with water in the exhaust to form sulfuric acid aerosols. The aerosols grow to a filterable size range within the tunnel and are collected on a fluorocarbon membrane filter. Particulate sulfate salts are also collected on the filter.

Sulfuric acid collected on the filter is then converted to ammonium sulfate by exposure to ammonia vapor. The soluble sulfates are leached from a filter with a measured volume of an isopropyl alcohol-water solution (60 percent IPA). A fixed volume of the sample extract is injected into a high-pressure liquid chromatograph (HPLC) and pumped through a column of strong cation exchange resin in $Ag+$ form to scrub out the halides ($CL^-$, $Br^-$) and then through a column of strong cation exchange resin in $H^+$ form to scrub out the cations and convert the sulfate to sulfuric acid. Passage through a reactor column of barium chloranilate crystals precipitates out barium sulfate and releases the highly UV-absorbing chloranilate ions. The amount of chloranilate ions released is equivalent to the sulfate in the sample and is measured by a sensitive liquid chromatograph UV detector at 310-313 nanometers. All the reactions and measurement take place in a flowing stream of 60 percent IPA. The scrubber and reactor columns also function as efficient filter media for any solid reaction products formed during passage of the sample through the column system.

5. Particulate

The "particulate" is collected on 47-mm Pallflex filters. The amount of "particulate" collected is determined by weighing the filter on a microbalance before and after sampling.

### 6. Phenols

Phenols (phenol; salicylaldehyde; m-cresol/p-cresol; p-ethylphenol/2-isopropylphenol/2,3-xylenol/3,5-xylenol/2,4,6-trimethylphenol; 2,3,5-trimethylphenol; and 2,3,5,6-tetramethylphenol) in exhaust are sampled and quantitatively analyzed with a gas chromatograph (GC) equipped with a flame ionization detector. The exhaust is passed through two Greenburg-Smith impingers in series, each containing 200 mL of 1 N KOH chilled in an ice bath. The contents of each impinger are acidified and extracted with diethyl ether. The samples are partially concentrated, combined, and then further concentrated to about 1 mL. An internal standard is added, and the volume is adjusted to 2 mL. The final sample is analyzed by the use of a GC, and concentrations of individual phenols are determined by comparison to external and internal standards.

### 7. Diesel Odor Analysis System (DOAS)

The DOAS separates and measures the quantity of the odorous components present in a collected diesel exhaust sample eluted from an exhaust sampling trap charged with Chromosorb 102. The separation is achieved by liquid-column chromatography on a silica-type adsorbent, and the detection unit is a UV detector sensitive to 254-mm radiation.

## B. Accuracy of the Analytical Procedures

A difficult, but very important, endeavor was the determination of procedural accuracy for each analytical method. The primary difficulty involved those procedures in which the exhaust compounds are trapped or absorbed, an extraction or subsequent reaction is performed, and then a portion of the extraction is analyzed. The decision was reached to initially define the accuracy in terms of a "minimum detection value" (MDV). The MDV, as used in this report, is defined as the value above which it can be said that the compound has been detected in the exhaust (i.e., at a measured value equal to the MDV, the accuracy is equal to plus or minus the MDV). Determination of accuracy over the entire range of each procedure was beyond the scope of this project.

For compounds collected by bag samples, the MDV was determined from the instrument detection limits only, and is independent of the sampling rate and duration. For compounds which are concentrated in impingers or traps, the MDV is dependent on the instrument detection limit, chemical workup, sampling rate, and sampling duration. The MDV's listed in Table 8 were derived using the listed sampling rate and a 10-minute sampling period.

TABLE 8. UNREGULATED EMISSION PROCEDURAL SAMPLE RATES AND ACCURACY

| | Sample Flow, L/min | Procedural Minimum Detection Values | | MDV for 10 min SS Test, mg/hour |
|---|---|---|---|---|
| | | ppm | μg/m³ | |
| Aldehydes and Ketones | 4 | | | |
| Formaldehyde | | 0.01 | 15 | 2 |
| Acetaldehyde | | 0.01 | 20 | 2 |
| Acrolein | | 0.01 | 25 | 3 |
| Propionaldehyde | | 0.01 | 25 | 3 |
| Acetone | | 0.01 | 25 | 3 |
| Crotonaldehyde | | 0.01 | 30 | 3 |
| Isobutryaldehyde | | 0.01 | 30 | 3 |
| Methylethylketone | | 0.01 | 30 | 3 |
| Benzaldehyde | | 0.01 | 45 | 5 |
| Hexanaldehyde | | 0.01 | 40 | 5 |
| Sulfur Dioxide | 4 | 0.05 | 135 | 15 |
| Organic Sulfides | 0.13 | | | |
| Carbonyl Sulfide | | 0.001 | 3 | <1 |
| Methyl Sulfide | | 0.001 | 3 | <1 |
| Ethyl Sulfide | | 0.001 | 3 | <1 |
| Methyl Disulfide | | 0.001 | 5 | <1 |
| Sulfate | 14 | <0.01 | 6 | <1 |
| Particulate | 14 | ---- | <50 | <5 |
| Phenols | 14 | | | |
| Phenol | | 0.03 | 125 | 15 |
| Salicylaldehyde | | 0.03 | 150 | 15 |
| m-/p-cresol | | 0.02 | 100 | 10 |
| Five phenols* | | 0.02 | 250 | 30 |
| 2-n-Propylphenol | | 0.05 | 75 | 10 |
| 2,3,5-Trimethylphenol | | 0.01 | 50 | 5 |
| 2,3,5,6-Tetramethylphenol | | <0.01 | 25 | 5 |

*Includes sum of p-ethylphenol + 2-isopropylphenol + 2,3-xylenol + 3,5-xylenol + 2,4,6-trimethylphenol

## IV. RESULTS

This section presents the results of emission tests conducted on both engines for Group I (CO, $CO_2$, $NO_x$, HC, smoke), Group II (particulates, sulfur dioxide, sulfate), and Group III (organic sulfides, DOAS odor, phenols, and aldehydes).

### A. Group I--Emissions

Gaseous and smoke emissions were obtained at each engine load and speed in the test matrix shown in Table 1. The specific steady-state speed and load combinations were selected to represent the range of possible forklift operation and would serve to identify emission trends on both engines. Group I emission results for the Deutz F3L 912W are presented in Table 9, with brake specific emission rates being expressed in g/hp-hr and mass emissions (g/hr) as well as observed concentrations. Table 10 provides similar Group I emissions data from the Perkins 4.203.2 engine.

#### 1. 13-Mode Emission Results

The test matrix of this program included the steady-state test conditions of an EPA 13-mode emissions test. These data were processed to provide 13-mode emissions results for both engines, which provides a comparison of engines using a reference test procedure. The computer printout of the 13-mode emissions data is presented in the appendix. These data are summarized for both engines in Table 11. In reviewing the 13-mode results, the brake specific hydrocarbons (BSHC) for the Deutz F3L 912W was 0.454 g/hp-hr, BSCO was 1.627 g/hp-hr, and $BSNO_x$ emissions were 4.445 g/hp-hr. The Perkins 4.203.2 engine produced a BSHC of 3.215 g/hp-hr. The 13-mode EPA heavy-duty diesel engine emission standard is 1.5 g/hp-hr BSHC, 25 g/hp-hr BSCO, and 10 g/hp-hr $BSNO_x$ + BSHC. Other options involving trade-offs between BSHC and $BSNO_x$ are also available. Comparison of the Deutz F3L 912W and Perkins 4.203.2 engine emissions to the EPA standard is not suggested since these engines were not necessarily designed to meet the heavy-duty diesel engine standard.

TABLE 9. GASEOUS AND SMOKE (GROUP I) EMISSIONS FROM DEUTZ F3L 912W DIESEL ENGINE

| Test No. | Speed, rpm | Load, % | Fuel Consumption, lb/hr | Smoke Opacity | Emission Rate, g/hp-hr HC | Emission Rate, g/hp-hr CO | Emission Rate, g/hp-hr $NO_x$ | Emission Rate g/hr HC | Emission Rate g/hr CO | Emission Rate g/hr $NO_x$ | Raw Exhaust Concentration, ppm HC(1) | Raw Exhaust Concentration, ppm CO | Raw Exhaust Concentration, ppm $NO_x$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3-1 | 600 | 2 | 1.50 | 0.5 | 7.86 | 39.13 | 126.30 | 1 | 6 | 19 | 30 | 75 | 164 |
| 1 | 850 | 2 | 1.38 | 0.5 | 8.18 | 23.35 | 27.11 | 3 | 10 | 12 | 90 | 129 | 99 |
| 3-2 | 1100 | 2 | 1.98 | 1.0 | 5.14 | 14.79 | 29.50 | 2 | 8 | 16 | 60 | 87 | 114 |
| 3-3 | 1600 | 2 | 3.12 | 1.0 | 5.26 | 20.05 | 27.52 | 4 | 16 | 22 | 65 | 125 | 114 |
| 3-4 | 2650 | 2 | 6.00 | 1.0 | 19.75 | 86.05 | 46.36 | 13 | 57 | 31 | 160 | 356 | 129 |
| 2 | 850 | 7 | 1.68 | 0.5 | 3.96 | 8.10 | 11.32 | 5 | 10 | 14 | 130 | 134 | 124 |
| 1-1 | 1100 | 7 | 1.68 | 0.8 | 0.72 | 3.43 | 11.20 | 1 | 6 | 18 | 34 | 82 | 180 |
| 1-5 | 1600 | 7 | 3.30 | 1.0 | 1.59 | 5.86 | 13.10 | 4 | 14 | 31 | 58 | 108 | 160 |
| 1-9 | 2650 | 7 | 6.18 | 2.0 | 6.31 | 26.80 | 16.38 | 17 | 71 | 43 | 172 | 371 | 150 |
| 3 | 850 | 12.5 | 1.98 | 0.5 | 1.44 | 4.45 | 8.33 | 3 | 9 | 18 | 80 | 125 | 155 |
| 1-2 | 1100 | 12.5 | 1.98 | 0.8 | 0.48 | 2.11 | 8.28 | 1 | 6 | 23 | 37 | 82 | 215 |
| 1-6 | 1600 | 12.5 | 4.38 | 1.0 | 1.00 | 3.60 | 11.14 | 4 | 16 | 49 | 59 | 108 | 215 |
| 1-10 | 2650 | 12.5 | 6.78 | 1.5 | 2.62 | 12.37 | 9.51 | 14 | 66 | 50 | 142 | 342 | 175 |
| 2-1 | 600 | 25 | 1.80 | 0.5 | 0.24 | 1.56 | 9.04 | 1 | 4 | 23 | 24 | 79 | 293 |
| 4 | 850 | 25 | 2.70 | 0.5 | 0.43 | 1.83 | 5.65 | 2 | 8 | 25 | 48 | 104 | 208 |
| 2-2 | 1100 | 25 | 4.80 | 0.5 | 0.37 | 1.38 | 6.14 | 2 | 8 | 37 | 45 | 87 | 248 |
| 2-3 | 1600 | 25 | 6.00 | 1.0 | 0.39 | 1.59 | 7.88 | 3 | 13 | 66 | 45 | 95 | 293 |
| 2-4 | 2650 | 25 | 9.48 | 1.0 | 1.27 | 4.84 | 7.17 | 13 | 51 | 76 | 130 | 255 | 243 |
| 5 | 850 | 37.5 | 3.12 | 0.5 | 0.33 | 1.15 | 4.94 | 2 | 8 | 33 | 60 | 108 | 298 |
| 1-3 | 1100 | 37.5 | 3.78 | 0.8 | 0.20 | 0.61 | 4.69 | 2 | 5 | 40 | 42 | 65 | 330 |
| 1-7 | 1000 | 37.5 | 6.60 | 1.0 | 0.28 | 0.79 | 6.60 | 4 | 10 | 84 | 52 | 74 | 400 |
| 1-11 | 2650 | 37.5 | 11.92 | 2.1 | 0.87 | 3.43 | 6.02 | 14 | 54 | 96 | 117 | 239 | 270 |
| 3-5 | 1100 | 50 | 5.10 | 0.5 | 0.17 | 0.58 | 3.39 | 2 | 7 | 39 | 45 | 70 | 313 |
| 3-6 | 1600 | 50 | 7.80 | 0.5 | 0.20 | 0.42 | 4.56 | 3 | 7 | 79 | 50 | 54 | 387 |
| 3-7 | 2650 | 50 | 11.58 | 0.5 | 0.40 | 1.88 | 4.06 | 11 | 40 | 86 | 110 | 214 | 308 |
| 1-4 | 1100 | 75 | 7.20 | 0.8 | 0.13 | 0.33 | 4.25 | 2 | 6 | 72 | 48 | 65 | 545 |
| 1-8 | 1600 | 75 | 10.68 | 2.0 | 0.13 | 0.40 | 4.44 | 3 | 10 | 114 | 50 | 82 | 585 |
| 1-12 | 2650 | 75 | 15.00 | 2.5 | 0.36 | 1.08 | 4.49 | 11 | 34 | 140 | 113 | 177 | 470 |
| 3-8 | 1100 | 100 | 9.60 | 2.5 | 0.20 | 0.66 | 2.41 | 5 | 15 | 56 | 106 | 191 | 447 |
| 3-9 | 1600 | 100 | 13.80 | 2.0 | 0.14 | 0.55 | 2.33 | 5 | 19 | 79 | 72 | 151 | 402 |
| 3-10 | 2650 | 100 | 16.92 | 1.0 | 0.25 | 0.94 | 3.09 | 11 | 39 | 129 | 106 | 209 | 437 |

(1) Hydrocarbon concentrations reported in parts per million carbon (ppmC)

