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EFFECT OF JP-8 FUEL ON MATERIAL-HANDLING ENGINES

INTERIM REPORT
BFLRF No. 285

By

D.M. Yost
Belvoir Fuels and Lubricants Research Facility (SwRI)
Southwest Research Institute
San Antonio, Texas

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The effect of MIL-T-83133C grade JP-8 fuel, with respect to MIL-F-46162C 1% S DF-2, was established for Army Material Handling Equipment clean-burn diesel engines. The areas investigated included emissions (gaseous and particulate), power, performance, and durability. The engines revealed reduced emissions utilizing JP-8, with an average decrease in power at 5 percent and an increase in fuel consumption of 2 percent. The durability of an Isuzu C-240 engine with JP-8 was enhanced relative to the MIL-F-46162C fuel. Rough-terrain forklifts were evaluated for fuel consumption and power availability while utilizing JP-8 fuel. The results indicated an average 4-percent increase in fuel consumption and a 3-percent mean decrease in vehicular performance.

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EXECUTIVE SUMMARY

<u>Problems and Objectives</u>: The use of diesel engine-powered warehouse forklifts was initiated to reduce the logistical burden of supporting the operation of propane- and electric-powered vehicles. The use of internal combustion engines in poorly ventilated areas such as ammunition igloos necessitated tailpipe emission specifications. The evaluation of JP-8 in warehouse forklifts was performed to determine if the emissions characteristics of the engines were altered.

<u>Importance of Project</u>: To support the "One Fuel Forward" scenario, the knowledge of emissions, performance, and durability impacts on clean-burn engines while operating on JP-8 was considered necessary. The vehicular performance and fuel consumption impacts of JP-8 fuel on Material-Handling Equipment rough-terrain forklift trucks were also viewed as important.

<u>Technical Approach</u>: The clean-burn diesel engines were evaluated for gaseous and particulate emissions and performance deviations using MIL-T-83133C grade JP-8 and MIL-F-46162C referee diesel fuel. In addition, an Isuzu C-240 engine underwent 210-hour high-duty cycle evaluations for durability with both fuels. The rough-terrain forklift trucks were evaluated for fuel consumption and power availability using JP-8 and a commercial grade diesel fuel.

<u>Accomplishments</u>: The results of this study indicate lower overall gaseous and particulate emissions from the clean-burn engines when JP-8 is utilized. The performance results indicate an averaged power decrease of 5 percent and a mean fuel consumption increase of 2 percent. The durability of the Isuzu C-240 engine with JP-8 appeared to be superior to the MIL-F-46162C fuel. The rough-terrain forklifts performance results indicate an averaged 4-percent increase in fuel consumption and a mean 3-percent decrease in vehicular performance.

<u>Military Impact</u>: The reduced gaseous and particulate emissions with JP-8 indicate the warehouse forklifts are not adversely affected by the use of JP-8. The knowledge of fuel consumption increases and performance loss will provide operators with guidelines for estimating fuel quantities and labor. The durability results indicate the Isuzu C-240 engine would not be adversely affected by JP-8 usage. The rough-terrain forklift truck fuel usage and performance results will enable mission requirements to be adjusted for operation with JP-8.

FOREWORD

This work was performed by the Belvoir Fuels and Lubricants Research Facility (BFLRF) located at Southwest Research Institute (SwRI), San Antonio, TX, during the period December 1989 to October 1992 under Contract Nos. DAAK70-87-C-0043 and DAAK70-92-C-0059 with the U.S. Army Belvoir Research, Development and Engineering Center (Belvoir RDE Center). Mr. T.C. Bowen of Belvoir RDE Center (SATBE-FL) served as the contracting officer's representative, and Mr. W.K. Brower, Jr. of Belvoir RDE Center (SATBE-FMR) served as the project technical monitor.

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I. INTRODUCTION

The use of diesel engine-powered warehouse forklifts was initiated to reduce the logistical burden of operating electric- and propane-powered forklifts. However, internal combustion engines with the accompanying emissions in poorly ventilated areas such as ammunition igloos necessitate tailpipe emission specifications. These specifications were defined by emissions performance testing of low-emissions versions of candidate industrial diesel engines.(1-3)* The engines that meet the emission specifications that have been incorporated into the purchase specification MIL-T-52932C, entitled "Military Specification, Trucks, Lift, Fork, Internal Combustion Engine, 2000-4000-6000-Pound Capacity," (4) are considered clean-burn diesels.

II. BACKGROUND

The "One Fuel on the Battlefield" concept requires that warehouse forklifts with clean-burn diesel engines operate sufficiently on JP-8 in the areas of emissions, performance, and endurance. Additionally, material-handling equipment rough-terrain forklifts must also be capable of performing their mission utilizing JP-8 fuel, without adverse impact on power or performance.

Previous experience with DF-1/Jet A (5) in diesel-powered transit authority buses indicates that the smoke opacity and particulate levels with JP-8 should be lower for the clean-burn diesel buses than with DF-2. The lower volumetric heat of combustion and viscosity of JP-8 could result in full-rack power loss on the order of 3 to 7 percent (6); however, this result appears to be dependent on the fuel injection system geometry and engine sensitivity to thermal efficiency improvements with the lighter JP-8 fuel. Partial-rack fuel-consumption debits should be on the order of the heating value difference between JP-8 and DF-2. Endurance testing with combat and tactical vehicle engines indicates lower oil contamination levels, lower combustion chamber deposits, and lower top ring wear when operating with JP-8.(7)

* Underscored numbers in parentheses refer to the list of references at the end of this report.

III. APPROACH

A. Clean-Burn Diesel Engines

The emissions, power, and performance characteristics of four clean-burn diesel engines were evaluated. The four engines were tested for comparative performance characteristics between MIL-F-46162C (Fuel, Diesel, Referee Grade) (8) 1-percent sulfur referee fuel and MIL-T-83133C (Turbine Fuel, Aviation Kerosene Type, Grade JP-8) (9) grade JP-8 fuel. These are the referee fuels specified by U.S. Army Regulation, AR 70-12, for standardization of fuels for vehicle propulsion engines. Generally, durability specifications must be met in accordance with MIL-F-46162C, and power and performance specifications must be met with MIL-T-83133C.(10) These engines included an Isuzu C-240 engine utilized in 1814- and 2722-kg (4000- and 6000-lb) capacity Hyster forklifts, a Deutz F3L912W engine used in 1814-kg (4000-lb) capacity Still forklifts, a Deutz F4L912W engine used in 2722-kg (6000-lb) capacity Still forklifts, and a Perkins 4.154 engine being considered as a candidate engine for future forklifts.

The comparative emission performance tests were performed utilizing the modal steady-state procedure required in the 13-mode Federal Test Procedure.(11) The test modes and measurements acquired for each fuel/engine combination, plus duplicates, are shown in TABLE 1. The steady-state performance measurements of each engine were analyzed to reflect the power deviations between JP-8 and DF-2 at the full-rack conditions and the fuel-consumption variations at the partial-rack conditions. For both emission and performance measurements, the engines were operated at equivalent brake mean effective pressures, regardless of fuel, for the partial-rack conditions.

The endurance testing was performed with the Isuzu C-240 engine on both test fuels. The Isuzu C-240 engine was chosen for evaluation due to the number of fielded units that utilize this engine. The endurance test used in this evaluation was a 210-hour wheeled vehicle cycle, which is a high-load factor cycle consisting of a cumulative 150 hours at rated power and 60 hours at idle. Historically, the 210-hour cycle lubricant degradation and wear metal concentrations

TABLE 1. Test Matrix for 13-Mode Federal Test Procedure for Evaluation of Emissions and Performance of Clean-Burn Diesel Engines Operating on Specifications MIL-F-46162C and MIL-T-83133C

Mode	Engine Speed	Engine Load, %	Measurement*
1	Idle	--	Group I, Performance
2	Peak Torque	2	Group I, Performance
3	Peak Torque	25	Group I, Group II, Performance
4	Peak Torque	50	Group I, Group II, Performance
5	Peak Torque	75	Group I, Performance
6	Peak Torque	100	Group I, Group II, Performance
7	Idle	--	Group I, Performance
8	Rated Power	100	Group I, Group II, Performance
9	Rated Power	75	Group I, Performance
10	Rated Power	50	Group I, Group II, Performance
11	Rated Power	25	Group I, Group II, Performance
12	Rated Power	2	Group I, Performance
13	Idle	--	Group I, Performance

* Group I includes CO, CO_2, HC, NO_x, Bosch smoke number.
Group II includes particulate.
Performance includes fuel flow, load, air/fuel ratio, etc.

correspond to 20,000 vehicle miles. In fuel's performance evaluations, this cycle has revealed severe fuel injection system performance degradation that can be attributed to the high-load factor.(7)

The engines were disassembled for inspection and measurement before and after each endurance test. Any parts that exceeded the manufacturer's tolerances were replaced, and all other part conditions and measurements were recorded. The measurements included bearing weights, piston ring end gaps, cylinder bore diameter, cylinder bore taper, piston skirt diameter, valve guide-to-stem clearance, valve recession, and fuel injection system calibrations. Both pre- and post-test power curves were performed to determine any power loss at the conclusion of the endurance runs.

B. Rough-Terrain Forklifts

Material-Handling Equipment (MHE) rough-terrain forklifts were evaluated at the U.S. Army Belvoir Research, Development and Engineering Center (Belvoir RDE Center) Engineering Proving Grounds. The forklifts evaluated included an M4K 1814-kg (4000-lb) capacity Rough-Terrain Forklift Truck (RTFLT) powered by a JI Case G207D engine, an M6K 2722-kg (6000-lb) capacity Variable Reach Rough-Terrain Forklift Truck (VRRTFLT) powered by a Cummins 6BT5.9C engine, and an M10A 4536-kg (10,000-lb) capacity RTFLT powered by an International DT-466B engine. These forklifts were tested back-to-back with a referee grade diesel fuel and MIL-T-83133C grade JP-8 fuel for comparisons of fuel consumption and performance. The testing included load-placement, steady-state fuel consumption, acceleration, and gradability tests. TABLE 2 summarizes the test matrix for the rough-terrain forklift truck evaluations. Each vehicle was instrumented for fuel inlet, fuel return, oil sump, and exhaust temperatures, along with fuel flow instrumentation, which included a fuel totalizer. All measured engine variables were recorded with a data logger and transferred to a computer for data reduction and analysis.

IV. EXPERIMENTAL RESULTS

A. Clean-Burn Diesel Engines

All evaluations, including emissions, performance, and durability, for the clean-burn diesel engines were performed utilizing the fuels listed in TABLES 3 and 4. The two fuels are shown compared to their respective specifications and are representative of fuels purchased against those specifications.

TABLE 2. Matrix for Rough-Terrain Forklifts (Three Total) Evaluation With JP-8 Versus DF-2

Load Placement	Steady-State Fuel Consumption	
Time, hr	Vehicle Speed, km/hr (mph)	Loading
1	16 (10)	Capacity
	24 (15)	Capacity

Acceleration Times		Gradability
Time-to-Distance, m (ft)	Loading	Speed on 45% Grade
0 to 46 (0 to 151)	0	
0 to 46 (0 to 151)	Capacity	Capacity Load
0 to 92 (0 to 302)	0	
0 to 92 (0 to 302)	Capacity	

A test cell was modified to accept the clean-burn diesel engines, along with the instrumentation to support the performance and emission measurements. TABLE 5 lists the instrumentation utilized for the performance and emission measurements throughout the program. The gaseous exhaust emission instrumentation, Fig. 1, was connected to the engine through an exhaust pipe probe and a heated sample line. The gaseous emission instrumentation calibration curves were developed with traceable standards in the following detector ranges, and the instrument span and zero adjustments were performed with gases of 2-percent accuracy and nitrogen, respectively.