TABLE 10. GASEOUS AND SMOKE (GROUP I) EMISSIONS FROM PERKINS 4.203.2 ENGINE

| Test No. | Speed, rpm | Load, % | Fuel Consumption, lb/hr | Smoke Opacity | Emission Rate, g/hp-hr HC | Emission Rate, g/hp-hr CO | Emission Rate, g/hp-hr $NO_x$ | Emission Rate, g/hr HC | Emission Rate, g/hr CO | Emission Rate, g/hr $NO_x$ | Raw Exhaust Concentration, ppm HC(1) | Raw Exhaust Concentration, ppm CO | Raw Exhaust Concentration, ppm $NO_x$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3-1 | 500 | 2 | 0.72 | 0.5 | 106.28 | 80.52 | 61.90 | 13 | 10 | 8 | 720 | 274 | 146 |
| 1 | 750 | 2 | 1.02 | 0.5 | 61.89 | 65.38 | 28.65 | 23 | 25 | 11 | 824 | 437 | 128 |
| 3-2 | 1000 | 2 | 1.50 | 1.0 | 67.31 | 82.38 | 55.48 | 34 | 41 | 28 | 896 | 552 | 230 |
| 3-5 | 1500 | 2 | 3.00 | 0.5 | 68.76 | 118.45 | 55.43 | 52 | 89 | 42 | 720 | 624 | 195 |
| 3-8 | 2500 | 2 | 5.82 | 3.0 | 73.00 | 212.93 | 43.02 | 91 | 266 | 54 | 912 | 1348 | 167 |
| 2 | 750 | 7 | 1.62 | 0.5 | 33.34 | 29.10 | 15.98 | 38 | 33 | 18 | 1040 | 457 | 168 |
| 1-1 | 1000 | 7 | 1.92 | 1.0 | 13.71 | 20.97 | 18.38 | 24 | 37 | 32 | 560 | 431 | 261 |
| 1-5 | 1500 | 7 | 3.42 | 0.5 | 15.53 | 30.70 | 19.16 | 41 | 81 | 50 | 560 | 558 | 234 |
| 1-9 | 2500 | 7 | 6.00 | 0.5 | 17.23 | 55.14 | 16.55 | 65 | 207 | 62 | 648 | 1051 | 207 |
| 3 | 750 | 12.5 | 1.92 | 0.5 | 18.98 | 14.00 | 8.95 | 43 | 31 | 20 | 1200 | 447 | 195 |
| 1-2 | 1000 | 12.5 | 2.28 | 0.7 | 9.07 | 10.12 | 11.80 | 27 | 30 | 35 | 640 | 361 | 290 |
| 1-6 | 1500 | 12.5 | 4.32 | 1.0 | 8.12 | 13.96 | 12.36 | 46 | 70 | 70 | 616 | 536 | 313 |
| 1-10 | 2500 | 12.5 | 7.38 | 0.5 | 10.09 | 30.04 | 13.51 | 69 | 207 | 93 | 640 | 970 | 276 |
| 2-1 | 500 | 25 | 0.60 | 1.0 | 121.96 | 78.02 | 48.32 | 15 | 10 | 6 | 928 | 298 | 131 |
| 4 | 750 | 25 | 2.52 | 1.5 | 10.45 | 6.19 | 6.17 | 45 | 27 | 27 | 1280 | 386 | 258 |
| 2-2 | 1000 | 25 | 3.72 | 1.2 | 7.66 | 7.00 | 10.52 | 48 | 44 | 66 | 960 | 447 | 432 |
| 2-3 | 1500 | 25 | 5.58 | 0.5 | 7.19 | 7.24 | 10.42 | 70 | 71 | 102 | 960 | 494 | 447 |
| 2-4 | 2500 | 25 | 9.48 | 0.5 | 9.21 | 13.45 | 7.14 | 115 | 168 | 89 | 1104 | 828 | 273 |
| 5 | 705 | 37.5 | 3.12 | 1.5 | 5.98 | 3.35 | 5.43 | 39 | 22 | 36 | 1104 | 317 | 348 |
| 1-3 | 1000 | 37.5 | 4.38 | 1.0 | 2.99 | 2.35 | 6.61 | 29 | 23 | 64 | 664 | 269 | 507 |
| 1-7 | 1500 | 37.5 | 7.62 | 2.0 | 3.08 | 3.57 | 7.90 | 48 | 56 | 125 | 612 | 366 | 531 |
| 1-11 | 2500 | 37.5 | 10.98 | 0.5 | 3.45 | 6.98 | 7.08 | 67 | 135 | 137 | 604 | 630 | 402 |
| 3-3 | 1000 | 50 | 5.70 | 3.0 | 3.46 | 2.40 | 7.76 | 45 | 31 | 101 | 936 | 337 | 685 |
| 3-6 | 1500 | 50 | 8.40 | 1.0 | 2.69 | 2.56 | 7.44 | 52 | 50 | 145 | 728 | 361 | 675 |
| 3-9 | 2500 | 50 | 13.20 | 0.5 | 3.04 | 6.56 | 3.56 | 76 | 164 | 89 | 704 | 790 | 273 |
| 1-4 | 1000 | 75 | 7.98 | 1.5 | 1.47 | 0.88 | 6.23 | 28 | 17 | 118 | 608 | 195 | 904 |
| 1-8 | 1500 | 75 | 12.00 | 2.0 | 1.37 | 1.31 | 5.84 | 41 | 39 | 173 | 540 | 274 | 785 |
| 1-12 | 2500 | 75 | 18.00 | 0.5 | 1.68 | 2.65 | 3.38 | 65 | 103 | 131 | 592 | 494 | 402 |
| 3-4 | 1000 | 100 | 9.72 | 7.5 | 1.45 | 2.12 | 7.54 | 35 | 51 | 183 | 776 | 613 | 1380 |
| 3-7 | 1500 | 100 | 14.40 | 2.0 | 1.23 | 1.11 | 5.06 | 45 | 41 | 186 | 620 | 303 | 859 |
| 3-10 | 2500 | 100 | 20.52 | 1.5 | 1.04 | 3.28 | 3.16 | 48 | 152 | 146 | 464 | 790 | 482 |

(1) Hydrocarbon concentrations reported in parts per million carbon (ppmC)

TABLE 11. SUMMARY OF 13-MODE GASEOUS EMISSIONS DATA, g/hp-hr

| | | | Brake Specific Emission Rates, g/hp-hr | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Deutz F3L 912W | | | Perkins 4.203.2 | | |
| Mode | Engine Load, % | Engine Speed, rpm | HC | CO | $NO_x$ | HC | CO | $NO_x$ |
| 1 | --- | Idle | --- | --- | --- | --- | --- | --- |
| 2 | 2 | Peak-Torque | 5.26 | 20.05 | 27.52 | 68.76 | 118.45 | 55.43 |
| 3 | 25 | Peak-Torque | 0.39 | 1.59 | 7.88 | 7.19 | 7.24 | 10.42 |
| 4 | 50 | Peak-Torque | 0.20 | 0.42 | 4.56 | 2.69 | 2.56 | 7.44 |
| 5 | 75 | Peak-Torque | 0.13 | 0.40 | 4.44 | 1.37 | 1.31 | 5.84 |
| 6 | 100 | Peak-Torque | 0.14 | 0.55 | 2.33 | 1.23 | 1.11 | 5.06 |
| 7 | --- | Idle | --- | --- | --- | --- | --- | --- |
| 8 | 100 | Rated | 0.25 | 0.94 | 3.09 | 1.04 | 3.28 | 3.16 |
| 9 | 75 | Rated | 0.36 | 1.08 | 4.49 | 1.68 | 2.65 | 3.38 |
| 10 | 50 | Rated | 0.50 | 1.88 | 4.06 | 3.04 | 6.56 | 3.56 |
| 11 | 25 | Rated | 1.27 | 4.84 | 7.17 | 9.21 | 13.45 | 7.14 |
| 12 | 2 | Rated | 19.73 | 86.05 | 46.47 | 73.00 | 212.93 | 43.02 |
| 13 | --- | Idle | --- | --- | --- | --- | --- | --- |

Cycle Composite Using 13-Mode Weight Factors

| | | Deutz F3L 912W | Perkins 4.203.2 |
|---|---|---|---|
| BSHC | = | 0.454 | 3.215 |
| BSCO | = | 1.627 | 5.438 |
| $BSNO_x$ | = | 4.445 | 5.361 |

The 13-mode data presented represents engine operation under steady-state operation and may not reflect the emissions due to heavy repeated accel/decel modes of operation characteristic of typical forklift operation. Previous experience indicated that steady-state tests do not typically predict transient emission rates. This is confirmed by EPA developing a transient cycle for heavy-duty engine certification to replace the 13-mode.

## 2. Emission Trends

The variety of engine speed and load combinations provided an opportunity to determine the effect of engine load on brake specific emission rates at peak torque and rated speeds for both engines. The effects of engine load on BSHC, BSCO, and $BSNO_x$ emission rates at 1600 rpm (peak torque) and 2650 rpm (rated) for the Deutz

F3L 912W are illustrated in Figure 6. BSHC emissions were less than 0.4 g/hp-hr at 25 percent or greater load at 1600 rpm, but increased dramatically to 5.3 g/hp-hr at 2 percent load. The BSHC emission rates at 2650 rpm were somewhat higher (1.27 g/hp at 25 percent load), increasing to 20 g/hp-hr at 2 percent load. Mass emission rates for hydrocarbons ranged from 11-17 g/hr over the entire range of loads at 2650 rpm. The HC g/hr emission rate at 1600 rpm varied from 3-5 g/hr over the range of loads. At 2650 rpm, HC raw exhaust concentrations ranged from 106 ppmC to 172 ppmC, while HC exhaust concentrations ranged from 45-72 ppmC at 1600 rpm.

The effect of engine load on BSCO emissions is shown in Figure 6. The BSCO emissions at 2650 rpm were less than 5 g/hp-hr at 25 percent or greater load, but increased significantly to 86 g/hp-hr at 2 percent load. BSCO emissions at 1600 rpm for the Deutz F3L 912W followed similar trends, i.e., the BSCO at 25 percent or greater load was less than 2 g/hp-hr but increased to 20 g/hp-hr at 2 percent load. Mass CO emission rates ranged from 34-71 g/hr at 2650 rpm as compared to 7-19 g/hr at 1600 rpm. The CO concentrations for the Deutz F3L 912W ranged from 177-371 ppm at 2650 rpm. At 1600 rpm, the CO concentrations varied from 54-151 ppm.

Figure 6 also illustrates the effect of engine load on $BSNO_x$ emission rates from the Deutz F3L 912W. The general emission trends observed with CO and HC were also observed with $NO_x$, i.e., relatively low $BSNO_x$ at 25 percent or greater load (7 g/hp-hr), escalating to 46 g/hp-hr at 2 percent load at 2650 rpm. At 1600 rpm, this increase was not quite so dramatic where the $BSNO_x$ went from 8 g/hp-hr at 25 percent or greater loads to 28 g/hp-hr at 2 percent load. Mass $NO_x$ emission rates ranged from 31-140 g/hr at 2650 rpm to 22-114 g/hr at 1600 rpm. $NO_x$ concentrations ranged from 129-470 ppm $NO_x$ at 2650 ppm as compared to 114-585 ppm $NO_x$ at 1600 rpm.

A summary of the range of emissions reported for the Deutz F3L 912W over the entire test matrix is presented in Table 12. This table includes the three primary methods of expressing emissions, g/hp-hr, g/hr, and ppm. Smoke opacity ranges are also included for reference.

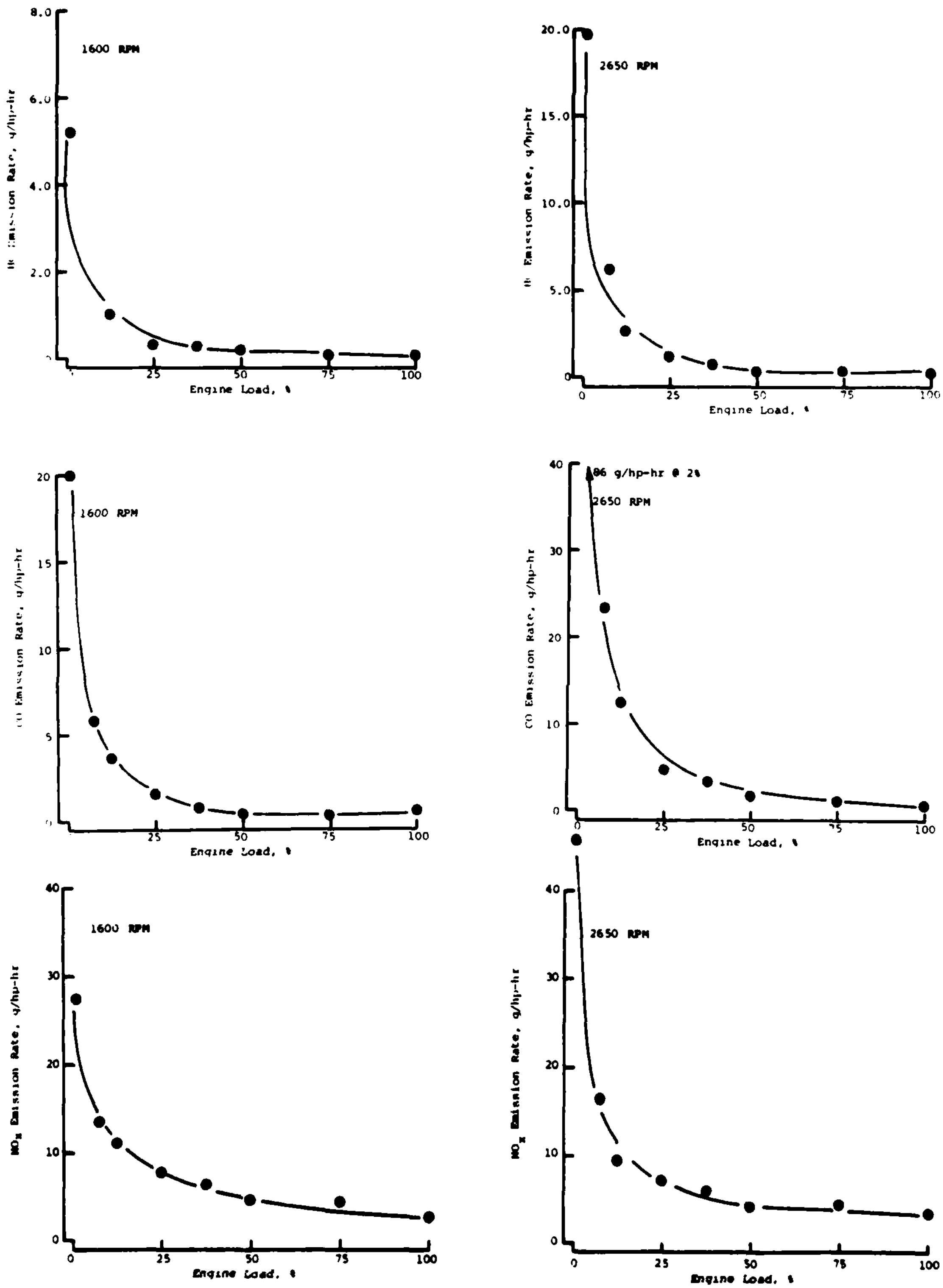



FIGURE 6. THE EFFECT OF ENGINE LOAD ON HYDROCARBONS, CARBON MONOXIDE AND OXIDES ON NITROGEN EMISSION RATES FROM A DEUTZ F3L 912W AT TWO ENGINE SPEEDS