	Instrument Calibrations		Span Adjustments	
	Low	High	Low	High
HC	100 ppm	500 ppm	35 ppm	153 ppm
CO	1000 ppm	3000 ppm	863 ppm	2866 ppm
CO_2	6%	16%	5.406%	14.51%
NO_x	250 ppm	1000 ppm	210 ppm	825 ppm
O_2	10%	25%	8.85%	21%

TABLE 3. MIL-T-83133C Property Requirements and Test Fuel Inspections

Property	ASTM Method	MIL-T-83133C JP-8 Requirements	Test Fuel AL-19225-F
Color	D 156	Report	+18
TAN, mg KOH/g	D 3242	0.015, max	0.006
Aromatics, vol%	D 1319	25.0, max	20.2
Olefins, vol%	D 1319	5.0, max	1.4
Sulfur, mass%	D 4294	0.30, max	0.07
Mercaptan Sulfur, mass%	D 3227	0.002, max	<0.001
Hydrogen, mass%	D 3178	13.4, min	13.68
Distillation, °C	D 86		
Initial Boiling Point		Report	166
10% Evaporation		205, max	191
20% Evaporation		Report	197
50% Evaporation		Report	211
90% Evaporation		Report	241
End Point		300, max	272
Residue, vol%		1.5, max	1
Gravity, °API	D 1298	37 to 51	41.4
Density, kg/L	D 1298	0.840 to 0.775	0.818
Freeze Point, °C	D 2386	-47, max	-46
Flash Point, °C	D 93	38, min	59
K. Vis, cSt, at			
-20°C	D 445	8.0 max	5.28
40°C	D 445	NR*	1.44
70°C	D 445	NR	0.99
Net Heat of Combustion,	D 240		
MJ/kg		42.8, min	42.873
Btu/lb		18,400, min	18,432
Btu/gal.		NR	125,705
Smoke Point, mm	D 1322	25.0, min	20.2
Thermal Stability, JFTOT	D 3241		
Change in Pressure Drop, mm of Hg		25, max	0
Visual Rating		<3	4 Peacock
Cetane Number	D 613	NR	42
Cetane Index	D 976	Report	41.7
Existent Gum, mg/100 mL	D 381	7.0, max	1.1
Particulate Contamination, mg/L	D 2276	1.0, max	1
Accelerated Stability, mg/100 mL	D 2274	NR	0.1
FSII, vol%		0.10 to 0.15	0.17
Fuel Conductivity, pS/m		150 to 600	195
Corrosion Inhibitor, mg/L		QPL-25017	ND**
Visual	D 4176	Clean/Bright	Clean/Bright
Microseparometer	D 3948	Note 7	0.0
Water Reaction Interface Rating	D 1094	1b, max	1

* NR= No Requirement.

** ND = Not Determined.

TABLE 4. MIL-F-46162C Property Requirements and Test Fuel Inspections

Property	ASTM Method	MIL-F-46162C 1% S DF-2 Requirements	Test Fuel AL-19298-F
TAN, mg KOH/g	D 974	0.2, max	0.06
Aromatics, vol%	D 1319	Report	55.2
Sulfur, wt%	D 4294	0.95 to 1.0	0.95
Hydrogen, wt%	D 3178	Report	12.29
Distillation, °C	D 86		
Initial Boiling Point		Report	181
10% Evaporation		220, min	224
50% Evaporation		255 to 305	276
90% Evaporation		310 to 360	332
95% Evaporation		315 to 365	345
End Point		385, max	359
Residue, vol%		3.0, max	1.3
Gravity, °API	D 1298	Report	29.6
Density, kg/L	D 1298	Report	0.873
Flash Point, °C	D 93	52, min	77
Cloud Point, °C	D 2500	-13, max	-31
Pour Point, °C	D 97	-18, max	-37
K. Vis, cSt, at 40°C	D 445	1.9 to 4.1	3.1
Net Heat of Combustion,	D 240		
MJ/kg		Report	42.43
Btu/lb		Report	18,241
Btu/gal.		NR*	132,881
Cetane Number	D 613	37 to 43	39.4
Cetane Index	D 976	Report	40.6
Ash, wt%	D 482	0.02, max	0.01
Carbon Residue, 10% Bottoms, wt%	D 524	0.20, max	0.16
Particulate Contamination, mg/L	D 2276	10.0, max	4
Accelerated Stability, mg/100 mL	D 2274	1.5, max	1.3
Copper Strip Corrosion	D 130	1, max	1
Free Water and Particulate Contamination	D 4176	Pass	Pass

* NR = No Requirement.

TABLE 5. Test Cell Instrumentation for Evaluation of Clean-Burn Diesel Engine Performance and Emissions

Engine Speed

Digalog Dynamometer Controller

60-Tooth Gear

Engine Load

General Electric 160-bhp Eddy Current Dynamometer

BLH 227-kg (500-lb) Electronic Load Cell

3- to 15-psig Air Throttle

Fuel Flow

Flow-Tron 0 to 45 kg/hr (0 to 100 lb/hr) Mass Flow Indicator

Inlet Airflow

Calibrated Flow Nozzle 0 to 227 kg/hr (0 to 500 lb/hr) Mass Flow

U-Tube Manometer 0 to 747 N/m^2 (0 to 30 in.) H_2O ΔP

Gaseous Exhaust Emissions

Beckman Model 402 Flame Ionization Detector for Unburned Hydrocarbons

Beckman Model 315B Infrared Analyzer for Carbon Monoxide

Beckman Model 315B Infrared Analyzer for Carbon Dioxide

TECO Chemiluminescence Analyzer for Oxides of Nitrogen

Beckman Model OM-11 EA Polarographic Oxygen Analyzer

Particulate Exhaust Emissions

Bosch Spotmeter

20-cm (8-in.) Full-Flow Exhaust Dilution Tunnel

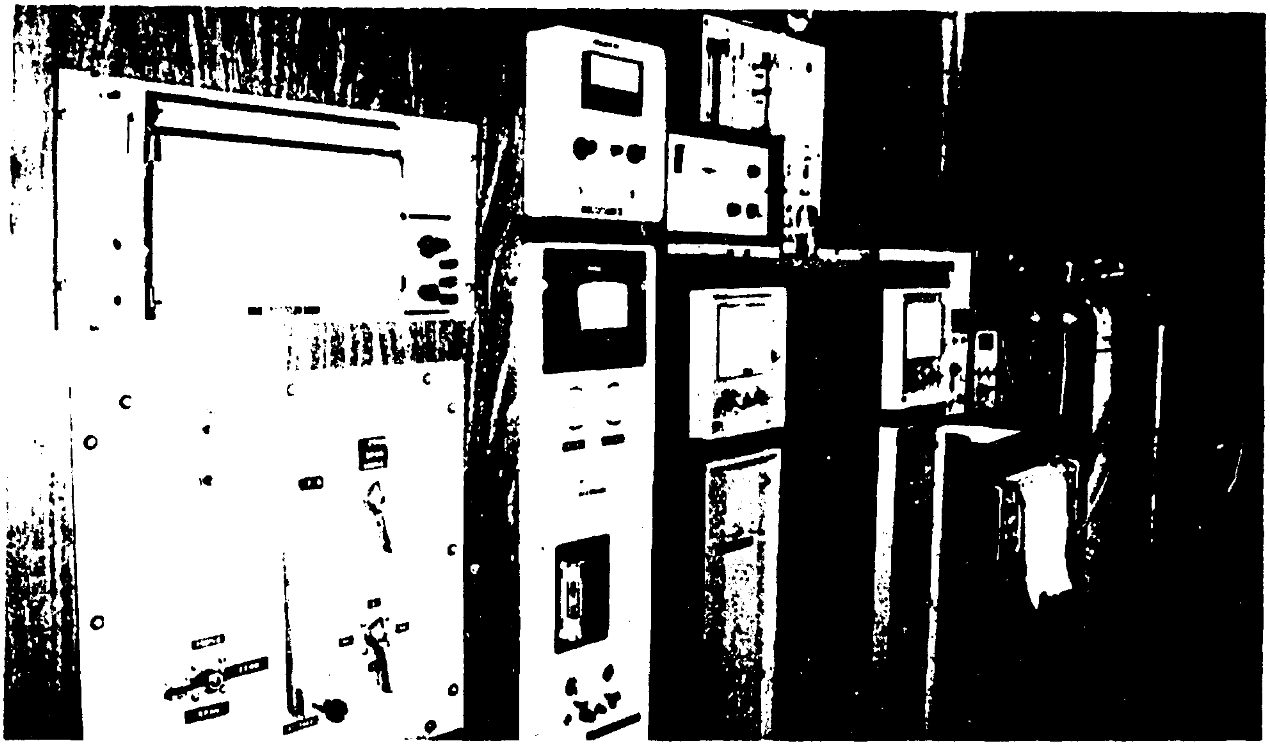

Figure 1. Gaseous exhaust emission instrumentation

The particulate mass emissions were collected by diluting the engine exhaust to the collection filter face temperature of 52°C (125°F) with ambient air via a 20-cm (8-in.) dilution tunnel with a positive displacement-type blower. The Bosch smoke number was determined using a constant volume sampler, which impinges an exhaust sample onto a controlled density paper filter. The filter is then evaluated utilizing a reflectance meter. The absorption of light is proportional to the concentration of soot on the filter. The smoke number sampling probe was located at the exhaust manifold head pipe.

1. Engine Description

a. Isuzu C-240 Engine

The Isuzu C-240 engine is a water-cooled, four-cylinder, in-line, indirect injected, four-cycle industrial diesel engine. The specifications for the C-240 are in TABLE 6, and a photograph of the engine is shown in Fig. 2. Of particular interest with this engine is the use of a throttle body

TABLE 6. Isuzu C-240 Engine Specifications

Rated Power	36 kW at 2400 rpm
Rated Torque	142 Nm at 2000 rpm
Bore	86 mm
Stroke	102 mm
Displacement	2369 cm^3
Compression Ratio	20:1
Injection Timing (BTDC Static)	14°
Injection Pump	Bosch In-Line A Type With Automatic Timer
Governor	Pneumatic and Mechanical Variable Speed
Injection Nozzle	Bosch Throttling Pintle
Combustion Chamber	Swirl Chamber

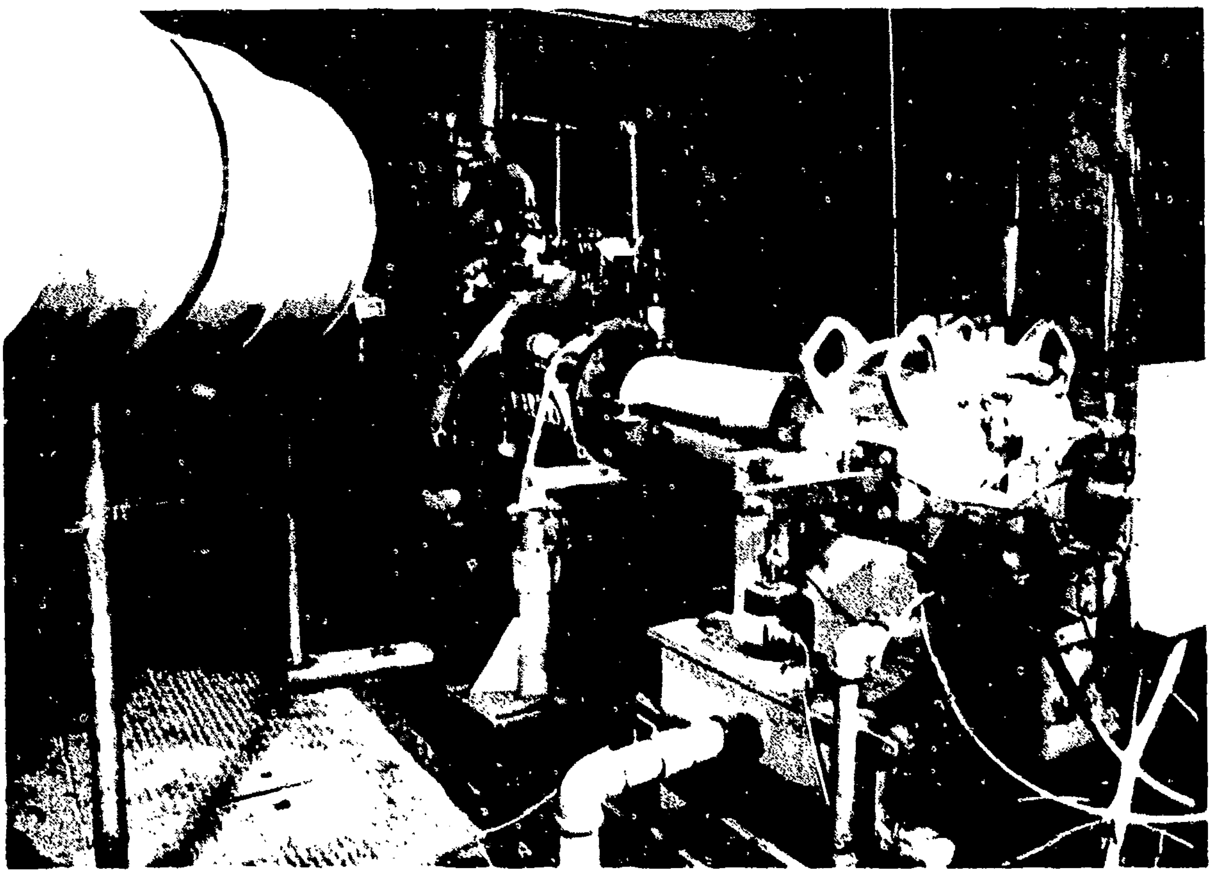

Figure 2. Photograph of Isuzu C-240 engine

on the intake manifold. Operator input actuates a butterfly valve in the throttle body, which alters the vacuum supply to the injector pump rack actuator. The injection system, a pump-line-nozzle arrangement, uses a Bosch-licensed four-barrel and plunger in-line pump, and Bosch pintle nozzles. This engine, which was supplied as Government-Furnished Equipment (GFE), had previously been operated. The engine was inspected, tuned to factory specifications, then operated through a break-in cycle.

b. Deutz F3L912W Engine

The Deutz F3L912W engine is an air-cooled, three-cylinder, in-line, indirect injected, four-cycle industrial diesel engine. The specifications for the F3L912W engine are in TABLE 7, and a photograph of the engine is shown in Fig. 3. The injection system, a pump-line-nozzle arrangement, uses a Bosch three-barrel and plunger in-line pump and Bosch pintle nozzles. This engine was supplied as GFE and had previously been operated. The engine was inspected, tuned to factory specifications, operated through a break-in cycle, and then the clearances of the valves were checked according to specifications. A Deutz dealer recommended that the valve lash adjustments be checked periodically on the air-cooled Deutz engines.

c. Deutz F4L912W Engine

The Deutz F4L912W engine is an air-cooled, four-cylinder, in-line, indirect injected, four-cycle industrial diesel engine. The specifications for the F4L912W engine are in TABLE 8, and a photograph of the engine is shown in Fig. 4. The injection system uses a Bosch four-barrel and plunger in-line pump, and Bosch pintle nozzles in a pump-line-nozzle arrangement. This engine had also been operated previously. The engine was inspected, tuned to factory specifications, then operated through a break-in cycle, after which the lash clearances of the valves were checked with specifications.

TABLE 7. Deutz F3L912W Engine Specifications

Rated Power	34 kW at 2650 rpm
Rated Torque	147 Nm at 1600 rpm
Bore	100 mm
Stroke	120 mm
Displacement	2827 cm^3
Compression Ratio	19:1
Injection Timing, BTDC	
$\leq$ 2300 rpm	15°
$\geq$ 2301 rpm	18°
Injection Pump	Bosch In-Line A Type
Governor	Mechanical
Injection Nozzle	Bosch Throttling Pintle
Combustion Chamber	Two-Stage (Swirl Chamber)

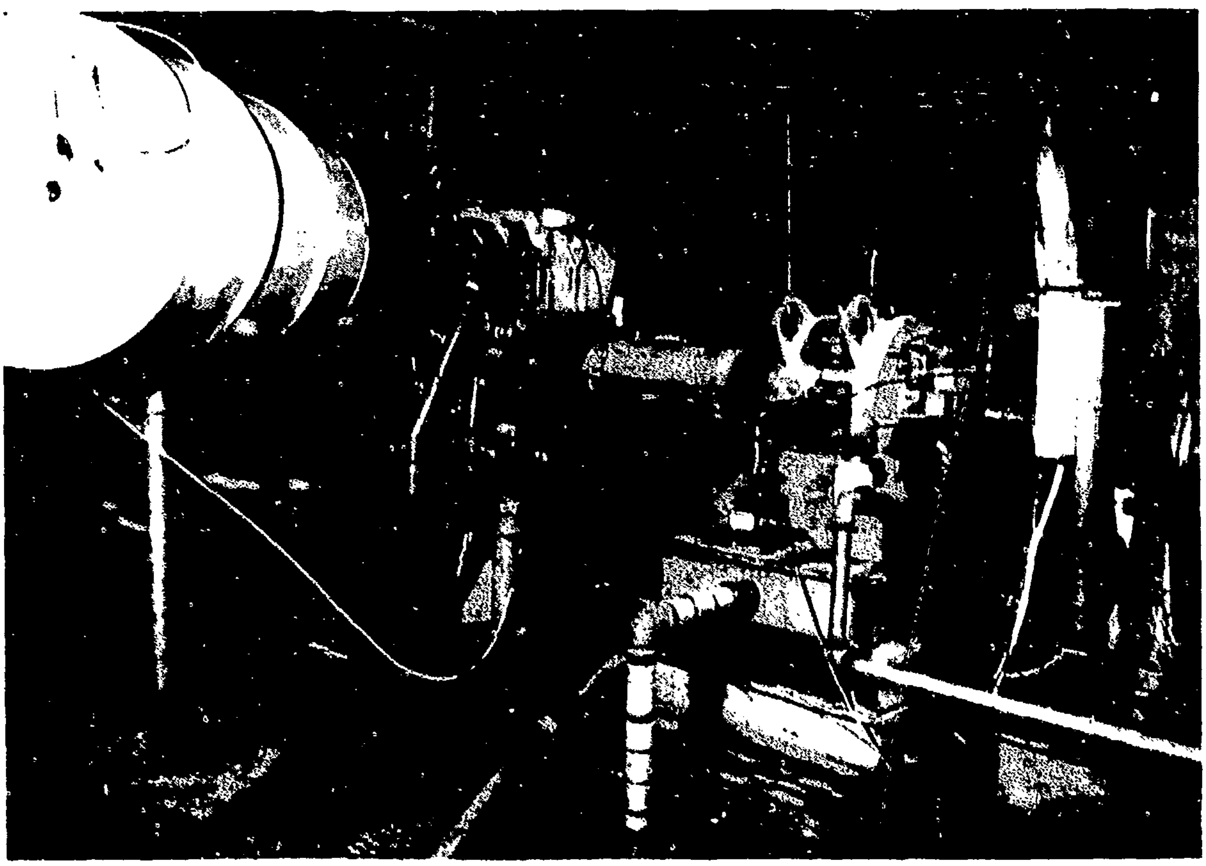

Figure 3. Photograph of Deutz F3L912W engine

TABLE 8. Deutz F4L912W Engine Specifications

Rated Power	44 kW at 2300 rpm
Rated Torque	202 Nm at 1500 rpm
Bore	100 mm
Stroke	120 mm
Displacement	3770 cm^3
Compression Ratio	19:1
Injection Timing, BTDC	
≤ 2300 rpm	15°
Injection Pump	Bosch In-Line A Type
Governor	Mechanical
Injection Nozzle	Bosch Throttling Pintle
Combustion Chamber	Two-Stage (Swirl Chamber)

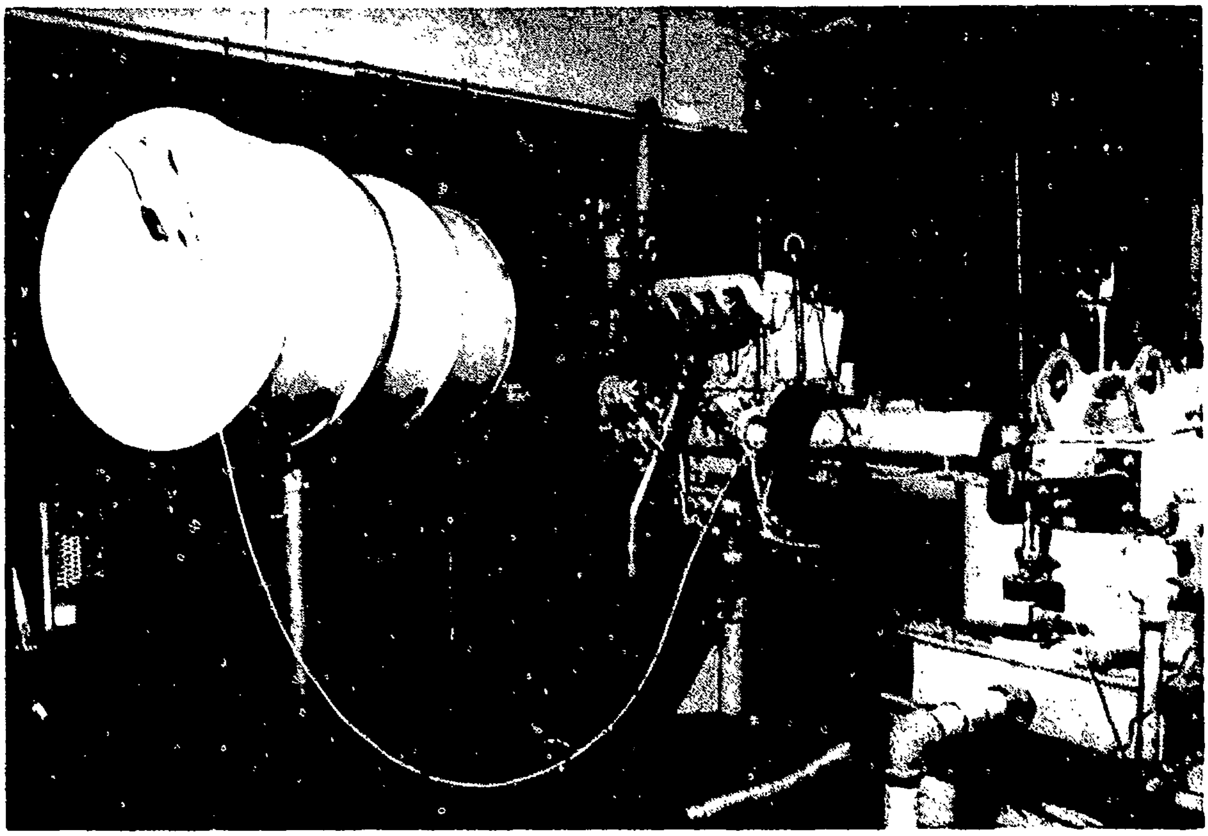

Figure 4. Photograph of Deutz F4L912W engine

d. Perkins 4.154 Engine

The Perkins 4.154 engine is a water-cooled, four-cylinder, in-line, indirect injected, four-cycle industrial diesel engine. The specifications for the 4.154 engine are in TABLE 9. The injection system, a pump-line-nozzle arrangement, uses a Bosch-licensed four-port rotary distributor pump and Bosch pintle nozzles. Since this engine was purchased new for the evaluations, in accordance with specification MIL-T-52932C, it was operated for an extended 80-hour break-in before the start of testing.

TABLE 9. Perkins 4.154 Engine Specifications

Rated Power	41 kW at 2600 rpm
Rated Torque	159 Nm at 1800 rpm
Bore	89 mm
Stroke	102 mm
Displacement	2500 cm^3
Compression Ratio	21:1
Injection Timing (BTDC Static)	14°
Injection Pump	Bosch Rotary VE Type
Governor	Mechanical
Injection Nozzle	Bosch Throttling Pintle
Combustion Chamber	Swirl Chamber

2. Evaluations

a. Emissions

The brake specific emissions results for all the four clean-burn diesel engines, on both JP-8 and MIL-F-46162C, were computed to evaluate the deviations in emission response between the two Army referee fuels, not to certify the engines under MIL-T-52932C. A summary of the mean results for the calculated weighted averages, Society of Automotive Engineers (SAE) J1003 (12), is shown in TABLE 10. The weights utilized for calculating the weighted averages were 0.2 for the average of the three idle modes and 0.08 for each of the other ten modes. The modal emission results, plus duplicates, for all test engines are included in the Appendix. Overall, the weighted average emissions are generally lower with JP-8 fuel when compared to the MIL-F-46162C referee diesel fuel for all four engines tested. The Isuzu C-240 engine revealed equivalent weighted average carbon dioxide emissions, and the Deutz F3L912W engine did have higher weighted average unburned hydrocarbon emissions when utilizing JP-8. A more thorough discussion and analysis of the emission results are included in this report.

TABLE 10. Materials-Handling Equipment Clean-Burn Diesel 13-Mode Weighted Average Emissions

Emission	Perkins 4.154			Isuzu C-240		
g/bhp-hr	1% S DF-2	JP-8	Δ, %	1% S DF-2	JP-8	Δ, %
HC	0.732	0.527	-28.0	0.644	0.627	-2.6
CO	6.602	2.988	-54.7	8.205	2.996	-63.5
NO_X	3.334	2.738	-17.9	5.156	4.193	-18.7
CO_2	565	539	-4.6	565	567	0.4
Part	0.978	0.333	-66.0	4.215	1.862	-55.8
(HC + NO_X)	4.067	3.265	-19.7	5.800	4.820	-16.9

Emission	Deutz F3L912W			Deutz F4L912W		
g/bhp-hr	1% S DF-2	JP-8	Δ, %	1% S DF-2	JP-8	Δ, %
HC	0.312	0.353	13.1	0.602	0.399	-33.7
CO	2.430	1.745	-28.2	2.937	1.850	-37.0
NO_X	8.333	7.724	-7.3	4.920	4.759	-3.3
CO_2	592	573	-3.2	561	541	-3.6
Part	2.196	1.095	-50.1	1.529	0.861	-43.7
(HC + NO_X)	8.645	8.077	-6.6	5.522	5.158	-6.6

Since the brake specific particulate emissions are usually not included in the weighted averages, it was chosen to include them in the summary to reflect the average particulate emissions for both test fuels. The particulate emissions were not measured for all 13 modes; thus weighing factor of 0.167, or the simple average of the 6 modes measured, was utilized in the weighted average particulate emission calculations. When compared to the MIL-F-46162C 1% S referee diesel fuel, a reduction in particulate emissions for all engines is realized when MIL-T-83133C grade JP-8 is utilized in the clean-burn diesel engines. A more thorough discussion and analysis of the fuel property effects on the particulate emissions is included in this report.

b. Performance

The performance data were analyzed for the 13-mode cycle. Performance variables at the peak torque and peak power modes (TABLE 11) indicate that, for three of the engines tested, the power decrement with JP-8 is on the order of the volumetric heating value (Btu/gal.) difference of the test fuels. The volumetric heating value decrement for the JP-8 fuel was 5.4 percent. The power loss due to use of JP-8 is closely related with reduced energy input offset by thermal efficiency gains (due to increased volatility of JP-8 and its effect on the premixed combustion heat release fraction).(13) The reduced energy input is due in part to the lower volumetric heating value of JP-8 and increased leakage in the injection system due to the lower viscosity.