TABLE 12. SUMMARY OF EMISSION RATES AND CONCENTRATION MINIMUM AND MAXIMUM VALUES FOR THE DEUTZ F3L 912W AND PERKINS 4.203.2 OVER COMPLETE TEST MATRIX

| Exhaust Species | Emission Rate/Conc. | Deutz F3L 912W | | Perkins 4.203.2 | |
|---|---|---|---|---|---|
| | | Minimum | Maximum | Minimum | Maximum |
| HC | g/hp-hr | 0.13 | 19.75 | 1.04 | 122 |
| | g/hr | 2 | 17 | 13 | 115 |
| | ppmC | 24 | 172 | 464 | 1280 |
| CO | g/hp-hr | 0.33 | 86.05 | 0.88 | 213 |
| | g/hr | 4 | 71 | 10 | 266 |
| | ppm | 54 | 371 | 195 | 1348 |
| $NO_x$ | g/hp-hr | 2.33 | 126.30 | 3.16 | 61.90 |
| | g/hr | 12 | 140 | 6 | 186 |
| | ppm | 99 | 585 | 128 | 1380 |
| Smoke | opacity | 0.5 | 2.5 | 0.5 | 7.5 |

The effect of engine load on BSHC, BSCO, and $BSNO_x$ emissions for the Perkins 4.203.2 is illustrated in Figure 7. The BSHC emissions increased from 7-8 g/hp-hr at 25 percent load to 69 and 73 g/hp-hr at 1500 rpm and 2500 rpm, respectively. Mass HC emissions ranged from 48-115 g/hr at 3500 rpm and from 41-70 g/hr at 1500 rpm. Observed HC concentrations varied from 464-1104 ppm at 2500 rpm to 540-960 ppm at 1500 rpm.

Figure 7 also illustrates the effect of engine load on BSCO emission rates from the Perkins 4.203.2 engine. The BSCO emission rate was less than 14 g/hr at 25 percent or greater load but increased substantially to 213 g/hp-hr at 2 percent load at 2500 rpm. At 1500 rpm, the BSCO emissions were less than 8 g/hp-hr at 25 percent and greater engine loads and increased to 118 g/hp-hr at 2 percent load. The CO mass emission rates ranged from 103-266 g/hr at 2500 rpm as compared to 39-89 g/hr at 1500 rpm. Raw CO exhaust concentrations varied from 494-1348 ppm at 2500 rpm and 274-624 ppm at 1500 rpm.

$BSNO_x$ emission trends from the Perkins 4.203.2 are also presented in Figure 7. At 2500 $BSNO_x$, emission rates were less than 7 g/hp-hr at 25 percent or greater loads and increased to 43 g/hp-hr at 2 percent load. The $NO_x$ mass emission rates ranged

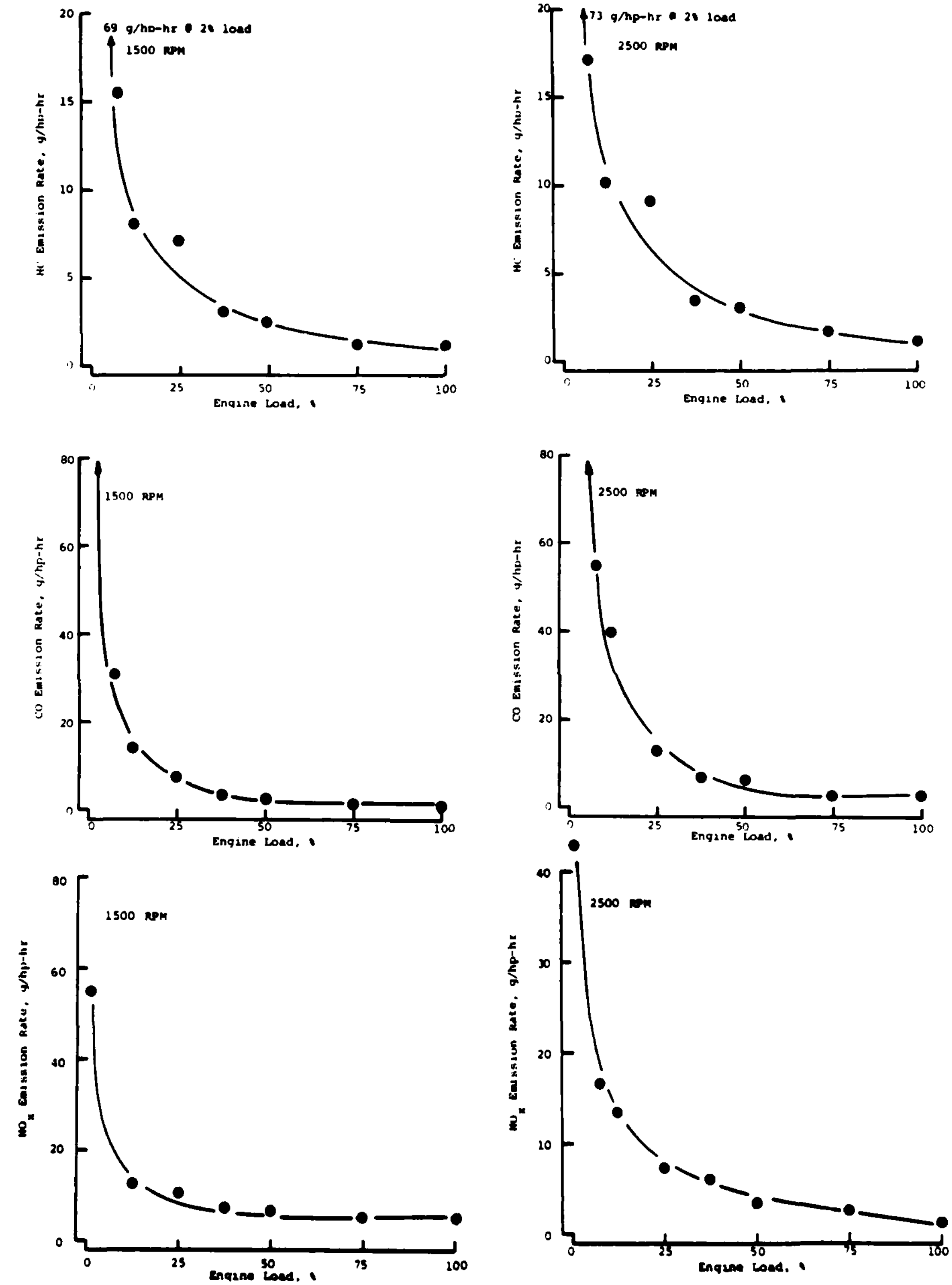



FIGURE 7. THE EFFECT OF ENGINE LOAD ON HYDROCARBONS, CARBON MONOXIDE AND OXIDES OF NITROGEN EMISSION RATES FROM A PERKINS 4.203.2 AT TWO ENGINE SPEEDS

from 54-146 g/hr at 2500 rpm and 42-186 g/hr at 1500 rpm. Raw $NO_x$ exhaust concentrations for the Perkins 4.203.2 ranged from 167-482 ppm $NO_x$ at 2500 rpm and from 195-859 ppm $NO_x$ at 1500 rpm. Table 12 summarizes the minimum and maximum emission rates (g/hp-hr and g/hr), ppm concentrations, and smoke opacity for the Perkins 4.203.2 engine for all modes tested.

## B. Group II Emissions

Specific analyses included in the Group II analyses were particulates, sulfur dioxide, and sulfate. These emissions were collected at four engine speeds (idle, intermediate, peak torque, and rated) at 2- and 25-percent load and three engine speeds (intermediate, peak torque, and rated) at 50- and 100-percent load. Emission rates and concentrations from tests with the Deutz F3L 912W engine are presented in Table 13, while results from the Perkins 4.203.2 engine are found in Table 14.

### 1. Particulate

The effect of engine load on particulate emission rates is presented in Figure 8 for the Deutz F3L 912W engine for intermediate, peak torque, and rated engine speeds. Figure 9 illustrates the effect of engine load on particulate emission rates from the Perkins 4.203.2 engine. In reviewing these data, several trends were observed, namely:

- At constant speed, particulate mass emission rates increased with increasing load. The rate of particulate mass rate increase was more pronounced at the intermediate and peak torque speeds.

- The 2-percent load condition produced significantly higher brake specific particulate emission rates (g/hp-hr) than the higher loads.

- The Perkins 4.203.2 brake specific particulate emission rates ranged from 0.55 g/hp-hr to 1.81 g/hp-hr under loaded conditions 25-100 percent load at the intermediate, peak torque, and rated speeds. At

TABLE 13. PARTICULATE, SULFUR DIOXIDE, AND SULFATE (GROUP II) EMISSIONS FROM A DEUTZ F3L 912W DIESEL ENGINE

| | | | Emission Rate, g/hr | | | Emission Rate, g/hp-hr | | | Concentration | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test No. | Speed, rpm | Load, % | Particulate | $SO_2$ | Sulfate | Particulate | $SO_2$ | Sulfate | Particulate, $mg/m^3$ | $SO_2$, ppm | Sulfate, $mg/m^3$ |
| 3-1 | 600 | 2 | 1.57 | 2.30 | 0.278 | 9.81 | 11.50 | 1.390 | 32 | 17.24 | 5.7 |
| 3-2 | 1100 | 2 | 2.12 | 5.08 | 0.177 | 5.17 | 8.47 | 0.295 | 26 | 23.11 | 2.2 |
| 3-3 | 1600 | 2 | 6.97 | 8.59 | 0.318 | 9.68 | 10.74 | 0.398 | 58 | 26.43 | 2.7 |
| 3-4 | 2650 | 2 | 9.70 | 16.48 | 0.404 | 11.28 | 23.54 | 0.577 | 43 | 26.75 | 1.8 |
| 2-1 | 600 | 25 | 1.56 | 5.18 | 0.061 | 0.61 | 1.99 | 0.024 | 33 | 40.11 | 1.7 |
| 2-2 | 1100 | 25 | 2.69 | 12.94 | 0.252 | 0.45 | 2.12 | 0.041 | 33 | 58.57 | 3.1 |
| 2-3 | 1600 | 25 | 5.05 | 15.93 | 0.452 | 0.59 | 1.90 | 0.054 | 42 | 48.65 | 3.8 |
| 2-4 | 2650 | 25 | 10.90 | 28.79 | 1.021 | 1.03 | 2.72 | 0.096 | 60 | 58.47 | 5.7 |
| 3-5 | 1100 | 50 | 3.73 | 14.92 | 0.270 | 0.32 | 1.29 | 0.023 | 48 | 69.75 | 3.4 |
| 3-6 | 1600 | 50 | 4.06 | 23.27 | 0.501 | 0.24 | 1.35 | 0.029 | 35 | 73.15 | 4.3 |
| 3-7 | 2650 | 50 | 9.33 | 23.04 | 0.784 | 0.44 | 1.09 | 0.037 | 53 | 47.93 | 4.4 |
| 3-8 | 1100 | 100 | 16.51 | 32.19 | 0.401 | 0.71 | 1.39 | 0.017 | 215 | 153.81 | 5.2 |
| 3-9 | 1600 | 100 | 12.97 | 36.14 | 0.693 | 0.38 | 1.06 | 0.020 | 110 | 112.46 | 5.9 |
| 3-10 | 2600 | 100 | 11.81 | 51.61 | 1.021 | 0.28 | 1.24 | 0.024 | 66 | 105.57 | 5.7 |

TABLE 14. PARTICULATE, SULFUR DIOXIDE, AND SULFATE (GROUP II) EMISSIONS FROM A PERKINS 4.203.2 DIESEL ENGINE

| | | | Emission Rate, g/hr | | | Emission Rate, g/hp-hr | | | Concentration, ppm | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test No. | Speed, rpm | Load, % | Particulate | $SO_2$ | Sulfate | Particulate | $SO_2$ | Sulfate | Particulate, $mg/m^3$ | $SO_2$, ppm | Sulfate, mg/m |
| 3-1 | 500 | 2 | 1.24 | 0.73 | 0.115 | 12.40 | 7.30 | 1.150 | 33 | 7.04 | 3.0 |
| 3-2 | 1000 | 2 | 5.99 | 4.20 | 0.256 | 11.98 | 8.40 | 0.512 | 72 | 10.11 | 3.1 |
| 3-5 | 1500 | 2 | 5.24 | 8.79 | 0.241 | 6.55 | 10.99 | 0.301 | 40 | 24.92 | 1.9 |
| 3-8 | 2500 | 2 | 21.28 | 15.21 | 0.709 | 16.37 | 11.70 | 0.545 | 114 | 29.96 | 3.8 |
| 2-1 | 500 | 25 | 1.69 | 1.09 | 0.132 | 16.90 | 10.90 | 1.320 | 44 | 10.41 | 3.4 |
| 2-2 | 1000 | 25 | 6.94 | 6.45 | 0.247 | 1.10 | 1.02 | 0.039 | 87 | 29.67 | 3.1 |
| 2-3 | 1500 | 25 | 9.84 | 16.88 | 0.455 | 1.00 | 1.72 | 0.046 | 76 | 47.67 | 3.5 |
| 2-4 | 2500 | 25 | 22.64 | 17.98 | 0.760 | 1.81 | 1.44 | 0.061 | 121 | 35.24 | 4.1 |
| 3-3 | 1000 | 50 | 8.61 | 13.35 | 0.324 | 0.66 | 1.03 | 0.025 | 106 | 60.14 | 4.0 |
| 3-6 | 1500 | 50 | 10.85 | 24.90 | 0.639 | 0.55 | 1.28 | 0.033 | 83 | 70.22 | 4.9 |
| 3-9 | 2500 | 50 | 16.70 | 39.02 | 0.888 | 0.67 | 1.56 | 0.036 | 89 | 76.65 | 4.8 |
| 3-4 | 1000 | 100 | 22.21 | 34.11 | 0.418 | 0.91 | 1.40 | 0.017 | 282 | 158.67 | 5.3 |
| 3-7 | 1500 | 100 | 22.26 | 41.94 | 0.678 | 0.60 | 1.14 | 0.018 | 170 | 117.67 | 5.2 |
| 3-10 | 2500 | 100 | 31.56 | 40.12 | 1.422 | 0.68 | 0.87 | 0.031 | 166 | 77.47 | 7.5 |

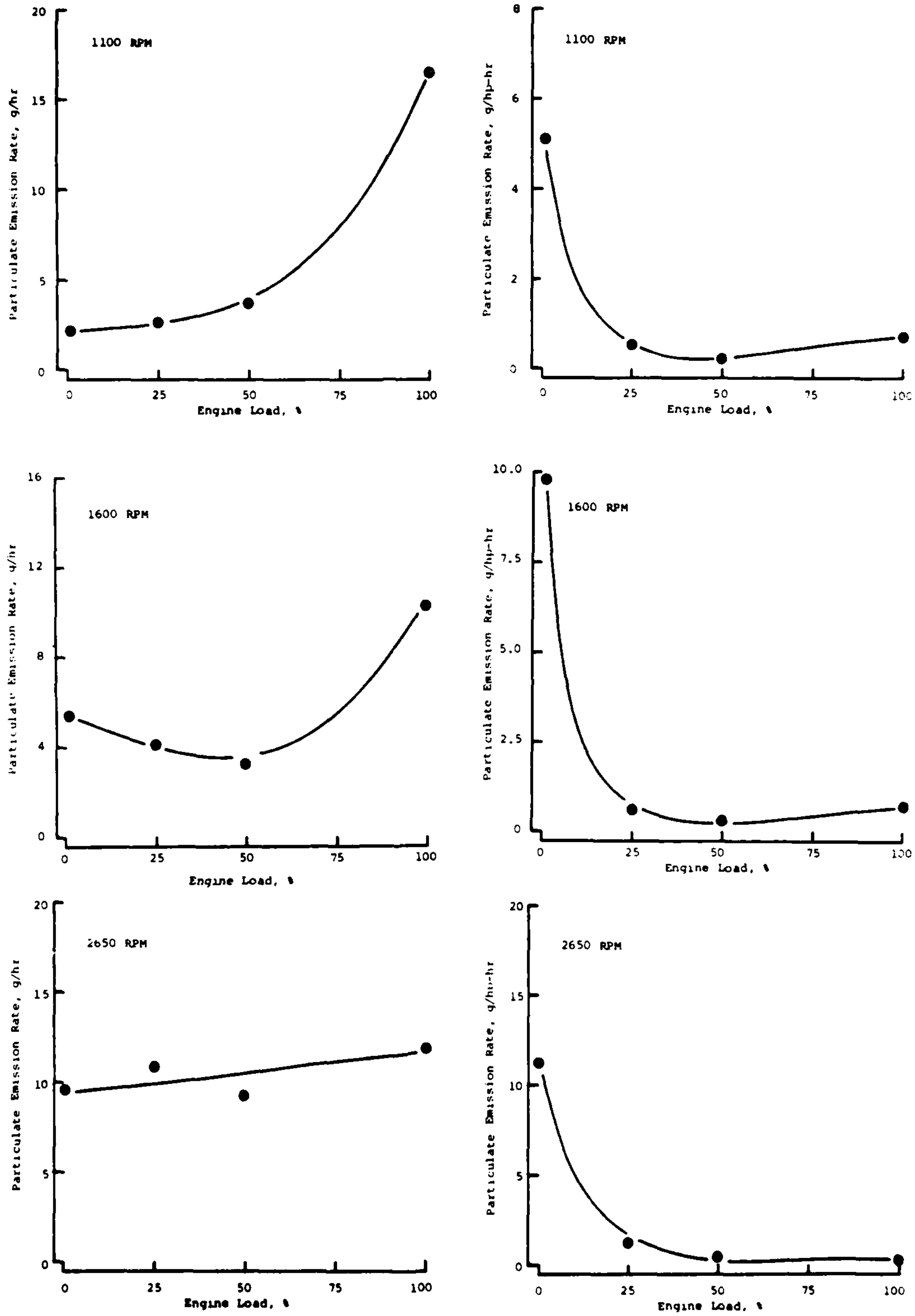



FIGURE 8. EFFECT OF ENGINE LOAD ON PARTICULATE EMISSION RATES FROM A DEUTZ F3L 912W AT THREE ENGINE SPEEDS

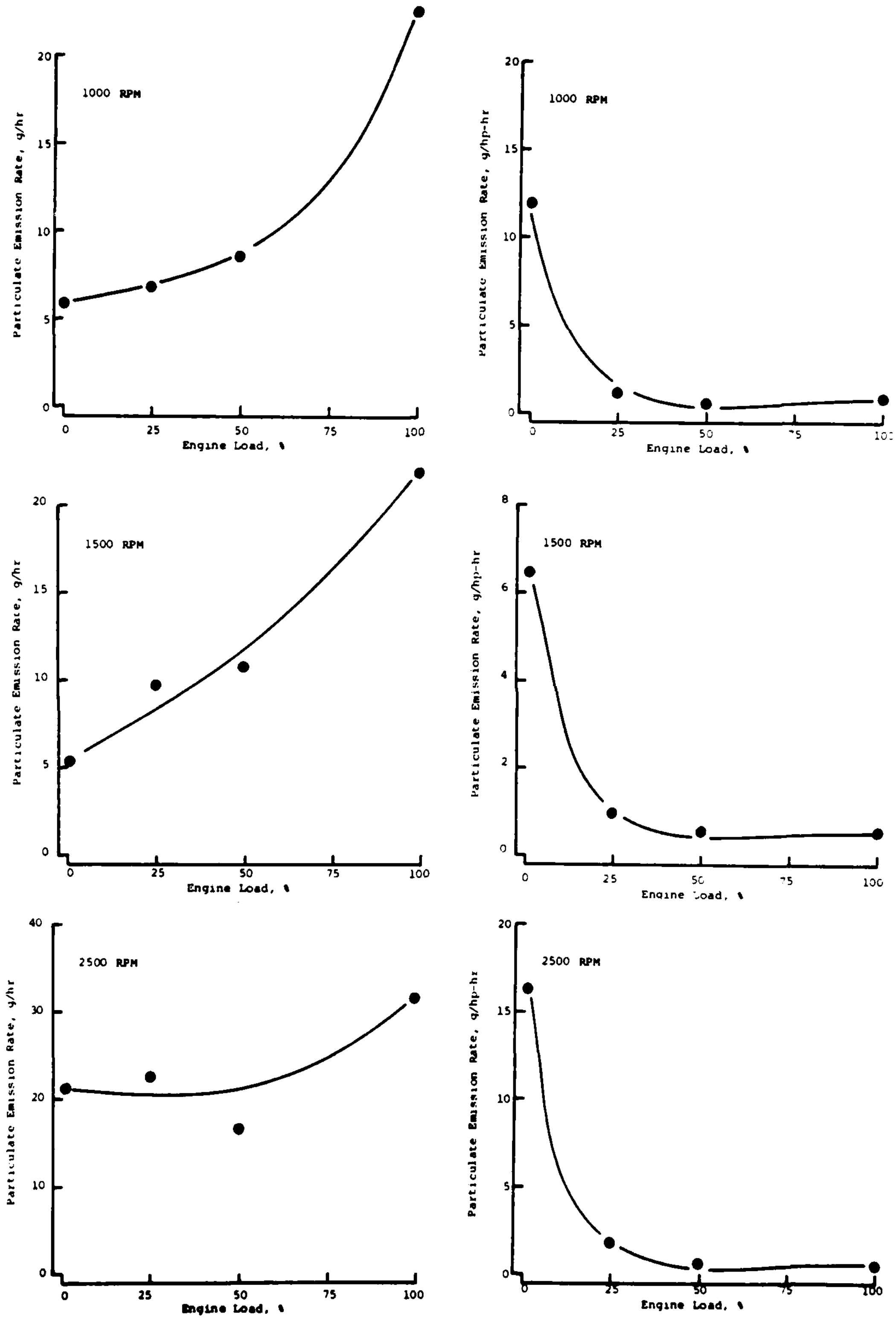



FIGURE 9. EFFECT OF ENGINE LOAD ON PARTICULATE EMISSION RATES FROM A PERKINS 4.203.2 AT THREE ENGINE SPEEDS

2-percent load, the brake specific particulate emission rate ranged from 6.55-16.37 g/hp-hr.

- o The Deutz F3L 912W brake specific particulate emission rates ranged from 0.24-1.03 g/hp-hr for the loaded conditions (25-100 percent load) at the three engine speeds, i.e., intermediate, peak torque, and rated. At the 2-percent load, the brake specific particulate emission rates ranged from 5.17-11.28 g/hp-hr.

2. <u>Sulfur Dioxide</u>

Sulfur dioxide emission rates and concentrations from the Deutz F3L 912W and the Perkins 4.203.2 engines are presented in Tables 13 and 14, respectively. The mass and brake specific sulfur dioxide emission rates are presented as a function of engine load at several engine speeds in Figures 10 and 11 for the Deutz F3L 912W and the Perkins 4.203.2 respectively. Several trends are apparent from these results, namely:

- At constant speed, sulfur dioxide mass emission rates increase with an increase in load at all three speeds (intermediate, peak torque, and rated), probably as a result of more fuel (and sulfur) being burned.

- Significantly higher brake specific sulfur dioxide emission rates were observed at the 2-percent load at the intermediate, peak torque, and rated speeds, than at 25-100 percent loads.

- Brake specific sulfur dioxide emission rates ranged from 0.87-1.72 g/hp-hr at the 25-100 percent loads for intermediate, peak torque, and rated engine speeds for the Perkins 4.203.2.

- Brake specific sulfur dioxide emission rates ranged from 1.09-2.72 g/hp-hr at the 25-100 percent loads at intermediate, peak torque, and rated engine speeds for the Deutz F3L 912W.