TABLE 11. Percent Deviations for Peak Torque (PT) and Peak Power (PP) Modes

	Perkins 4.154		Isuzu C-240		Deutz F3L912W		Deutz F4L912W	
	PT	PP	PT	PP	PT	PP	PT	PP
Energy, Btu/cycle	-12.8	-14.3	-5.3	-7.4	-7.7	-5.9	-11.2	-9.4
Thermal Efficiency, %	+1.9	+6.7	+1.1	+3.4	+11.0	+4.6	+6.5	+2.5
Power, Bhp	-11.1	-8.6	-4.3	-4.3	+2.3	-1.6	-5.4	-7.1
BSFC, lb/bhp-hr	-3.5	-7.8	-2.7	-4.8	-11.3	-5.9	-7.6	-4.0
BSVC, gal./bhp-hr	+3.0	-1.6	+3.9	+1.6	-5.4	+0.4	-1.4	+2.5
Bosch Smoke Number	-39.1	-69.9	-22.0	-33.3	-21.2	-19.6	-39.8	-46.4

Deviations calculated as [(JP-8 - DF-2)/DF-2]*100.

The Perkins 4.154 engine displays a performance debit greater than would be expected based on heating value comparisons. The Perkins engine uses a rotary distributor injection pump, which was unique from the other three engines. This configuration indicates the rotary distributor pump is more sensitive to fuel viscosity than the in-line pumps used on the other engines.

The Brake Specific Fuel Consumption (BSFC) values indicate the effective conversion of fuel chemical energy to mechanical work. The values at peak torque and peak power conditions indicate that each engine utilizes JP-8 more efficiently than MIL-F-46162C. The Brake Specific Volumetric Consumption (BSVC) is a measure of the effective range of an engine, for a given fuel volume. The data indicate that the Perkins 4.154, Isuzu C-240, and Deutz F4L912W engines would have reductions in range when utilizing JP-8, which mirrors the lower volumetric heating value of the fuel. The Deutz F3L912W engine reveals an increased range at the peak torque mode. TABLE 12 is a brief summary of the averaged BSVC of all modes at the rated torque and rated power speeds for each engine.

TABLE 12. Percent Deviations in Brake Specific Volumetric Consumption for Averaged Rated Torque and Rated Power Speeds

Speed	Perkins 4.154	Isuzu C-240	Deutz F3L912W	Deutz F4L912W
Rated Torque (all modes)	0.7	-3.3	2.90	-2.30
Rated Power (all modes)	-2.9	-3.2	-3.94	-2.61

c. Durability

The Isuzu C-240 engine was disassembled, cleaned, measured, off-specification parts replaced, injection pump calibrated, and then installed on a test stand. A break-in and power check were completed for a durability evaluation with JP-8, and the engine was filled with an SAE 15W-40 lubricant. A 210-hour wheeled vehicle cycle, a high-load cycle that corresponds to 32,187 vehicle kilometers (20,000 vehicle miles), was completed with the Isuzu C-240 engine while operating on JP-8. This test is performed without an oil change, other than the daily additions to makeup for the engine oil consumed during the test. Post-test wear measurements and performance evaluations indicated the engine was still within specifications. The 210-hour used engine oil analysis revealed a viscosity increase from 13.55 cSt at 100°C to 61 cSt at 100°C, and a Thermal Gravimetric Analysis (TGA) soot level of 6.93 percent. The Total Acid Number (TAN) was 4.76 at 210 hours, increasing from an initial 2.35 mg KOH/g, and the Total Base Number (TBN) was 1.40, decreasing from an initial 8.02 mg KOH/g.

The engine was disassembled, measured, cleaned, inspected for worn parts; then reassembled and installed on the test stand for a durability evaluation with the MIL-F-46162C fuel. The test evaluation with the MIL-F-46162C fuel was halted at 70 hours due to rough engine operation and severe oil thickening. When the oil was changed, the engine proceeded to run rough, at which time the test was terminated. Upon engine inspection, it was found all rings in cylinder three were stuck, which was leading to excessive blowby and poor engine performance. A Thermal Gravimetric Analysis (TGA) of the oil revealed 8.76-percent soot in the 70-hour oil sample with the MIL-F-46162C fuel. The 70-hour oil sample viscosity with MIL-F-46162C was 4,832 cSt at 100°C. The oil used for both fuel evaluations was identical with an initial viscosity of 13.55 cSt at 100°C. The TAN was 8.70 at 70 hours, increasing from an initial 2.35 mg KOH/g, and the TBN was 0.27, decreasing from an initial 8.02 mg KOH/g.

The Isuzu C-240 engine was rebuilt with new cylinder components, and the test initiated with the MIL-F-46162C fuel. The test was terminated at 30 hours due to poor engine operation. Upon inspection, the rings in all cylinders were stuck, primarily due to oxidation and subsequent deposition of the engine oil. A Thermal Gravimetric Analysis (TGA) of the used engine oil at 30 hours revealed 5.89-percent soot. The viscosity increased to 544 cSt at 100°C from an initial 13.55 cSt at 100°C. The TAN was 3.90 at 30 hours, increasing from an initial 2.35 mg KOH/g, and the TBN was 1.19, decreasing from an initial 8.02 mg KOH/g. A summary of the new and used oil analysis for the three tests is shown in TABLE 13.

From the particulate emissions data shown in TABLE 10, it can be noted the Isuzu C-240 engine produced significantly higher levels of particulate matter with the DF-2 fuel compared to the

TABLE 13. New and Used Oil Analysis for the Isuzu C-240 Engine Durability Tests With JP-8 and MIL-F-46162C

Fuel	JP-8/DF-2	DF-2	DF-2	JP-8
Test Hours	0	30 EOT*	70 EOT	210 EOT
Viscosity at 100°C, cSt	13.55	544	4832	61.0
TGA Soot, %	0	5.89	8.76	6.93
TAN, mg KOH/gr	2.35	3.90	8.70	4.76
TBN, mg KOH/gr	8.02	1.19	0.27	1.40

* EOT = End of Test.

levels with JP-8. The excess exhaust particulate appears to be detrimental to the engine durability. A synopsis of the durability results indicated that the engine performed well with JP-8 for the 210-hour wheeled vehicle cycle, while it appeared to have an oil thickening, oxidation problem with the 1% S MIL-F-46162C referee fuel. The results of this testing indicate that the utilization of JP-8, at least in the Isuzu C-240 engine, provides improvements in durability over a representative high-sulfur fuel such as MIL-F-46162C. Although some level of improvement was expected in the oil oxidation and engine deposit levels, the broad separation in performance realized was not envisioned.

B. Rough-Terrain Forklifts

All rough-terrain forklift evaluations, load placement, steady-state fuel consumption, acceleration, and gradability were performed utilizing the JP-8 fuel shown in TABLE 3 and the Reference No. 2 diesel fuel (Cat 1-H) shown in TABLE 14.

Each vehicle during its respective evaluation was instrumented with the equipment shown in TABLE 15. The load-placement tests were performed for 1 hour, in duplicate, with a course layout and spacing as described in MIL-T-53038(ME).(14) The steady-state fuel-consumption

TABLE 14. Inspection Properties of Diesel Fuel Utilized for Rough-Terrain Forklift Evaluations

Property	ASTM Method	Ref. No. 2 Diesel Fuel Requirements	Test Fuel AL-19657-F
Sulfur, wt%	D 4294	0.48 to 0.42	0.4
Hydrogen, wt%	D 3178	NR*	13.15
Carbon, wt%	D 3178	NR	86.85
Distillation, °C	D 86		
Initial Boiling Point		NR	207
10% Evaporation		NR	239
50% Evaporation		260 to 277	268
90% Evaporation		310 to 327	321
95% Evaporation		NR	338
End Point		343 to 366	351
Residue, vol%		NR	0.8
Gravity, °API	D 1298	33.0 to 35.0	34.2
Density, kg/L	D 1298	NR	0.853
Flash Point, °C	D 93	60, min	84
Cloud Point, °C	D 2500	NR	-4
Pour Point, °C	D 97	-7, max	-9
K. Vis, cSt, at 40°C	D 445	2.0 to 4.0	2.93
Net Heat of Combustion,	D 240		
MJ/kg		NR	42.42
Btu/lb		NR	18,235
Btu/gal.		NR	129,658
Cetane Number	D 613	47 to 53	48.9
Cetane Index	D 976	NR	46.2
Ash, wt%	D 482	0.01, max	0.001
Carbon Residue, 10% Bottoms, wt%	D 524	0.20, max	0.1
Particulate Contamination, mg/L	D 2276	NR	0.6
Water and Sediment, vol%		0.05, max	0.012

* NR = No Requirement.

TABLE 15. Instrumentation Utilized for Materials-Handling Equipment Rough-Terrain Forklift Evaluations

Vehicle Speed

Fifth Wheel With Speed and Distance Computer (GFE)

Fuel Flow

EMCO/Fluidyne PDP-3D 0 to 100 gal./hr Positive Displacement Transducer

EMCO DFP-1120-RT-24VDC Digital Flow Rate Indicator With Totalizer

EMCO 1201D Return Fuel Day Tank

Fuel System

External 114-liter (30-gal.) JP-8/DF-2 Fuel Tanks

Holley Model 12-802 416-liter/hr (110-gal./hr) at 14 psig Electric Fuel Transfer Pump

10-micrometer Primary Fuel Filter

Return Fuel Heat Exchanger

Braided 13-mm (1/2-in.) Fuel Lines With Quick Disconnects

Temperatures

Type J Thermocouple — Fuel Inlet, Fuel Return, Fuel Day Tank, and Oil Sump

Type K Thermocouple — Exhaust System Outlet

Data Recording

Metrosonics dl-714 Analog Programmable Data Logger

Zenith Z-180 Laptop Personal Computer

evaluations were performed by driving the vehicle around the Belvoir Engineering Proving Grounds (BEPG) 2100-meter (1.3-mile) test track for three circuits at the test speed. The distance was measured with a fifth wheel, and the time was kept with calibrated stop watches.

Although the BEPG track did contain grades, the operator was able to maintain the test speeds for the complete circuit.

The accelerations were performed on a time-to-distance basis, on a level portion of the BEPG test circuit, utilizing prepositioned course markers. The acceleration times were performed with and without capacity loads, and measured six times per loading. The gradability portion of the evaluations was performed on a 45-percent slope available at the BEPG. A 11-meter (35-foot) test section was positioned on the grade, at a point where the grade was reasonably constant, utilizing dual markers at the start and stop section of the test section. The forklifts were operated utilizing a capacity load, with the operator starting or stopping the stopwatch when the course markers were aligned with the vehicle operator. The speed-on-grade evaluations were performed six times.

TABLE 16 summarizes the rough-terrain forklift evaluations. The load-placement results indicate fuel consumption under an operating condition typical to the forklifts. The results show higher fuel-consumption rate for the M4K and lower consumption rates for the M6K and M10A when utilizing JP-8. The steady-speed fuel-consumption determinations were to measure the part-rack fuel-economy deviations. The M6K revealed equivalent average fuel consumption at the two speeds evaluated, while the M10A showed an unexpectedly large decrease in fuel economy with JP-8. The decrease in fuel economy was expected to be on the order of the reduction in volumetric heating value of the JP-8.

The accelerations and speed-on-grade are measures of power availability with the test fuels. Under acceleration, the time-to-distance was longer for both the M6K and M10A in both the loaded and unloaded conditions. This increased time-to-distance indicates less power available with JP-8. The M4K revealed mixed results for the time-to-distance under the two loadings. For the speed-on-grade, the M4K revealed equivalent times using JP-8. The M6K displayed a reduced speed larger than expected from the volumetric heating value difference between JP-8 and DF-2. The M10A had a faster speed-on-grade when utilizing JP-8.