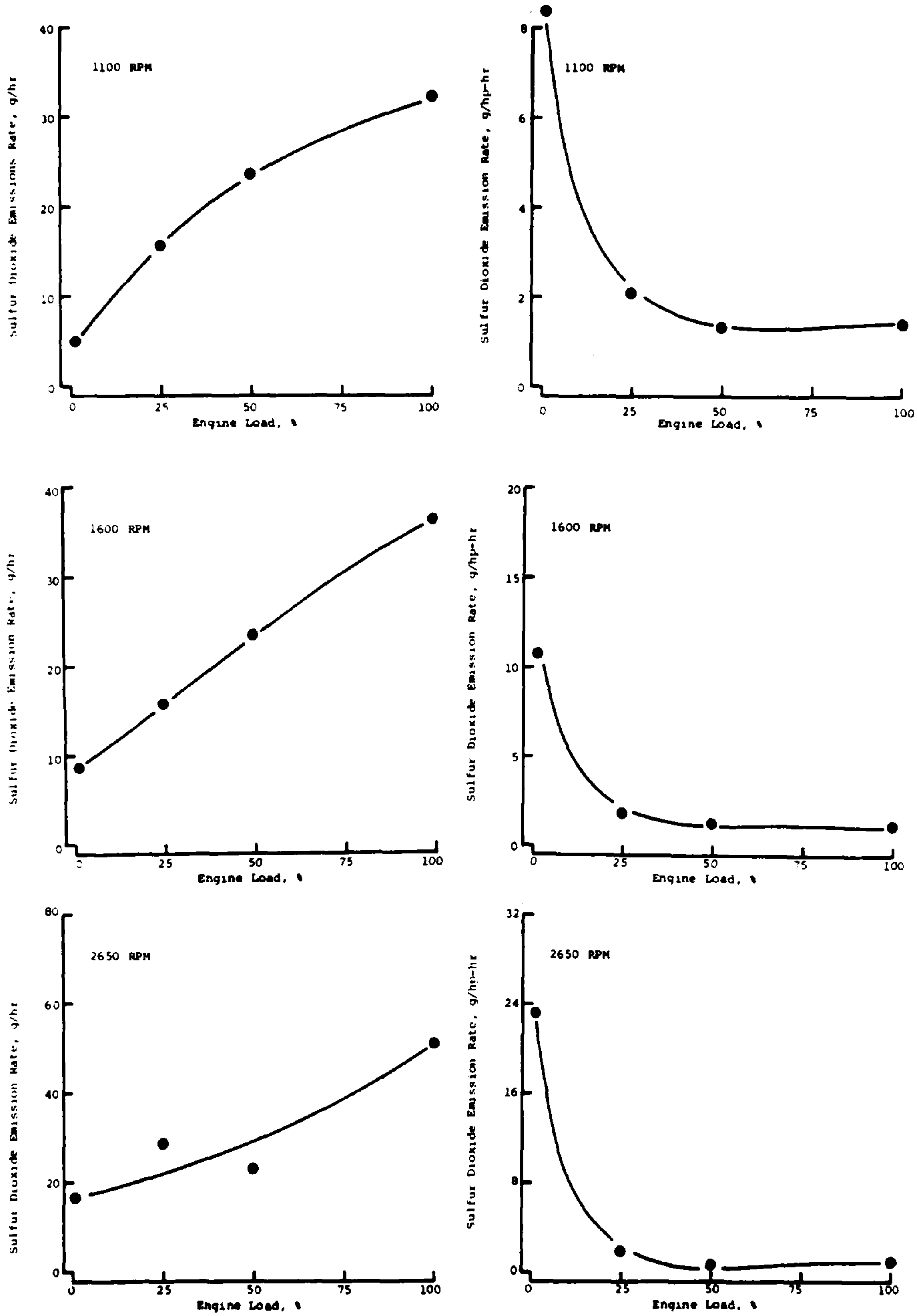



FIGURE 10. EFFECT OF ENGINE LOAD ON SULFUR DIOXIDE EMISSION RATES FROM A DEUTZ F3L 912W AT THREE ENGINE SPEEDS

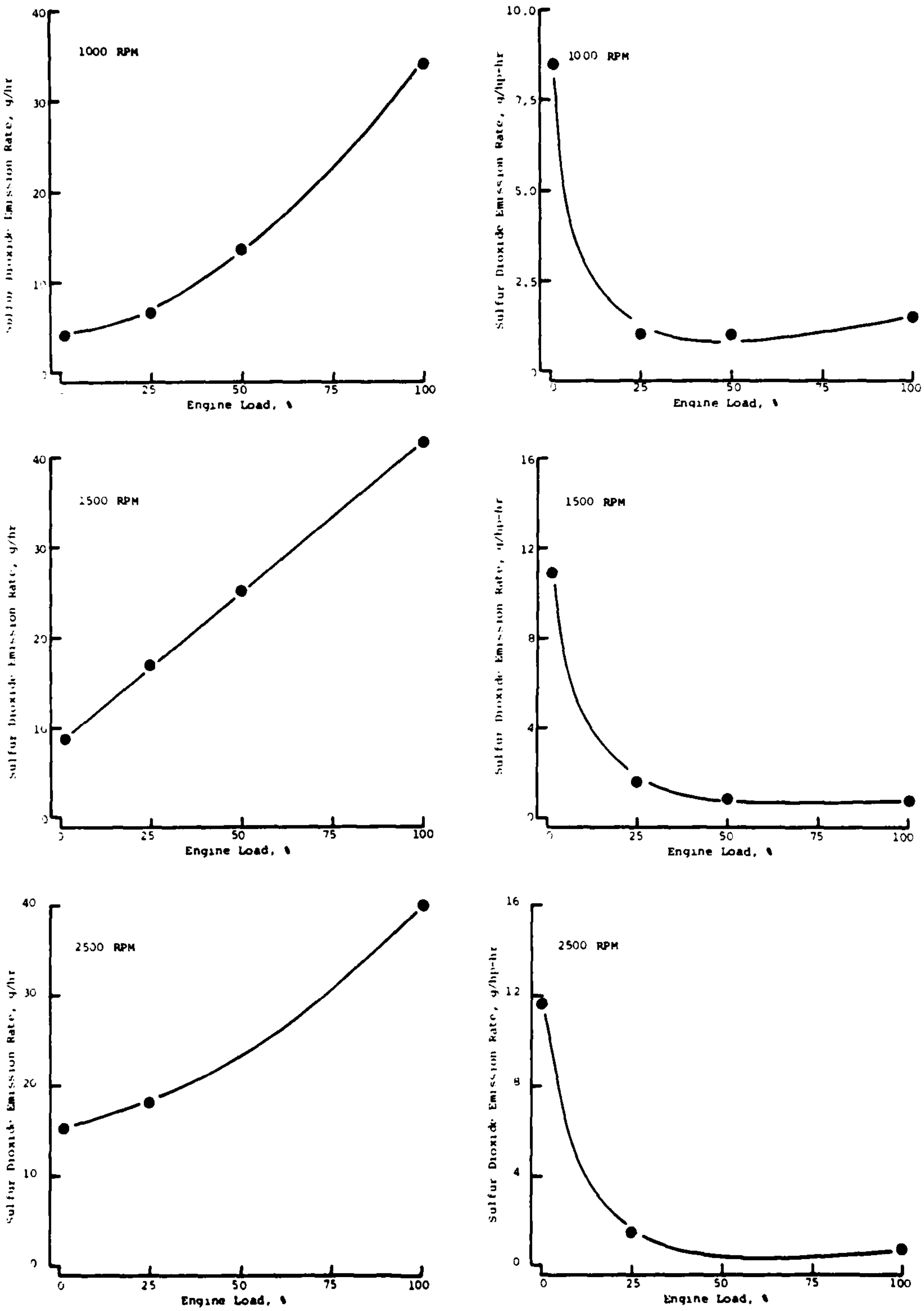



FIGURE 11. EFFECT OF ENGINE LOAD ON SULFUR DIOXIDE EMISSION RATES FROM A PERKINS 4.203.2 AT THREE ENGINE SPEEDS

### 3. Sulfate

Sulfate emission rates were obtained at various engine speeds and loads for both engines. Sulfate emission rates for the Deutz F3L 912W and the Perkins 4.203.2 are presented in Tables 13 and 14, respectively. The effect of engine load on sulfate emission rates at three engine speeds is illustrated in Figures 12 and 13 for the Deutz F3L 912W and the Perkins 4.203.2 engines. The sulfate emission trends from both engines were quite similar and are summarized below:

- Sulfate brake specific emission rates (g/hp-hr) were significantly higher at engine loads of 25 percent or less.
- Sulfate mass emission rates (g/hr) increased as the engine load (and fuel consumption) increased at all three speeds for both engines.
- In general, less than 5 percent of the fuel sulfur was converted to sulfate.

## C. Group III Emissions

Exhaust emissions included in the Group III analyses include aldehydes and ketones, organic sulfides, phenols, and DOAS odor. This section presents the results of these analyses for both engines. The Group III analyses were performed at 2-percent load (idle, intermediate, peak torque, and rated engine speed), 50- and 100-percent load (intermediate, peak torque, and rated engine speeds).

### 1. Aldehyde and Ketone Analysis

The aldehyde and ketone emission rates, expressed in mg/hp-hr, are presented in Table 15 for the Deutz F3L 912W engine. Observed concentrations for each aldehyde and ketone for these same tests are presented in Table 16, and absolute emission rates expressed in mg/hr are found in Table 17. The aldehyde and ketone emission rates from the Perkins 4.203.2 are found in Tables 18 (mg/hp-hr), 19 (mg/hr), and 20 (ppm). Summaries of the total aldehyde and ketone emission rates from both engines are presented in Table 21. In general, these results are summarized below:

- Formaldehyde was the predominate aldehyde detected, generally accounting for 30-50 percent of the total detected.

- Formaldehyde concentrations were less than 0.5 ppm for all test conditions for the Deutz F3L 912W engine and less than 3.2 ppm for all test conditions with the Perkins 4.203.2 engine.

- Brake specific aldehyde emission rates increased with a decrease in load at constant speed for the Deutz F3L 912W engine.

- Aldehyde and ketone emission rates for the Perkins 4.203.2 engine were higher than the Deutz F3L 912W engine on all modes tested.

2. Organic Sulfides

Organic sulfides were collected on Tenax-GC traps for analysis by gas chromatography using a flame photometric detector. Samples were collected on the same ten modes as for other Group III analyses on both engines. No organic sulfides were detected in exhaust of the Deutz F3L 912W engine for any of the ten modes sampled. Organic sulfide emission rates from the Perkins 4.203.2 engine are presented in Table 22, and minimum organic sulfide detection limits are shown in Table 8. Based on the limited data available, the following generalizations are made:

- Carbonyl sulfide was the predominate organic sulfide measured on the Perkins 4.203.2 engine; no organic sulfides were detected with the Deutz F3L 912W engine.

- At constant load, carbonyl sulfide mass emission rates increased with an increase in engine speed with the Perkins 4.203.2 engine.

- With the Perkins 4.203.2 engine at constant speed, the carbonyl sulfide mass emission rates decreased with an increase in load.

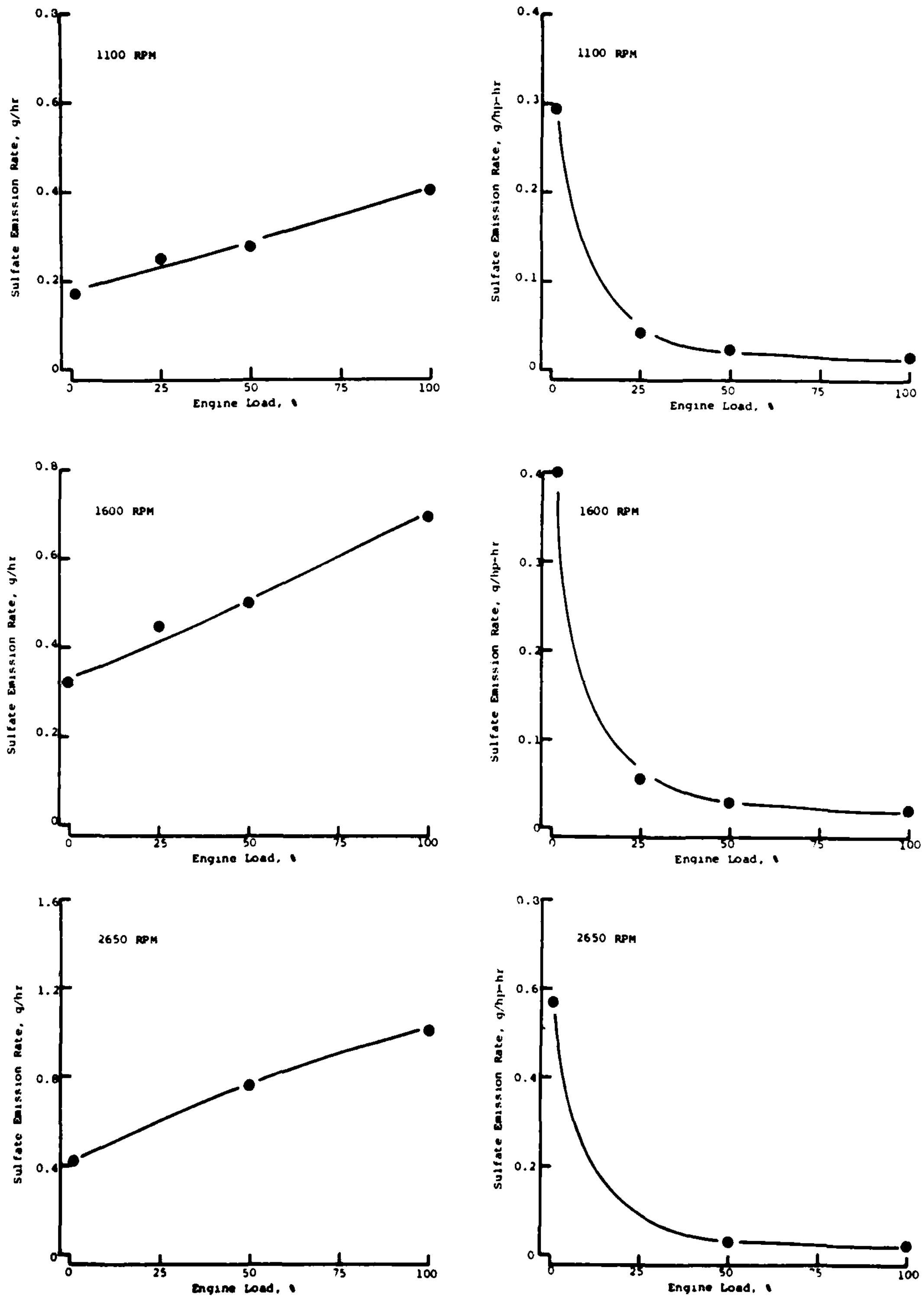



FIGURE 12. EFFECT OF ENGINE LOAD ON SULFATE EMISSION RATES FROM A DEUTZ F3L 912W AT THREE ENGINE SPEEDS

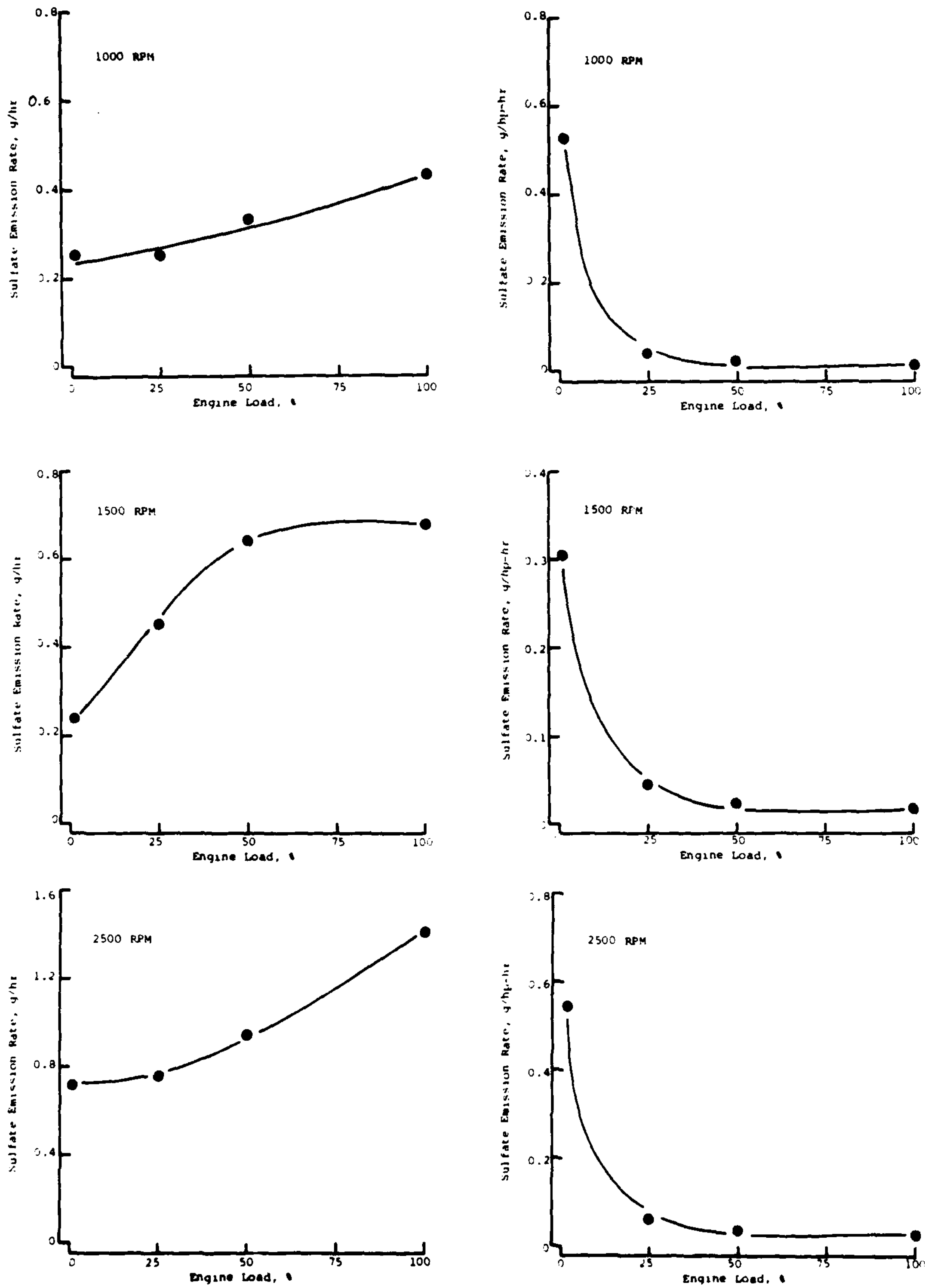



**FIGURE 13. EFFECT OF ENGINE LOAD ON SULFATE EMISSION RATES FROM A PERKINS 4.203.2 AT THREE ENGINE SPEEDS**

## TABLE 15. ALDEHYDE EMISSION RATES FROM A DEUTZ F3L 912W DIESEL ENGINE (MG/HP-HR)

| Test No. | Engine Speed, rpm | Load, % | Aldehyde Emission Rate, mg/hp-hr | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Formaldehyde | Acetaldehyde | Acrolein | Propionaldehyde | Acetone | Crotonaldehyde | Isobutyraldehyde | MEK | Benzaldehyde | Hexanaldehyde |
| 3-1 | 600 | 2 | 25 | ND | 10 | ND | ND | ND | 5 | 175 | ND | ND |
| 3-2 | 1100 | 2 | 12 | 3 | ND | 3 | ND | 7 | 7 | 23 | 5 | ND |
| 3-3 | 1600 | 2 | 18 | 3 | 4 | 4 | ND | 9 | 5 | 26 | 15 | ND |
| 3-4 | 2650 | 2 | 133 | 40 | 71 | 37 | ND | 47 | 39 | 333 | 87 | ND |
| 3-5 | 1100 | 50 | 1.3 | ND | 0.3 | ND | ND | 0.4 | 0.3 | 1.1 | ND | ND |
| 3-6 | 1600 | 50 | 1.9 | ND | 0.8 | ND | 0.5 | 0.3 | 0.2 | 1.2 | ND | 0.3 |
| 3-7 | 2650 | 50 | 3.9 | 0.2 | 1.0 | ND | 1.0 | 0.8 | ND | 1.3 | 0.3 | ND |
| 3-8 | 1100 | 100 | 0.3 | ND | ND | 0.1 | ND | 0.3 | 0.1 | 0.6 | 0.3 | ND |
| 3-9 | 1600 | 100 | 0.6 | ND | ND | 0.1 | ND | 0.6 | ND | 0.6 | 0.2 | ND |
| 3-10 | 2650 | 100 | 0.4 | ND | 0.1 | 0.1 | ND | 0.1 | ND | 0.6 | 0.3 | ND |

## TABLE 16. ALDEHYDE EMISSION CONCENTRATIONS FROM A DEUTZ F3L 912W DIESEL ENGINE (PPM)

| Test No. | Engine Speed, rpm | Load, % | Aldehyde and Ketone Raw Exhaust Concentration, ppm | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Formaldehyde | Acetaldehyde | Acrolein | Propionaldehyde | Acetone | Crotonaldehyde | Isobutyraldehyde | MEK | Benzaldehyde | Hexanaldehyde |
| 3-1 | 600 | 2 | 0.09 | ND | 0.02 | ND | ND | ND | 0.01 | 0.24 | ND | ND |
| 3-2 | 1100 | 2 | 0.07 | 0.01 | ND | 0.01 | ND | 0.02 | 0.02 | 0.06 | 0.01 | ND |
| 3-3 | 1100 | 2 | 0.10 | 0.01 | 0.01 | 0.01 | ND | 0.02 | 0.01 | 0.06 | 0.02 | ND |
| 3-4 | 2650 | 2 | 0.33 | 0.07 | 0.10 | 0.05 | ND | 0.05 | 0.04 | 0.34 | 0.06 | ND |
| 3-5 | 1100 | 50 | 0.06 | ND | 0.02 | ND | ND | 0.02 | 0.02 | 0.06 | ND | ND |
| 3-6 | 1600 | 50 | 0.22 | ND | 0.05 | ND | 0.03 | 0.02 | 0.01 | 0.06 | ND | 0.01 |
| 3-7 | 2650 | 50 | 0.38 | 0.01 | 0.05 | ND | 0.05 | 0.03 | ND | 0.05 | 0.01 | ND |
| 3-8 | 1100 | 100 | 0.09 | ND | ND | 0.01 | ND | 0.02 | 0.01 | 0.06 | 0.02 | ND |
| 3-9 | 1600 | 100 | 0.14 | ND | ND | 0.01 | ND | 0.02 | ND | 0.06 | 0.01 | ND |
| 3-10 | 2650 | 100 | 0.07 | ND | 0.01 | 0.01 | ND | 0.01 | ND | 0.05 | 0.02 | ND |

## TABLE 17. ALDEHYDE AND KETONE EMISSION RATES FROM A DEUTZ F3L 912W DIESEL ENGINE (MG/HR)

| Test No. | Engine Speed, rpm | Load, % | Aldehyde and Ketone Emission Rate, mg/hr | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Formaldehyde | Acetaldehyde | Acrolein | Propionaldehyde | Acetone | Crotonaldehyde | Isobutyraldehyde | MEK | Benzaldehyde | Hexanaldehyde |
| 3-1 | 600 | 2 | 5 | ND | 2 | ND | ND | ND | 1 | 35 | ND | ND |
| 3-2 | 1100 | 2 | 7 | 2 | ND | 2 | ND | 4 | 4 | 14 | 3 | ND |
| 3-3 | 1600 | 2 | 14 | 2 | 3 | 3 | ND | 7 | 4 | 21 | 12 | ND |
| 3-4 | 2650 | 2 | 93 | 28 | 50 | 26 | ND | 33 | 27 | 233 | 61 | ND |
| 3-5 | 1100 | 50 | 15 | ND | 4 | ND | ND | 5 | 4 | 13 | ND | ND |
| 3-6 | 1600 | 50 | 32 | ND | 13 | ND | 9 | 5 | 4 | 21 | ND | 5 |
| 3-7 | 2650 | 50 | 83 | 4 | 22 | ND | 21 | 16 | ND | 27 | 7 | ND |
| 3-8 | 1100 | 100 | 8 | ND | ND | 2 | ND | 7 | 2 | 13 | 6 | ND |
| 3-9 | 1600 | 100 | 20 | ND | ND | 3 | ND | 21 | ND | 19 | 7 | ND |
| 3-10 | 2650 | 100 | 17 | ND | 4 | 4 | ND | 5 | ND | 25 | 14 | ND |

## TABLE 18. ALDEHYDE EMISSION RATES FROM A PERKINS 4.203.2 DIESEL ENGINE (MG/HP-HR)

| Test No. | Engine Speed, rpm | Load, % | Emission Rate, mg/hp-hr | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Formaldehyde | Acetaldehyde | Acrolein | Propionaldehyde | Acetone | Crotonaldehyde | Isobutyraldehyde | MEK | Benzaldehyde | Hexanaldehyde |
| 3-1 | 500 | 2 | 1350 | 330 | ND | 150 | ND | ND | 90 | 110 | ND | ND |
| 3-2 | 1000 | 2 | 620 | 180 | ND | 106 | ND | ND | 62 | 100 | 98 | 330 |
| 3-5 | 1500 | 2 | 588 | 166 | ND | 83 | ND | ND | 49 | 49 | 48 | 304 |
| 3-8 | 2500 | 2 | 568 | 153 | 18 | 82 | ND | ND | 42 | 32 | 96 | 240 |
| 3-3 | 1000 | 50 | 0.6 | 4.8 | 1.2 | 2.4 | ND | 1.2 | 1.9 | 1.8 | 2.2 | 1.4 |
| 3-6 | 1500 | 50 | 2.5 | 0.7 | ND | ND | ND | ND | 0.2 | 2.1 | 1.2 | 1.4 |
| 3-9 | 2500 | 50 | 14.1 | 21.2 | ND | 9.6 | ND | 1.1 | 6.2 | 1.1 | 2.2 | 3.5 |
| 3-4 | 1000 | 100 | 5.9 | 1.0 | ND | 0.6 | ND | ND | ND | 1.0 | 0.7 | 3.7 |
| 3-7 | 1500 | 100 | 11.6 | 3.8 | ND | 1.4 | ND | ND | ND | ND | 1.0 | 4.3 |
| 3-10 | 2500 | 100 | 11.7 | 1.1 | 1.3 | 0.5 | ND | 0.9 | 1.6 | 0.9 | 3.6 | 0.8 |

## TABLE 19. ALDEHYDE EMISSION RATES FROM A PERKINS 4.203.2 DIESEL ENGINE (MG/HR)

| Test No. | Engine Speed, rpm | Load, % | Aldehyde Emission Rate, mg/hr | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Formaldehyde | Acetaldehyde | Acrolein | Propionaldehyde | Acetone | Crotonaldehyde | Isobutyraldehyde | MEK | Benzaldehyde | Hexanaldehyde |
| 3-1 | 500 | 2 | 135 | 33 | ND | 15 | ND | ND | 9 | 11 | ND | ND |
| 3-2 | 1000 | 2 | 310 | 90 | ND | 53 | ND | ND | 31 | 50 | 49 | 165 |
| 3-5 | 1500 | 2 | 470 | 133 | ND | 66 | ND | ND | 39 | 39 | 38 | 243 |
| 3-8 | 2500 | 2 | 739 | 199 | 23 | 106 | ND | ND | 55 | 41 | 125 | 312 |
| 3-3 | 1000 | 50 | 8 | 63 | 15 | 31 | ND | 15 | 25 | 24 | 28 | 18 |
| 3-6 | 1500 | 50 | 49 | 13 | ND | ND | ND | ND | 4 | 40 | 23 | 27 |
| 3-9 | 2500 | 50 | 352 | 531 | ND | 240 | ND | 28 | 155 | 28 | 55 | 88 |
| 3-4 | 1000 | 100 | 143 | 25 | ND | 15 | ND | ND | ND | 24 | 16 | 90 |
| 3-7 | 1500 | 100 | 426 | 141 | ND | 50 | ND | ND | ND | ND | 38 | 160 |
| 3-10 | 2500 | 100 | 541 | 49 | 60 | 25 | ND | 42 | 72 | 43 | 168 | 36 |

## TABLE 20. ALDEHYDE EMISSION RATES FROM A PERKINS 4.203.2 DIESEL ENGINE (PPM)

| Test No. | Engine Speed, rpm | Load, % | Aldehyde Emission, ppm | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Formaldehyde | Acetaldehyde | Acrolein | Propionaldehyde | Acetone | Crotonaldehyde | Isobutyraldehyde | MEK | Benzaldehyde | Hexanaldehyde |
| 3-1 | 500 | 2 | 2.84 | 0.48 | ND | 0.16 | ND | ND | 0.08 | 0.10 | ND | ND |
| 3-2 | 1000 | 2 | 2.99 | 0.59 | ND | 0.27 | ND | ND | 0.13 | 0.20 | 0.13 | 0.48 |
| 3-5 | 1500 | 2 | 2.91 | 0.56 | ND | 0.21 | ND | ND | 0.10 | 0.10 | 0.07 | 0.45 |
| 3-8 | 2500 | 2 | 3.17 | 0.58 | 0.05 | 0.24 | ND | ND | 0.10 | 0.07 | 0.15 | 0.40 |
| 3-3 | 1000 | 50 | 0.08 | 0.43 | 0.08 | 0.16 | ND | 0.06 | 0.10 | 0.10 | 0.08 | 0.05 |
| 3-6 | 1500 | 50 | 0.30 | 0.06 | ND | ND | ND | ND | 0.01 | 0.10 | 0.04 | 0.05 |
| 3-9 | 2500 | 50 | 1.51 | 1.55 | ND | 0.53 | ND | 0.05 | 0.28 | 0.05 | 0.07 | 0.11 |
| 3-4 | 1000 | 100 | 1.46 | 0.17 | ND | 0.08 | ND | ND | ND | 0.10 | 0.04 | 0.27 |
| 3-7 | 1500 | 100 | 2.61 | 0.39 | ND | 0.16 | ND | ND | ND | ND | 0.07 | 0.29 |
| 3-10 | 2500 | 100 | 2.28 | 0.14 | 0.13 | 0.05 | ND | 0.08 | 0.13 | 0.08 | 0.20 | 0.05 |

TABLE 21. SUMMARY OF ALDEHYDE AND KETONE EMISSION RATES FROM A DEUTZ F3L 912W AND PERKINS 4.203.2 ENGINES OPERATED ON MIL-F-46162A(MR) FUEL, AL-722-5

| Speed | Load, % | Total Aldehydes,* mg/hp-hr | | Percent Formaldehyde in Total Aldehydes | |
|---|---|---|---|---|---|
| | | Deutz | Perkins | Deutz | Perkins |
| Idle | 2 | 215 | 2030 | 12 | 67 |
| Intermediate | 2 | 60 | 1496 | 20 | 41 |
| Peak Torque | 2 | 84 | 1287 | 21 | 46 |
| Rated | 2 | 787 | 1231 | 17 | 46 |
| Intermediate | 50 | 3.4 | 17.5 | 38 | 3 |
| Peak Torque | 50 | 5.2 | 8.1 | 37 | 31 |
| Rated | 50 | 8.5 | 59.0 | 46 | 24 |
| Intermediate | 100 | 1.7 | 12.9 | 18 | 46 |
| Peak Torque | 100 | 2.1 | 22.1 | 29 | 52 |
| Rated | 100 | 1.6 | 22.4 | 25 | 52 |

*Total aldehydes are defined as the numerical sum of the individual emission rates for formaldehyde, acetaldehyde, acrolein, propionaldehyde, acetone, crotonaldehyde, isobutyraldehyde, methyl ethyl ketone, benzaldehyde, and hexanaldehyde.