TABLE 16. MHE Rough-Terrain Forklift Evaluations Summary
Percent Deviations of JP-8 From DF-2

Test	Vehicle		
	M4K	M6K	M10A
Load Placement Fuel Consumption, liter/hr (gal./hr)	5.8	-2.4	-5.9
Steady-Speed Fuel Consumption, mpg			
16 km/hr (10 mph), with capacity load	ND*	1.9	-19.3
24 km/hr (15 mph), with capacity load	ND*	-1.9	-10.9
Acceleration to 46 m (151 ft), seconds			
With capacity load	-0.6	4.9	1.1
Without capacity load	2.1	1.8	3.1
Acceleration to 92 m (302 ft), seconds			
With capacity load	4.2	5.0	1.1
Without capacity load	0.0	1.6	3.3
Speed on 45-Percent Grade, m/s (ft/s)			
With capacity load	0.0	-17.4	2.3

* ND = Not Determined due to unavailability of fifth wheel.

V. DISCUSSION OF RESULTS

A. Clean-Burn Diesel Engines

1. Emissions

The exhaust emission of a diesel engine is a function of engine configuration, engine power levels, and fuel properties. The two basic engine types, direct injected (DI) and indirect injected (IDI), exhibit different exhaust emission characteristics. IDI diesel engines typically exhibit greater air utilization, resulting in lower smoke and particulate levels than the DI counterpart engines at equivalent air/fuel ratios.(15) Carbon monoxide emissions, typically low in DI diesel engines due to lean air/fuel ratios, are generally lower in the IDI engine. This lower emission rate is due to high primary and secondary swirl, which mixes the unburned fuel and air and tends toward more complete combustion. Unburned hydrocarbons are lower with the IDI due to the turbulent fuel/air mixing, hotter combustion chamber walls, which reduce quench zones, and fuel rich combustion zones, which avoids overleaning.(16,17) NO_X is lower with the IDI engine because fuel-rich combustion occurring in the swirl chamber reduces NO formation (NO_X precursor), with peak NO_X occurring around half load.(17) The engines evaluated as clean-burn diesels were all indirect injected diesel engines.

Engine speed and engine load are two factors that combine to describe the power level at which an engine is operating. Engine speed is defined as the crankshaft angular velocity in revolutions per minute (rpm). Engine speed affects exhaust emissions by affecting the time available for specific physical events to occur. For example, higher engine speeds decrease residence time for heat transfer, while increasing the mass motion, which affects the convective heat transfer coefficient. Heat transfer influences flame quenching and gas temperatures, which have an effect on unburned hydrocarbons and NO_X, respectively. The variation of mass motion with engine speed also impacts fuel/air mixing. This fuel/air mixing may result in overleaning or undermixing, affecting unburned hydrocarbons.(16)

The engine load is the work in N-m (ft-lbf) produced by the engine. The diesel engine operates unthrottled, thus for a given engine speed, a similar mass of air is consumed regardless of shaft work produced. The mass fuel consumption (energy input) is the variable that governs the capability of an engine to produce an amount of work. Intuitively, the fuel is the source of all exhaust emissions, and the mass air/fuel ratio (AFR) is the relative measure of the oxidizer and fuel available for the combustion process. The chemically correct quantity of a specified fuel and air for complete combustion is known as the stoichiometric AFR. For a diesel engine the AFR has a major influence on the exhaust emissions. Generally, the AFR affects the temperatures reached during combustion, which, in turn, affect NO_X formation, and the oxidation of particulate and hydrocarbons. Carbon monoxide emissions are considered unimportant in diesel engines because these engines operate on the lean side of the stoichiometric AFR.(16)

As the primary source of emissions, it is expected that fuel properties would have an effect on diesel exhaust emissions. These effects have prompted the Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) to regulate several diesel fuel properties. These regulations are set to be enacted in October 1993 for all diesel fuels sold in National Ambient Air Quality Standard nonattainment zones. Several fuel properties being regulated include fuel sulfur, cetane number, and aromatic hydrocarbons. The sulfur content has a profound effect on diesel engine particulate. The present ASTM D 975 specification level of 0.5 wt% is being reduced to 0.05 wt% by the emission regulating bodies.(18) The cetane number affects both cold start white smoke and black smoke under load. Higher cetane numbers decrease all regulated gaseous emissions and lower particulate. EPA will require a 40 cetane number minimum, while CARB will require 45 minimum. Lowering fuel aromatic content will reduce both gaseous and particulate emissions, with the effects being more pronounced during transient emission testing.(18) The EPA requirement for fuel aromatic content will be 35 wt% aromatic maximum, while CARB will be 10 wt% aromatic maximum.

Fuel properties can also affect diesel exhaust emissions by affecting the power production of the engine. In this fuel comparison, the lower energy content, lower viscosity, and lower density of JP-8 result in lower AFR at full rack with JP-8. This leaning effect at full-rack accounts for most of the emissions variations between the two fuels. From TABLES 3 and 4, it can be seen that sulfur, cetane number, and aromatic content vary considerably for the test fuels. The values for MIL-T-83133C JP-8 were 0.07-percent sulfur, 42 cetane number, and 20-percent aromatic content. The MIL-F-46162C 1% S referee diesel fuel had 0.95-percent sulfur, 39.4 cetane number, and 55-percent aromatic content. With respect to the fuel properties and the aforementioned discussion, the clean-burn diesel engines should realize lower emissions with the JP-8 fuel.

a. Isuzu C-240 Engine

The averaged brake specific hydrocarbon and NO_X emissions for the Isuzu C-240 engine are shown in Fig. 5 for all loads at the two speeds evaluated. The 2000-rpm engine speed represents

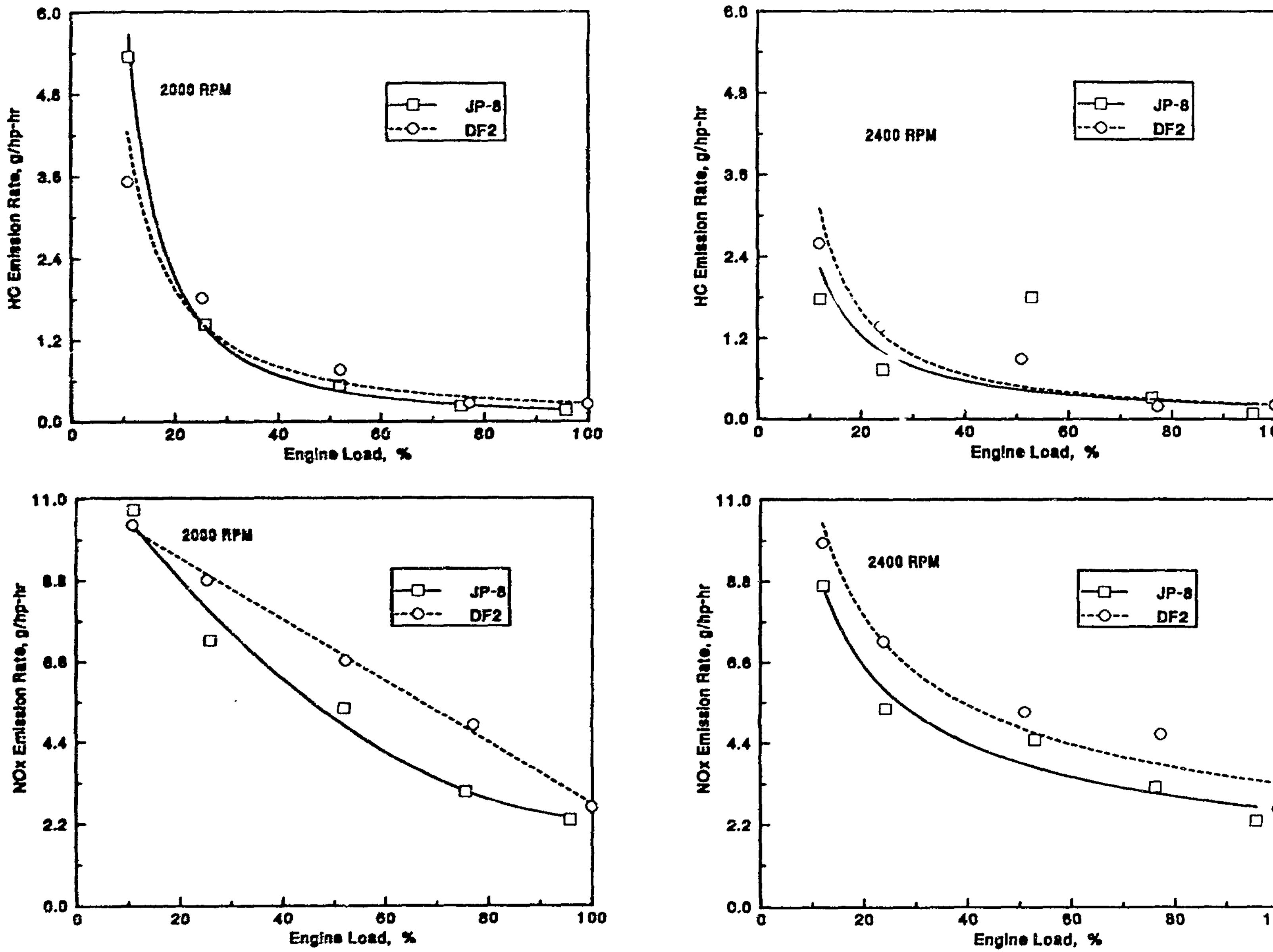

Figure 5. Isuzu C-240 engine specific mass emissions for unburned hydrocarbons and NOx

the speed for maximum torque, and 2400 rpm is the speed for maximum power. The data for each speed are plotted as a percentage of the maximum engine load obtained with the referee DF-2 fuel. The unburned hydrocarbon results generally indicate that JP-8 lowers emissions, except for the lightest load at 2000 rpm and the 50-percent load at 2400 rpm. Both the JP-8 and DF-2 show hydrocarbon emission increases, which appear uncharacteristic at the 50-percent load, 2400-rpm condition. The high value for JP-8 was influenced by an extremely high hydrocarbon reading during the second evaluation. The higher engine speed reveals lower hydrocarbon emissions, most likely due to better fuel/air mixing and less flame quenching due to the reduced residence time for heat transfer. The NO_X results for the two speeds indicate reduced emissions utilizing JP-8 for most of the loads evaluated. Lower NO_X emissions generally indicate lower maximum flame temperatures during combustion. Both unburned hydrocarbons and NO_X react photochemically to form ground-based ozone, which is an irritant.(17)

The averaged brake specific carbon monoxide and particulate emissions for the Isuzu C-240 engine are shown in Fig. 6 for all loads evaluated at the two speeds. The carbon monoxide results are generally equivalent or lower when JP-8 is utilized. The exception appears to be the 50-percent load at 2400 rpm, which is consistent with the unburned hydrocarbon results. Carbon monoxide is a product of incomplete combustion, most prevalent at light loads and full rack, and is affected by AFR. The full-rack data (100% load) demonstrates the leaning effect of using JP-8. The engine speeds reveal similar carbon monoxide emission response. The particulate results for the two speeds indicate reduced emissions utilizing JP-8 for all the loads evaluated. The fuel sulfur difference contributes to the lower particulate emissions with JP-8, but so does the leaning effect at full rack. Particulate increases at light loads are most likely due to mixture leaning, incomplete fuel droplet combustion, and reductions in particulate and hydrocarbon oxidation. Particulate in the IDI engine is dominated by hydrocarbons at light-load and carbon particles at high loads.(16) The speed effects indicate the highest particulate levels are generally at the speed for maximum torque and full rack.

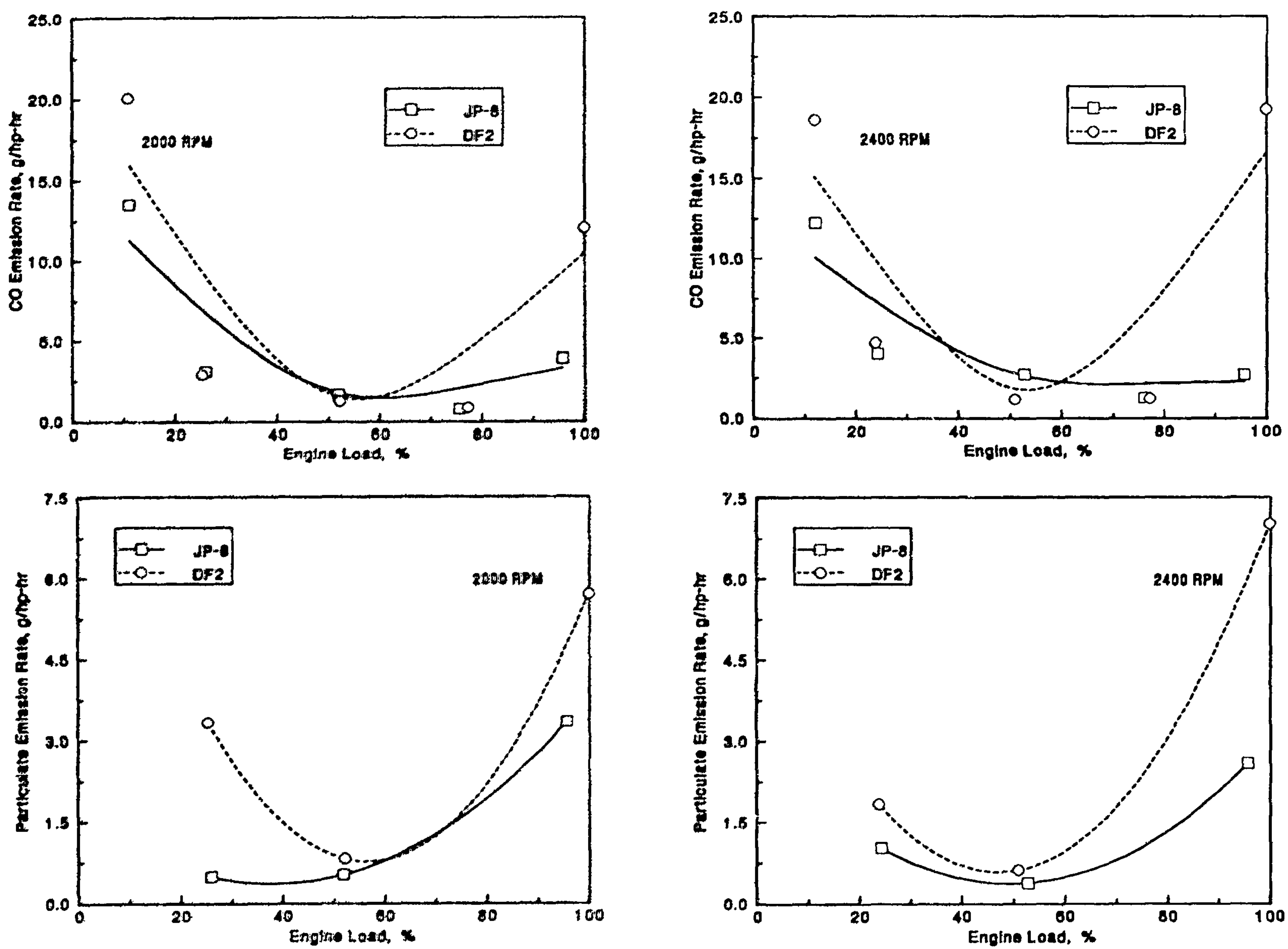

Figure 6. Isuzu C-240 engine specific mass emissions for carbon monoxide and particulates

b. Deutz F3L912W Engine

The averaged brake specific hydrocarbon and NO_X emissions for the Deutz F3L912W engine are shown in Fig. 7 for all loads at the two speeds evaluated. The 1600 rpm and 2650 rpm engine speeds represent the speeds for maximum torque and maximum power, respectively. Again the data for each speed are plotted as a percentage of the referee DF-2 load. The unburned hydrocarbon results indicate JP-8 has lower or equivalent emissions at 1600 rpm, except at light loads. The hydrocarbon emissions increase with JP-8 at all loads at 2650 rpm. The higher engine speed reveals greater overall hydrocarbon emissions, which indicate possible flame quenching and undermixing. Undermixing occurs when poorly atomized fuel at the end of the injection event results in locally fuel rich zones. The NO_X results indicate equivalent emissions when utilizing JP-8 for the loads and speeds evaluated.

The averaged brake specific carbon monoxide and particulate emissions for the Deutz F3L912W engine are shown in Fig. 8 for all loads evaluated at the two speeds. The carbon monoxide results are generally equivalent or lower when JP-8 is utilized. The leaner AFR at full rack with JP-8 demonstrates the leaning effect on carbon monoxide emissions. The engine speeds reveal similar carbon monoxide emission response. The particulate results for the two speeds indicate reduced emissions utilizing JP-8 for all the loads evaluated. Again fuel sulfur and leaner AFR at full rack contribute to the lower particulate emissions with JP-8. Particulate increases are seen at light loads for reasons discussed earlier. The highest particulate mass emissions for both fuels appear at the speed for maximum torque and full rack.

c. Deutz F4L912W Engine

The averaged brake specific hydrocarbon and NO_X emissions for the Deutz F4L912W engine are shown in Fig. 9 for the loads and speeds evaluated. The 1500 rpm and 2300 rpm engine speeds represent the speed for maximum torque and maximum power, respectively. Data for each speed are plotted as a percentage of the referee DF-2 load. The unburned hydrocarbon results indicate JP-8 has equivalent emissions at 1500 rpm at all loads. The hydrocarbon emissions decrease

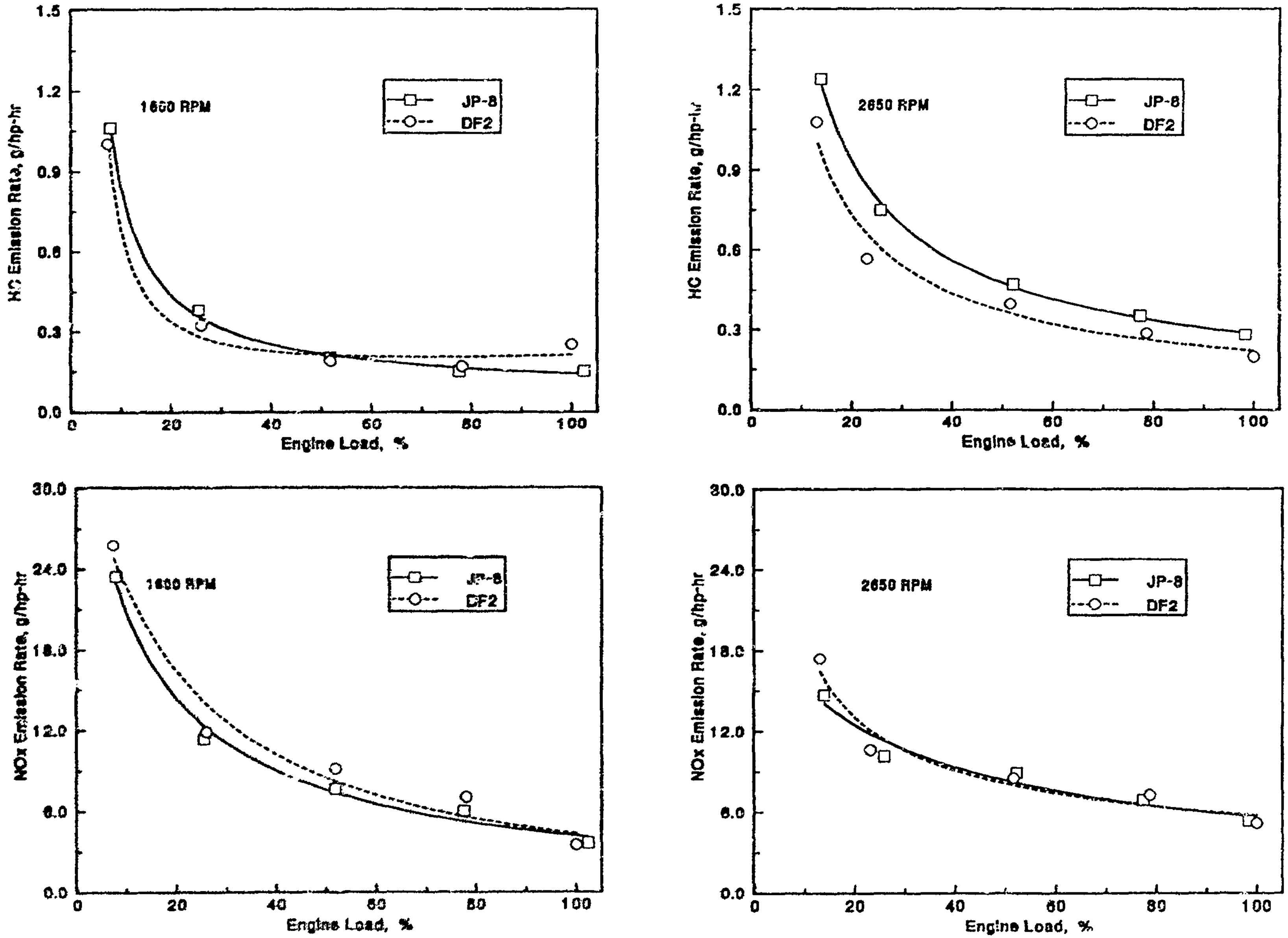

Figure 7. Deutz F3L912W engine specific mass emissions for unburned hydrocarbons and NO_x

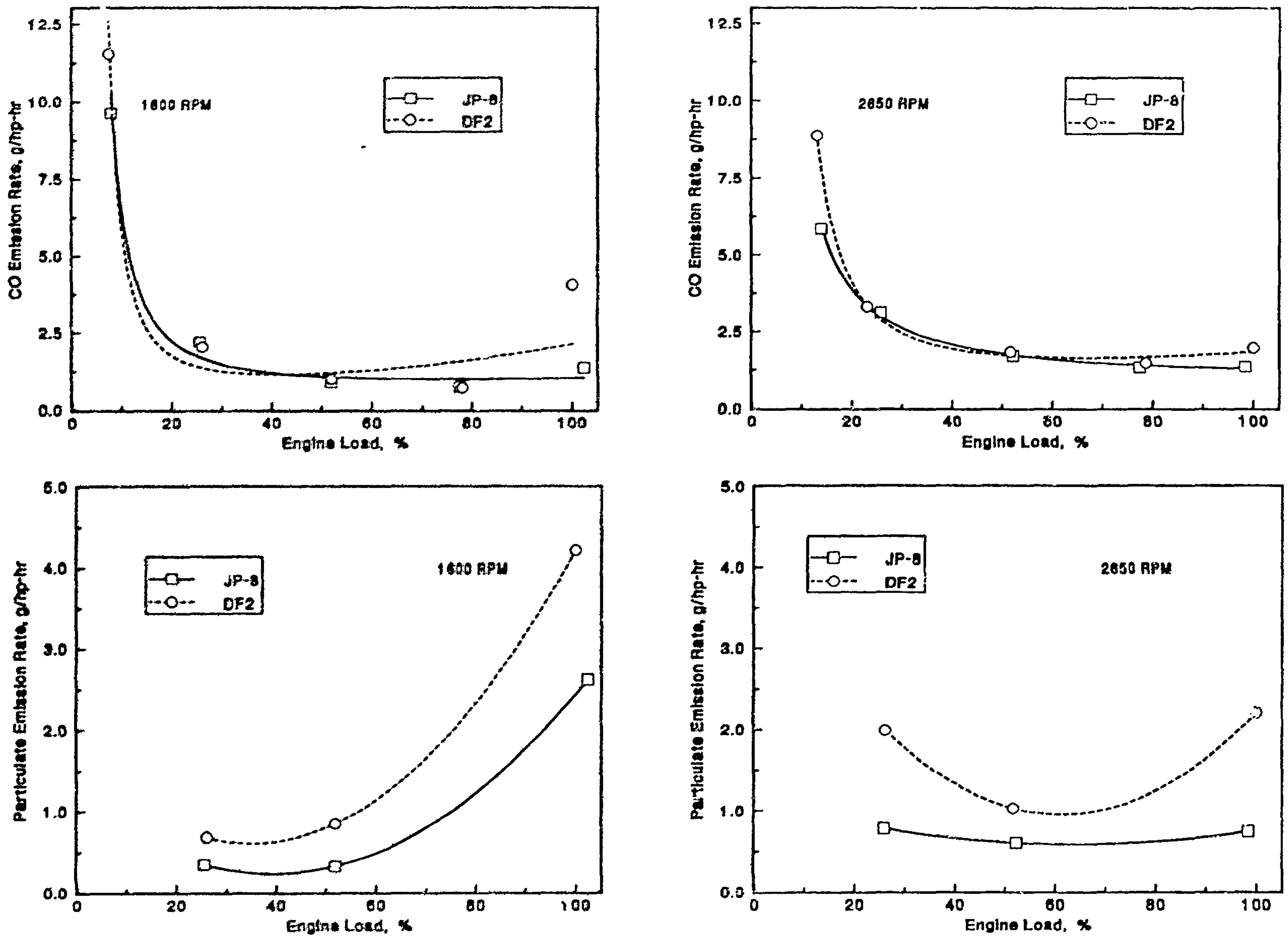

Figure 8. Deutz F3L912W engine specific mass emissions for carbon monoxide and particulates