3. Phenols

During this program, exhaust samples were collected for phenols analysis using procedures developed by Southwest Research Institute for the Environmental Protection Agency. Analysis of these samples by gas chromatography indicated either no phenols or only trace phenols with both engines. The detection limits of the phenols as measured by this method are presented in Table 23.

4. Diesel Odor Analysis System (DOAS) Odor

DOAS odor results from both engines are presented in Table 23. The DOAS from the Perkins 4.203.2 engine was generally higher (TIA 2.2 ± 0.3) than the Deutz F3L 912W (TIA 1.7 ± 0.3). No general trends were apparent as a function of engine speed or load for either engine.

The higher Total Aroma of Intensity (TIA) values observed with Perkins 4.203.2 were not surprising, considering that the Perkins also had higher unburned hydrocarbons, aldehydes and ketones, and organic sulfides than the Deutz F3L 912W engine. These species are all thought to contribute to or be an indicator of diesel exhaust odor.

TABLE 22. ORGANIC SULFIDE EMISSION RATES FROM PERKINS 4.203.2 DIESEL ENGINE (mg/hr)

| Test No. | Engine Speed | Load, % | Carbonyl Sulfide | Dimethyl Sulfide | Diethyl Sulfide | Dimethyl Disulfide |
|---|---|---|---|---|---|---|
| 3-1 | 500 | 2 | 0.90 | ND | ND | ND |
| 3-2 | 1000 | 2 | 3.41 | ND | ND | ND |
| 3-5 | 1500 | 2 | 4.77 | ND | ND | ND |
| 3-8 | 2500 | 2 | 45.08 | ND | 2.59 | ND |
| 3-3 | 1000 | 50 | 0.58 | ND | ND | ND |
| 3-6 | 1500 | 50 | 0.94 | ND | ND | ND |
| 3-9 | 2500 | 50 | 16.33 | ND | 1.55 | ND |
| 3-4 | 1000 | 100 | 1.00 | ND | ND | ND |
| 3-7 | 1500 | 100 | 1.32 | ND | 0.43 | ND |
| 3-10 | 2500 | 100 | 2.94 | ND | 3.42 | ND |

TABLE 23. DIESEL ODOR ANALYSIS SYSTEM (DOAS) RESULTS FOR DEUTZ F3L 912W AND PERKINS 4.203.2 DIESEL ENGINES

| Engine Speed | Engine Load, % | Total Aroma of Intensity (TIA) Deutz F3L 912W | Total Aroma of Intensity (TIA) Perkins 4.203.2 |
|---|---|---|---|
| Idle | 2 | 1.55 | 2.10 |
| Intermediate | 2 | 1.55 | 2.17 |
| Peak Torque | 2 | 1.71 | 2.07 |
| Rated | 2 | 1.92 | 2.08 |
| Intermediate | 50 | 1.77 | 2.21 |
| Peak Torque | 50 | 1.62 | 2.28 |
| Rated | 50 | 1.71 | 2.52 |
| Intermediate | 100 | 1.72 | 2.17 |
| Peak Torque | 100 | 1.41 | 2.57 |
| Rated | 100 | 1.38 | ---[a] |

[a]Sample contaminated

# V. SUMMARY

This section summarizes emission results from the Deutz F3L 912W and Perkins 4.203.2 engines for Groups I, II, and II emissions. The data for the Group I emissions produced several general trends and observations:

- Both engines produced higher BSHC, BSCO, and $BSNO_x$ at low-load conditions, regardless of speed.

- At constant load, BSHC and BSCO increased with increasing speed; $BSNO_x$ showed mixed trends.

- At constant speed, BSHC, BSCO, and $BSNO_x$ increased with decreasing load for both engines.

- The Perkins 4.203.2 engine had higher HC, CO, and $NO_x$ brake specific (g/hp-hr) and mass (g/hr) emission rates than the Deutz F3L 912W.

Results of Group II emissions for particulate, sulfur dioxide, and sulfate also produced some general trends, and are summarized below:

- At constant speed, particulate and sulfur dioxide emission rates increased with increasing load.

- Less than 5 percent of fuel sulfur was converted to sulfate for both engines.

- At constant intermediate, peak torque, and rated speeds, sulfate increased with increasing load.

- In most cases, particulate brake specific emission rates were higher on the Perkins 4.203.2 engine. Sulfur dioxide mass emission rates were generally proportional to fuel consumed.

Aldehydes, organic sulfides, DOAS odor, and phenols (Group III) were measured on selected modes. These results are summarized below:

- Formaldehyde concentrations generally accounted for 30-50 percent of the aldehydes and ketones detected.

- Formaldehyde concentrations were less than 0.5 ppm for all test conditions for the Deutz F3L 912W engine and less than 3.2 ppm for all test conditions with the Perkins 4.203.2 engine.

- Brake specific aldehyde emission rates increased with a decrease in load at constant speed for the Deutz F3L 912W engine.

- In general, at constant load and aldehyde and ketone mass, emission rates increased with an increase in speed, except at low load for the Perkins engine.

- No phenols were found above the minimum detection limit for the two engines tested.

- Carbonyl sulfide was the predominate organic sulfide measured with the Perkins 4.203.2 engine; no organic sulfides were detected with the Deutz F3L 912W engine.

- At constant load, carbonyl sulfide mass emission rates increased with an increase in engine speed with the Perkins 4.203.2 engine.

- With the Perkins 4.302.2 engine, at constant speed, the carbonyl sulfide mass emission rates decreased with an increase in load.

- The Diesel Odor Analysis System (DOAS) results from the Perkins 4.203.2 engine were generally higher (TIA $\approx$ 2.2 $\pm$ 0.3) than the Deutz F3L 912W (TIA $\approx$ 1.70 $\pm$ 0.3). No general trends for DOAS odor were apparent as a function of engine speed or load for either engine.

## VI. RECOMMENDATIONS

As a result of this program, several items have been identified as potential areas of additional work. These are summarized below:

1. Most engine emissions appear to be greatest at low loads regardless of the engine speed. Forklifts generally operate at low load and under essentially continual transient conditions. Previous experience has indicated that steady-state data cannot always predict transient emissions, particularly on a low-duty cycle. Since a "forklift cycle" is not currently available, it is recommended that an RFP issued by MERADCOM (RFP DAAK70-83-Q-0107 titled "Measurement of Pollutants from Diesel Engine Forklift Trucks During Operations in an Ammunition Storage Area") be modified to include monitoring engine parameters such as engine speed, fuel and exhaust temperatures. This would allow development of a "forklift cycle" at a minimal cost to MERADCOM, since forklift trucks, fuel, drivers, operators, and facilities will be available all at one time at one place and could be performed concurrently.

The availability of this transient cycle would allow determining emission rates based on a cycle developed from data collected during field operations. It is also consistent with EPA's philosophy, that is, requiring all heavy-duty diesel engines to be certified using the EPA heavy-duty engine transient cycle. Virtually all forklift engine manufacturers also produce heavy-duty engines and are quite familiar with the transient cycle.

2. Initially, it was planned to use 1-percent sulfur fuel, i.e., MIL-F-46162B (ME); however, due to time constraints and lack of immediate availability of the MIL-F-46162B(ME) fuel, the MERADCOM Project Manager approved the use of MIL-F-46162A(MR) for this program (at 0.35-percent sulfur). During this program, there were several discussions with MERADCOM regarding the effect of fuel sulfur level on emissions, particularly sulfur dioxide, sulfate, and trace organic sulfides. It is generally agreed that an increase in fuel sulfur level will produce a corresponding proportionate increase in sulfur dioxide and sulfate, although experimental data to confirm this are not available. As mentioned earlier, the nature and quantity of the trace organic sulfides may be influenced by the specific sulfur additive that is used

to increase the fuel sulfur level. Also, the question of the influence of natural versus added sulfur has not been investigated, at least to our knowledge.

3. After MERADCOM has established the test protocol and specifications for diesel forklift acceptance to MERADCOM, it is quite likely that several engine manufacturers may have diesel engines that are acceptable in every manner except emissions. These manufacturers may wish to add after-treatment devices (i.e., catalytic traps) to their engines to reduce emissions, particularly if this is already allowed in Great Britain. These devices are reportedly effective and are currently used in handling hazardous materials in England.

Although these devices may allow a nonconforming engine to meet the emissions specification during an acceptance test, it should be demonstrated to MERADCOM that these devices have demonstrated durability during typical forklift operations and that on-site catalytic trap regeneration is possible. Other areas of possible concern would be the use of after-treatment devices with the MIL-F-46162B(ME) high-sulfur fuel and its influence on sulfate formation. In addition, limited work may be warranted to investigate the formation of selected unregulated emissions (i.e., sulfate, aldehydes, odor) during engine malfunctions, such as plugged air cleaner, high exhaust back-pressure, engine overfueling, and injection pump mis-timing.

4. After MERADCOM has established the emission limits and test procedures for diesel forklift purchase specifications, it should be of concern to MERADCOM to develop a level confidence that ensures that engines purchased will meet the emission standards. There are essentially two variables that affect emission rates. The first variable is test-to-test variability and is influenced primarily by the analytical instrumentation, engine reproducibility, etc. It is likely that EPA has some data to provide some indication of this variability on large heavy-duty diesel engines. We are not aware of any data available for test-to-test variability on forklift-size diesel engines. If this is not available, MERADCOM may wish to conduct replicate 13-mode (or transient forklift if the cycle is available) to determine standard deviation on one or more candidate diesel engines to establish confidence limits on this size engine.

The second, and probably most critical, is the engine-to-engine variability of production engines. Again, EPA may have data available on the engine-to-engine variability during certification of heavy-duty engines, but extrapolation to small engines may not be appropriate. MERADCOM may wish to include in the purchase specifications that a certain percentage of production engines (i.e., four out of five engines) pass the emission tests, or alternatively, randomly select production engines for an emissions audit (test).

# VII. REFERENCES

1. Code of Federal Regulations, Title 40, Part 86, Subpart D, "Emission Regulations for New Gasoline-Fueled and Diesel Heavy-Duty Engines; Gaseous Exhaust Test Procedures," pp. 428-460, July 1, 1982.

2. Smith, L. R., Parness, M. A., Fanick, E. R., and Dietzmann, H. E., "Analytical Procedures for Characterizing Unregulated Emissions From Vehicles Using Middle-Distillate Fuels," EPA/600-2-80-068, April 1980.

3. CRC-APRAC Project No. CAPI-1-64, "Development and Evaluation of a Method for Measurement of Diesel Exhaust Odor Using a Diesel Odor Analysis System (DOAS)," January 1979.