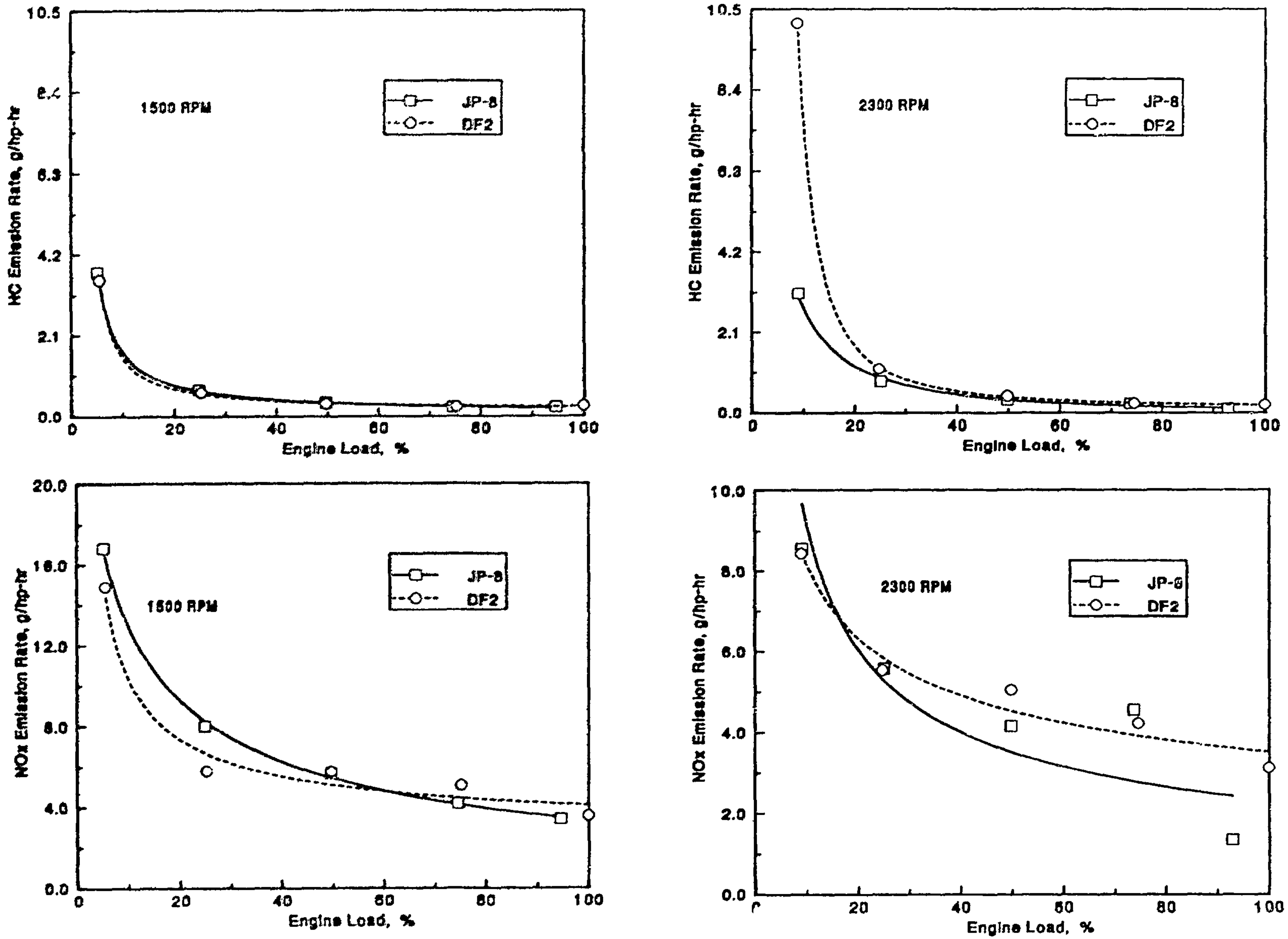

Figure 9. Deutz F4L912W engine specific mass emissions for unburned hydrocarbons and NO_x

slightly with JP-8 at all loads at 2300 rpm. The higher engine speed reveals equivalent overall hydrocarbon emissions, except at light load with the 1% S referee DF-2. The NO_X results indicate higher emissions for JP-8 at 1500 rpm and light loads. This condition indicates higher flame temperatures with JP-8 at light loads. At 2300 rpm, the JP-8 NO_X emissions are slightly lower. Overall, NO_X emissions appear to be lower at the higher engine speed.

The averaged brake specific carbon monoxide and particulate emissions for the Deutz F4L912W engine are shown in Fig. 10 for all loads and speeds evaluated. Similar or lower carbon monoxide emissions result with the use of JP-8, at both 1500 and 2300 rpm. The leaner full-rack AFRs with JP-8 are seen as lower carbon monoxide emissions. The engine speeds reveal similar carbon monoxide emission response, except at the light load with DF-2. This result coincides with the hydrocarbon data, indicating possible overleaning and incomplete combustion at light load with the DF-2. The particulate results for the two speeds indicate reduced emissions utilizing JP-8, except for the 25-percent load at 1500 rpm. At this load condition, the AFR was richer with JP-8, which contributes to the higher particulate. Fuel sulfur and leaner AFR at full rack contribute to the lower particulate emissions with JP-8. Particulate emissions show a speed dependency with the Deutz F4L912W engine. The increases seen at light loads at 2300 rpm coincide with data seen earlier. The highest particulate mass emissions for JP-8 appear at the speed for maximum torque and full rack.

d. Perkins 4.154 Engine

The averaged brake specific hydrocarbon and NO_X emissions for the Perkins 4.154 engine are shown in Fig. 11 for the loads and speeds evaluated. The 1800 and 2600 rpm engine speeds represent the speed for maximum torque and maximum power, respectively. The unburned hydrocarbon results indicate JP-8 has similar emissions at 1800 rpm with lower values at the light loads. The JP-8 hydrocarbon emissions are comparable to DF-2 at the 2600-rpm load. The two engine speeds reveal similar response to load of the unburned hydrocarbon emissions. The NO_X results indicate diminished emissions for JP-8 at both speeds and all loads. Except at the lightest load, overall NO_X emissions appear to be equivalent at the two engine speeds.

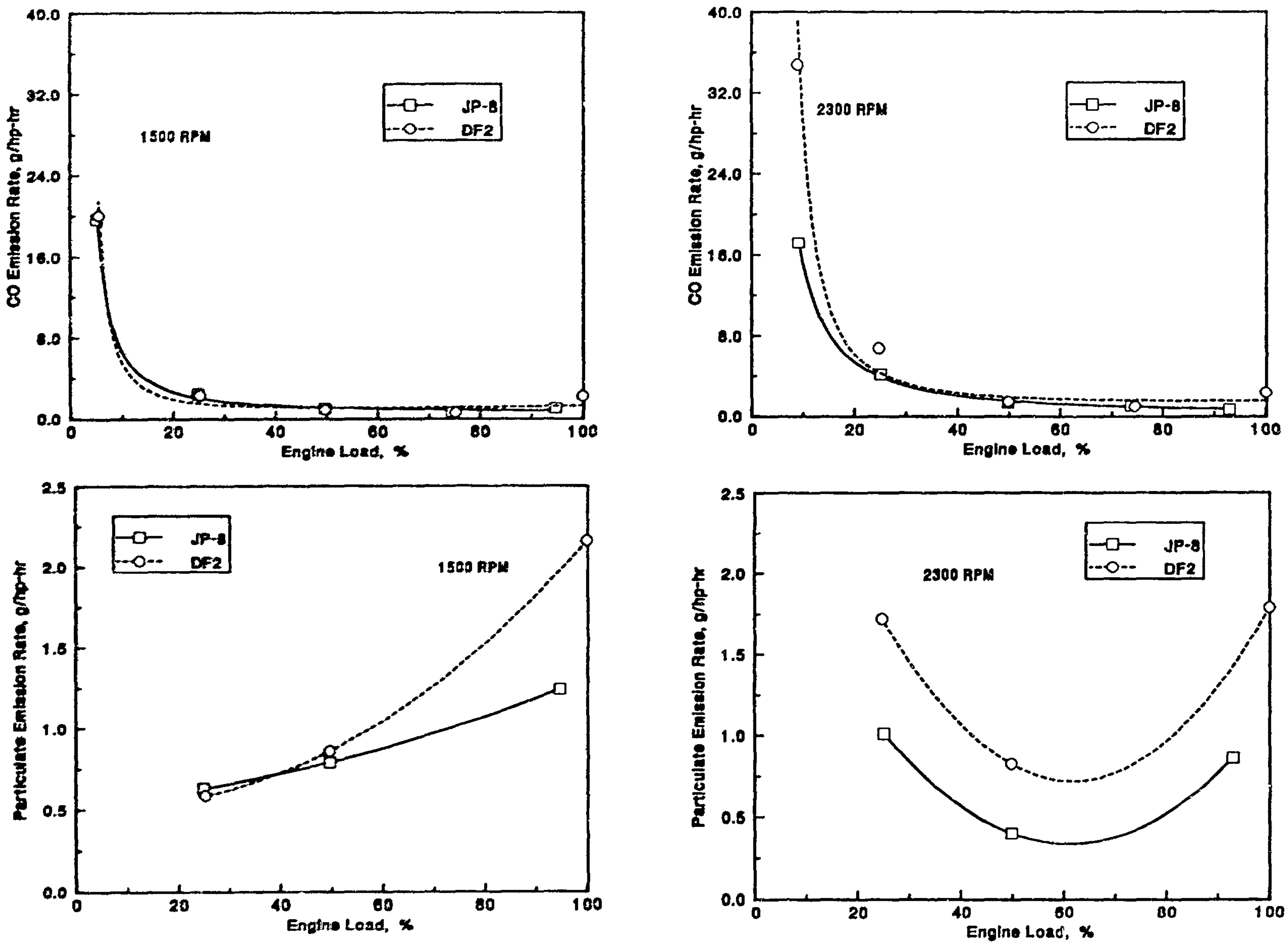

Figure 10. Deutz F4L912W engine specific mass emissions for carbon monoxide and particulates

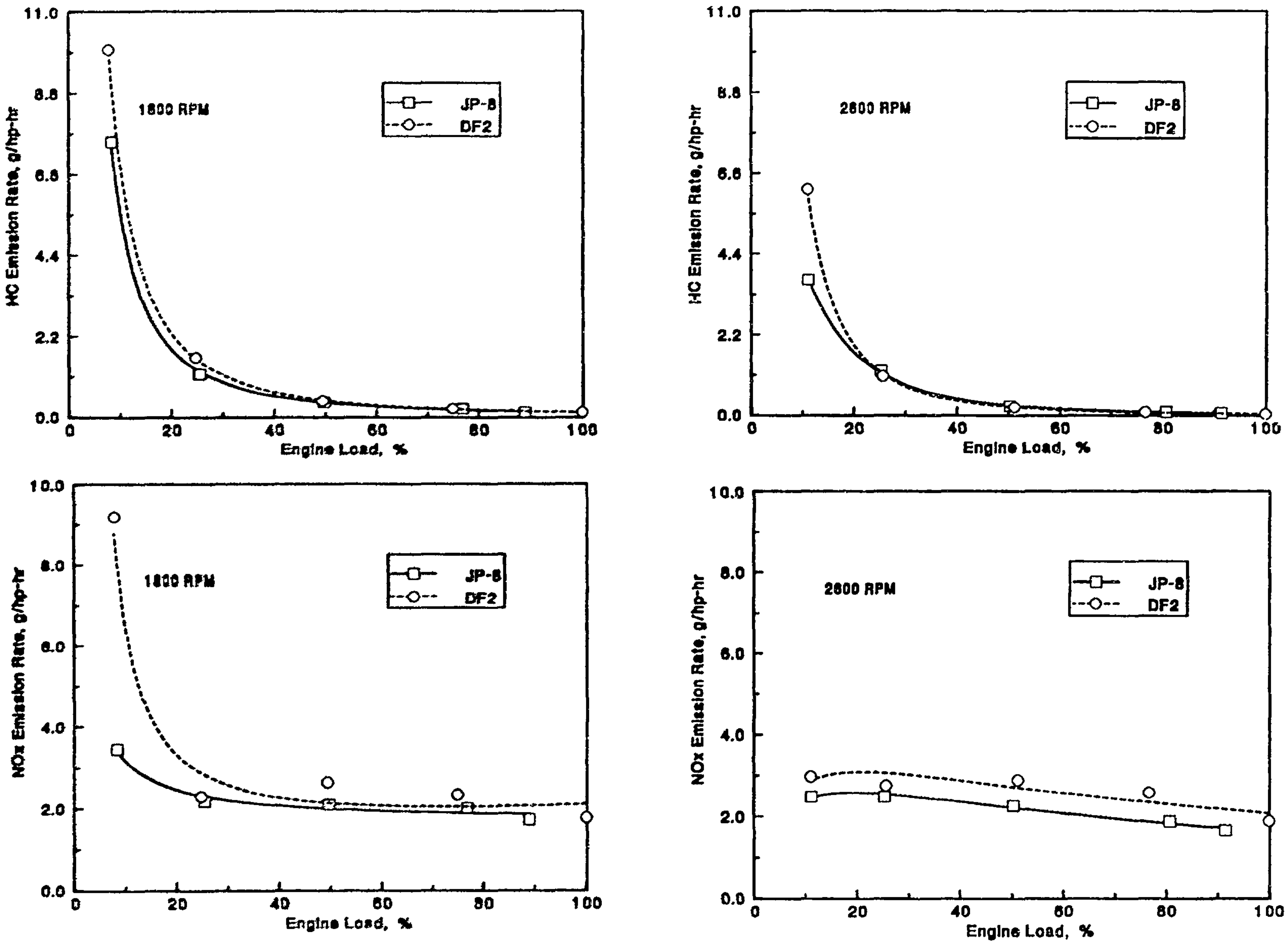

Figure 11. Perkins 4.154 engine specific mass emissions for unburned hydrocarbons and NOx