# APPENDIX

## 13-MODE EMISSION RESULTS

- Deutz F3L 912W Engine
- Perkins 4.203.2 Engine

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13-MODE FEDERAL DIESEL EMISSION CYCLE 1979

ENGINE:DEUTZ MODEL F3L912SW S/N 6498515 13 MODE
TEST-1 FUEL:EM-544-F PROJECT:05-6800-175 DATE:02/09/83

| MODE | POWER PCT | ENGINE SPEED COND / RPM | TORQUE OBS LB-FT | POWER OBS BHP | FUEL FLOW LB/MIN | AIR FLOW LB/MIN | INTAKE HUMID GR/LB | NOX CORR FACT | MEASURED HC PPM | MEASURED CO PPM | MEASURED CO2 PCT | MEASURED NOX PPM | CALCULATED GRAMS / HOUR HC | CALCULATED GRAMS / HOUR CO | CALCULATED GRAMS / HOUR NOX | MODE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | IDLE / 600. | 0. | .0 | .023 | 2.80 | 56. | .927 | 90. | 129. | 1.65 | 99. | 3. | 10. | 12. | 1 |
| 2 | 2 | INTER / 1600. | 3. | .8 | .052 | 5.23 | 49. | .922 | 65. | 125. | 2.20 | 114. | 4. | 16. | 22. | 2 |
| 3 | 25 | INTER / 1600. | 28. | 8.4 | .100 | 5.22 | 63. | .983 | 45. | 95. | 3.90 | 293. | 3. | 13. | 66. | 3 |
| 4 | 50 | INTER / 1600. | 56. | 17.2 | .130 | 5.04 | 53. | .935 | 50. | 54. | 5.38 | 387. | 3. | 7. | 79. | 4 |
| 5 | 75 | INTER / 1600. | 84. | 25.6 | .178 | 5.05 | 58. | .964 | 50. | 82. | 7.95 | 585. | 3. | 10. | 114. | 5 |
| 6 | 100 | INTER / 1600. | 112. | 34.0 | .230 | 4.99 | 63. | .980 | 72. | 151. | 10.25 | 402. | 5. | 19. | 79. | 6 |
| 7 | | IDLE / 600. | 0. | .0 | .023 | 2.80 | 56. | .927 | 90. | 129. | 1.65 | 99. | 3. | 10. | 12. | 7 |
| 8 | 100 | RATED / 2650. | 83. | 41.7 | .282 | 7.59 | 60. | .965 | 106. | 209. | 8.24 | 437. | 11. | 39. | 129. | 8 |
| 9 | 75 | RATED / 2650. | 62. | 31.1 | .250 | 7.82 | 56. | .958 | 113. | 177. | 7.21 | 470. | 11. | 34. | 140. | 9 |
| 10 | 50 | RATED / 2650. | 42. | 21.2 | .193 | 7.62 | 47. | .921 | 110. | 214. | 5.69 | 308. | 11. | 40. | 86. | 10 |
| 11 | 25 | RATED / 2650. | 21. | 10.6 | .158 | 7.84 | 58. | .953 | 130. | 255. | 4.30 | 243. | 13. | 51. | 76. | 11 |
| 12 | 2 | RATED / 2650. | 1. | .7 | .100 | 7.56 | 45. | .913 | 160. | 356. | 3.39 | 129. | 13. | 57. | 31. | 12 |
| 13 | | IDLE / 600. | 0. | .0 | .023 | 2.80 | 56. | .927 | 90. | 129. | 1.65 | 99. | 3. | 10. | 12. | 13 |

| MODE | CALCULATED GRAMS/LB-FUEL HC | CO | NOX | GRAMS/BHP-HR HC | CO | NOX | F/A DRY MEAS | F/A STOICH | "PHI" | WET HC CORR FACT | F/A CALC | F/A PCT MEAS | POWER CORR FACT | BSFC CORR LB/HP-HR | MODAL WEIGHT FACTOR | MODE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.48 | 7.09 | 8.23 | ****** | ****** | ****** | .0084 | .0690 | .122 | .983 | .0079 | -5.6 | 1.000 | ***** | .067 | 1 |
| 2 | 1.36 | 5.17 | 7.10 | 5.26 | 20.05 | 27.52 | .0099 | .0690 | .144 | .978 | .0105 | 5.5 | 1.023 | 3.788 | .080 | 2 |
| 3 | .54 | 2.23 | 11.03 | .39 | 1.59 | 7.88 | .0193 | .0690 | .280 | .963 | .0184 | -5.1 | 1.008 | .709 | .080 | 3 |
| 4 | .44 | .92 | 10.06 | .20 | .42 | 4.56 | .0260 | .0690 | .376 | .951 | .0251 | -3.3 | 1.023 | .443 | .080 | 4 |
| 5 | .31 | .95 | 10.61 | .13 | .40 | 4.44 | .0356 | .0690 | .516 | .931 | .0367 | 3.1 | 1.014 | .412 | .080 | 5 |
| 6 | .35 | 1.35 | 5.75 | .14 | .55 | 2.33 | .0465 | .0690 | .674 | .913 | .0469 | .8 | 1.007 | .403 | .080 | 6 |
| 7 | 2.48 | 7.09 | 8.23 | ****** | ****** | ****** | .0084 | .0690 | .122 | .983 | .0079 | -5.6 | 1.000 | ***** | .067 | 7 |
| 8 | .63 | 2.32 | 7.64 | .25 | .94 | 3.09 | .0374 | .0690 | .543 | .928 | .0381 | 1.7 | 1.041 | .389 | .080 | 8 |
| 9 | .76 | 2.25 | 9.32 | .36 | 1.08 | 4.49 | .0322 | .0690 | .467 | .936 | .0335 | 3.9 | 1.032 | .467 | .080 | 9 |
| 10 | .92 | 3.44 | 7.43 | .50 | 1.88 | 4.06 | .0255 | .0690 | .370 | .949 | .0266 | 4.3 | 1.040 | .526 | .080 | 10 |
| 11 | 1.42 | 5.40 | 8.00 | 1.27 | 4.84 | 7.17 | .0204 | .0690 | .295 | .960 | .0203 | -.2 | 1.032 | .868 | .080 | 11 |
| 12 | 2.18 | 9.50 | 5.13 | 19.73 | 86.05 | 46.47 | .0133 | .0690 | .193 | .968 | .0162 | 21.5 | 1.031 | 8.783 | .080 | 12 |
| 13 | 2.48 | 7.09 | 8.23 | ****** | ****** | ****** | .0084 | .0690 | .122 | .983 | .0079 | -5.6 | 1.000 | ***** | .067 | 13 |

CYCLE COMPOSITE USING 13-MODE WEIGHT FACTORS

BSHC ------- = .454 GRAM/BHP-HR
BSCO ------- = 1.627 GRAM/BHP-HR
BSNOX ------ = 4.445 GRAM/BHP-HR
BSHC + BSNOX = 4.899 GRAM/BHP-HR
CORR. BSFC - = .529 LBS/BHP-HR

## 13-MODE FEDERAL DIESEL EMISSION CYCLE 1979

ENGINE: PERKINS MODEL 4.203.2 — 13-MODE
TEST-1 — FUEL: EM-544-F — PROJECT: 05-6800-175 — DATE: 3/2/83

| MODE | POWER PCT | ENGINE SPEED COND / RPM | TORQUE OBS LB-FT | POWER OBS BHP | FUEL FLOW LB/MIN | AIR FLOW LB/MIN | INTAKE HUMID GR/LB | NOX CORR FACT | MEASURED HC PPM | MEASURED CO PPM | MEASURED CO2 PCT | MEASURED NOX PPM | CALCULATED GRAMS / HOUR HC | CALCULATED GRAMS / HOUR CO | CALCULATED GRAMS / HOUR NOX | MODE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | IDLE / 750. | 0. | .0 | .015 | 2.74 | 39. | .889 | 824. | 437. | 1.51 | 128. | 21. | 22. | 9. | 1 |
| 2 | 2 | INTER / 1500. | 3. | .8 | .050 | 5.68 | 47. | .918 | 720. | 624. | 1.80 | 195. | 52. | 89. | 42. | 2 |
| 3 | 25 | INTER / 1500. | 34. | 9.8 | .093 | 5.66 | 56. | .974 | 960. | 494. | 3.45 | 447. | 70. | 71. | 102. | 3 |
| 4 | 50 | INTER / 1500. | 68. | 19.5 | .140 | 5.62 | 53. | .951 | 728. | 361. | 5.46 | 675. | 52. | 50. | 145. | 4 |
| 5 | 75 | INTER / 1500. | 104. | 29.6 | .200 | 5.81 | 49. | .950 | 540. | 274. | 7.67 | 785. | 41. | 39. | 173. | 5 |
| 6 | 100 | INTER / 1500. | 129. | 36.8 | .240 | 5.55 | 64. | .982 | 620. | 303. | 9.69 | 859. | 45. | 41. | 186. | 6 |
| 7 | | IDLE / 750. | 0. | .0 | .015 | 2.74 | 39. | .889 | 824. | 437. | 1.51 | 128. | 21. | 22. | 9. | 7 |
| 8 | 100 | RATED / 2500. | 97. | 46.3 | .342 | 8.07 | 58. | .970 | 464. | 790. | 9.69 | 482. | 48. | 152. | 146. | 8 |
| 9 | 75 | RATED / 2500. | 81. | 38.8 | .300 | 8.19 | 52. | .961 | 592. | 494. | 7.85 | 402. | 65. | 103. | 131. | 9 |
| 10 | 50 | RATED / 2500. | 53. | 25.0 | .220 | 8.05 | 56. | .963 | 704. | 790. | 5.69 | 273. | 76. | 164. | 89. | 10 |
| 11 | 25 | RATED / 2500. | 26. | 12.5 | .158 | 8.13 | 61. | .987 | 1104. | 828. | 4.10 | 273. | 115. | 168. | 89. | 11 |
| 12 | 2 | RATED / 2500. | 3. | 1.3 | .097 | 8.15 | 63. | 1.000 | 912. | 1348. | 2.47 | 167. | 91. | 266. | 54. | 12 |
| 13 | | IDLE / 750. | 0. | .0 | .015 | 2.74 | 39. | .889 | 824. | 437. | 1.51 | 128. | 21. | 22. | 9. | 13 |

| MODE | CALCULATED GRAMS/LB-FUEL HC | CALCULATED GRAMS/LB-FUEL CO | CALCULATED GRAMS/LB-FUEL NOX | CALCULATED GRAMS/BHP-HR HC | CALCULATED GRAMS/BHP-HR CO | CALCULATED GRAMS/BHP-HR NOX | F/A DRY MEAS | F/A STOICH | "PHI" | WET HC CORR FACT | F/A CALC | F/A PCT MEAS | POWER CORR FACT | BSFC CORR LB/HP-HR | MODAL WEIGHT FACTOR | MODE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 23.20 | 24.52 | 10.42 | ****** | ****** | ****** | .0055 | .0690 | .080 | .984 | .0078 | 41.1 | 1.008 | ***** | .067 | 1 |
| 2 | 17.19 | 29.61 | 13.86 | 68.76 | 118.45 | 55.43 | .0089 | .0690 | .128 | .981 | .0092 | 3.6 | 1.032 | 3.875 | .080 | 2 |
| 3 | 12.51 | 12.61 | 18.14 | 7.19 | 7.24 | 10.42 | .0166 | .0690 | .241 | .967 | .0169 | 1.9 | 1.024 | .561 | .080 | 3 |
| 4 | 6.23 | 5.95 | 17.28 | 2.69 | 2.56 | 7.44 | .0251 | .0690 | .364 | .951 | .0260 | 3.5 | 1.028 | .419 | .080 | 4 |
| 5 | 3.38 | 3.25 | 14.41 | 1.37 | 1.31 | 5.84 | .0347 | .0690 | .502 | .933 | .0358 | 3.3 | 1.017 | .398 | .080 | 5 |
| 6 | 3.13 | 2.84 | 12.92 | 1.23 | 1.11 | 5.06 | .0436 | .0690 | .632 | .917 | .0448 | 2.7 | 1.027 | .382 | .080 | 6 |
| 7 | 23.20 | 24.52 | 10.42 | ****** | ****** | ****** | .0055 | .0690 | .080 | .984 | .0078 | 41.1 | 1.008 | ***** | .067 | 7 |
| 8 | 2.34 | 7.39 | 7.14 | 1.04 | 3.28 | 3.16 | .0427 | .0690 | .618 | .917 | .0449 | 5.3 | 1.047 | .423 | .080 | 8 |
| 9 | 3.62 | 5.70 | 7.27 | 1.68 | 2.65 | 3.38 | .0369 | .0690 | .535 | .931 | .0367 | -.5 | 1.029 | .451 | .080 | 9 |
| 10 | 5.76 | 12.42 | 6.75 | 3.04 | 6.56 | 3.56 | .0276 | .0690 | .399 | .948 | .0272 | -1.2 | 1.050 | .503 | .080 | 10 |
| 11 | 12.12 | 17.70 | 9.40 | 9.21 | 13.45 | 7.14 | .0197 | .0690 | .285 | .961 | .0202 | 2.6 | 1.043 | .728 | .080 | 11 |
| 12 | 15.73 | 45.89 | 9.27 | 73.00 | 212.93 | 43.02 | .0120 | .0690 | .173 | .974 | .0128 | 6.6 | 1.042 | 4.452 | .080 | 12 |
| 13 | 23.20 | 24.52 | 10.42 | ****** | ****** | ****** | .0055 | .0690 | .080 | .984 | .0078 | 41.1 | 1.008 | ***** | .067 | 13 |

CYCLE COMPOSITE USING 13-MODE WEIGHT FACTORS

BSHC ------- = 3.215 GRAM/BHP-HR
BSCO ------- = 5.438 GRAM/BHP-HR
BSNOX ------ = 5.361 GRAM/BHP-HR
BSHC + BSNOX = 8.577 GRAM/BHP-HR
CORR. BSFC - = .495 LBS/BHP-HR

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STSGP (COL CLIFTON) 1
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NEW CUMBERLAND PA 17070

CDR
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ATTN: SDSTO-TP-S 1
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ATTN: DRSDS 1
CHAMBERSBURG PA 17201

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YUMA AZ 85364

PROJ MGR, ABRAMS TANK SYS, DARCOM
ATTN: DRCPM-GCM-S 1
WARREN MI 48090

PROJ MGR, FIGHTING VEHICLE SYS
ATTN: DRCPM-FVS-SE 1
WARREN MI 48090

PROJ MGR, M60 TANK DEVELOPMENT
US ARMY TANK-AUTOMOTIVE CMD (TACCM)
ATTN: USMC-LNO, MAJ. VARELLA 1
WARREN MI 48090

PROG MGR, M113/M113A1 FAMILY
VEHICLES
ATTN: DRCPM-M113 1
WARREN MI 48090

PROJ MGR, MOBILE ELECTRIC POWER
ATTN: DRCPM-MEP-TM 1
7500 BACKLICK ROAD
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PROJ MGR, IMPROVED TOW VEHICLE
US ARMY TANK-AUTOMOTIVE CMD
ATTN: DRCPM-ITV-T 1
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US ARMY EUROPE & SEVENTH ARMY
ATTN: AEAGG-FMD 1
AEAGD-TE 1
APO NY 09403

PROJ MGR, PATRIOT PROJ OFC
US ARMY DARCOM
ATTN: DRCPM-MD-T-G 1
REDSTONE ARSENAL AL 35809

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THEATER ARMY MATERIAL MGMT
CENTER (200TH)
DIRECTORATE FOR PETROL MGMT
ATTN: AEAGD-MM-PT-Q 1
ZWEIBRUCKEN
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