The averaged brake specific carbon monoxide and particulate emissions for the Perkins 4.154 engine are shown in Fig. 12 for all loads and speeds evaluated. Similar or lower carbon monoxide emissions result with the use of JP-8, at both 1800 and 2600 rpm. The increased engine speed tends to lower carbon monoxide emissions at light loadings, except for the DF-2 response. Particulate results for the two speeds indicate reduced emissions utilizing JP-8, except for the 25-percent load at 1500 rpm. Light-load particulate increase is due to incomplete combustion of fuel droplets. Substantially leaner full-rack AFR contribute to the lower particulate emissions with JP-8 at the full-rack loads. It should be noted that the reduced full-rack loads with JP-8 are due to pumping losses in the fuel injection pump and the lower fuel energy density. A speed sensitivity of the particulate emissions is seen with the Perkins 4.154 engine. The highest particulate mass emissions for JP-8 appear at the speed for maximum torque and partial rack.

In reviewing these results, it should be kept in mind that a deviation from the 13-mode procedure occurred for these evaluations at the lightest load condition at each speed. The procedure calls for 2-percent load, which indicates a motoring dynamometer would be required to overcome engine and driveline friction to maintain loading. A motoring dynamometer was not available for these evaluations, so the tests were performed at the minimum stable load obtainable, which was generally around 10 percent. Overall, the emission results presented indicate the clean-burn diesel engines respond to the fuel properties, which are known to affect emissions. In general, MIL-T-83133C grade JP-8 lowers emissions with respect to the MIL-F-46162C 1% S referee diesel fuel.

2. Performance

Performance variables for each engine were evaluated for all loads at each of the two test speeds. The partial-load points for each engine at each speed were performed as a percentage of the maximum obtained load with the referee DF-2. This procedure simulates an operator extracting the same work from the engine regardless of fuel being used. The partial-load points should reflect the fuel-consumption differences between the fuels. The full-rack points dictate the maximum torque and power difference between the test fuels.

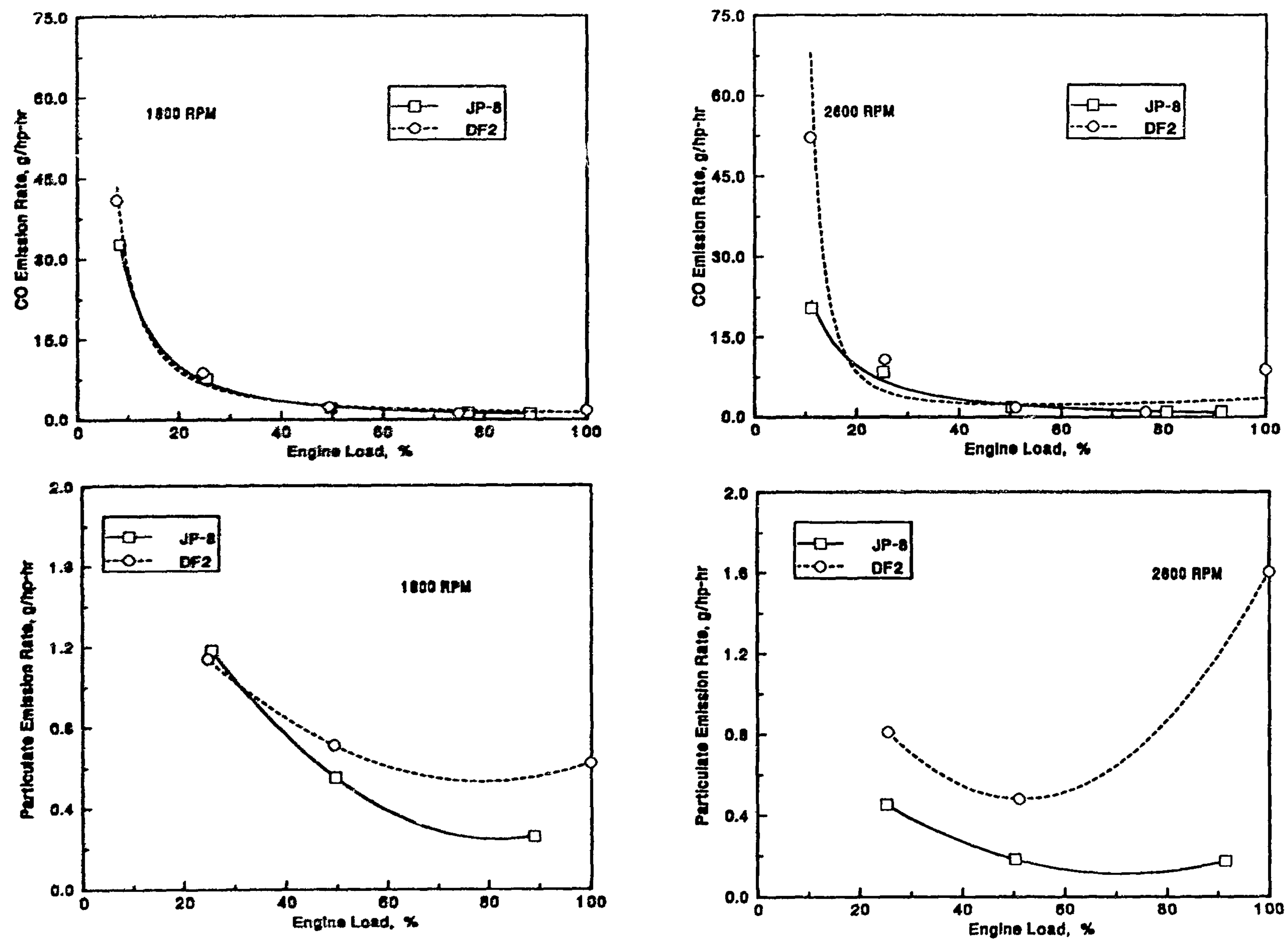

Figure 12. Perkins 4.154 engine specific mass emissions for carbon monoxide and particulates

a. Isuzu C-240 Engine

The brake horsepower and air/fuel ratio at both speeds are illustrated in Fig. 13 for the Isuzu C-240 engine. The partial-load points indicate the engine evaluations at constant power with both fuels were quite consistent. The results also indicate lower maximum power at full rack, for both speeds, when the engine is operated on JP-8. Generally for both speeds, at the loads evaluated, the air/fuel ratios for JP-8 are leaner than for the referee DF-2. Leaner air/fuel ratios are higher numerical values. The approximate stoichiometric air/fuel ratio for middle distillate fuels is 14.7:1.

Fig. 14 is a record of the fuel energy input into the engine and the brake specific volumetric fuel consumption (BSVC). The energy input values at part load coincide with the brake horsepower, i.e., equivalent power output is dictated by equivalent energy input. The curvature of the energy input line is most likely due to differences in engine conversion efficiencies at the various loads. The BSVC is essentially a measure of the work available for a volume of fuel. Since equipment fuel cell volumes are generally fixed, it is an indication of range of a vehicle. The results indicate an increase in fuel consumption when utilizing JP-8. A rule of thumb estimate for this increase is the heating value difference of the test fuels, which for these evaluations was 5.4 percent.

Engine thermal efficiency and Bosch smoke number are displayed in Fig. 15 for both speeds. The Isuzu C-240 engine shows similar thermal efficiencies at both speeds. The largest difference in thermal efficiency appears at 2400 rpm and full rack. The smoke numbers indicate equivalent or lower concentration of soot in the exhaust when utilizing JP-8.

b. Deutz F3L912W Engine

The brake horsepower and air/fuel ratio at both speeds are shown in Fig. 16 for the Deutz F3L912W engine. The partial-load points indicate the engine evaluations at constant power were consistent. The results indicate higher full-rack power at 1600 rpm when the engine is operated

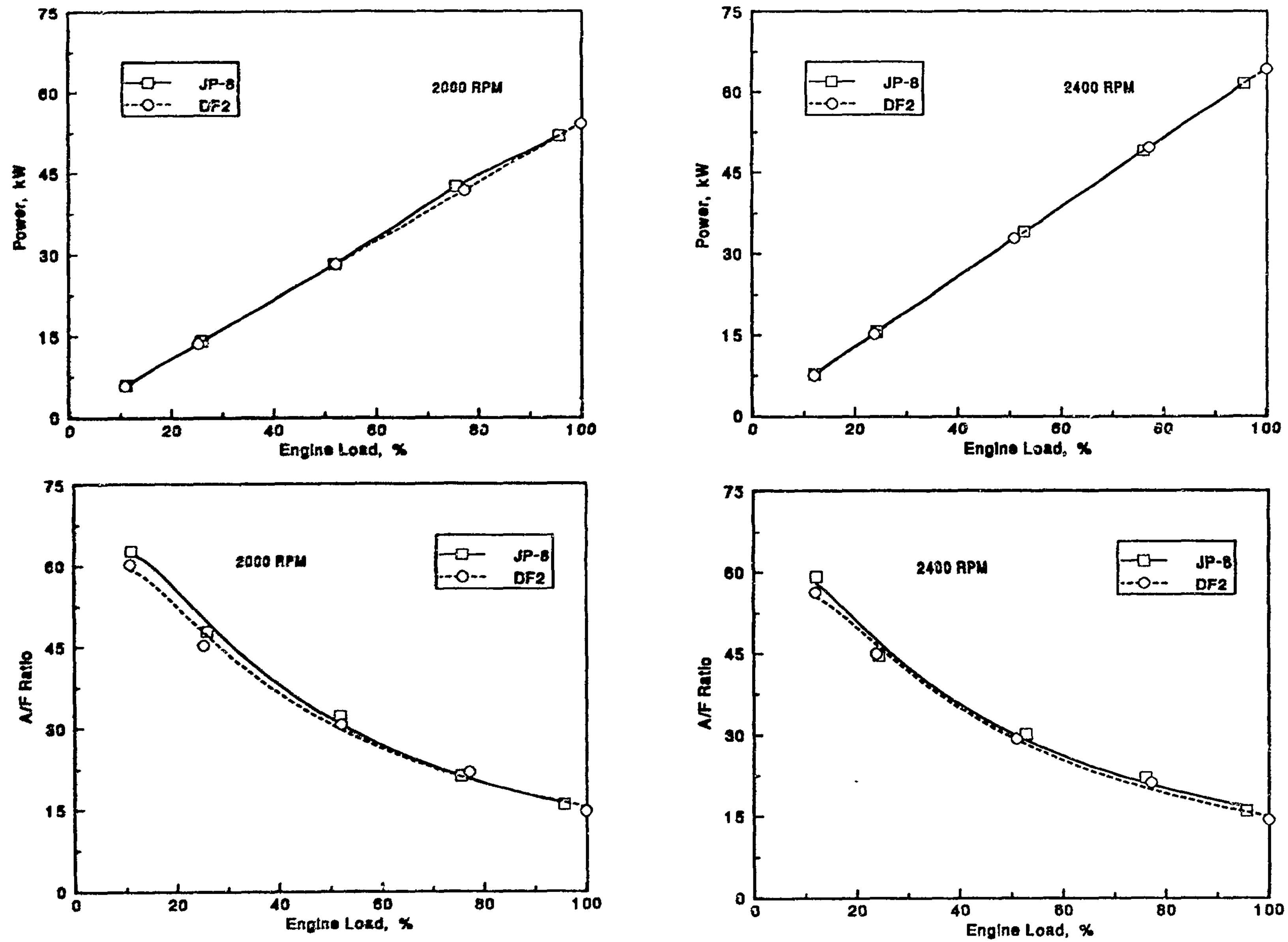

Figure 13. Isuzu C-240 engine brake horsepower and air/fuel ratio response

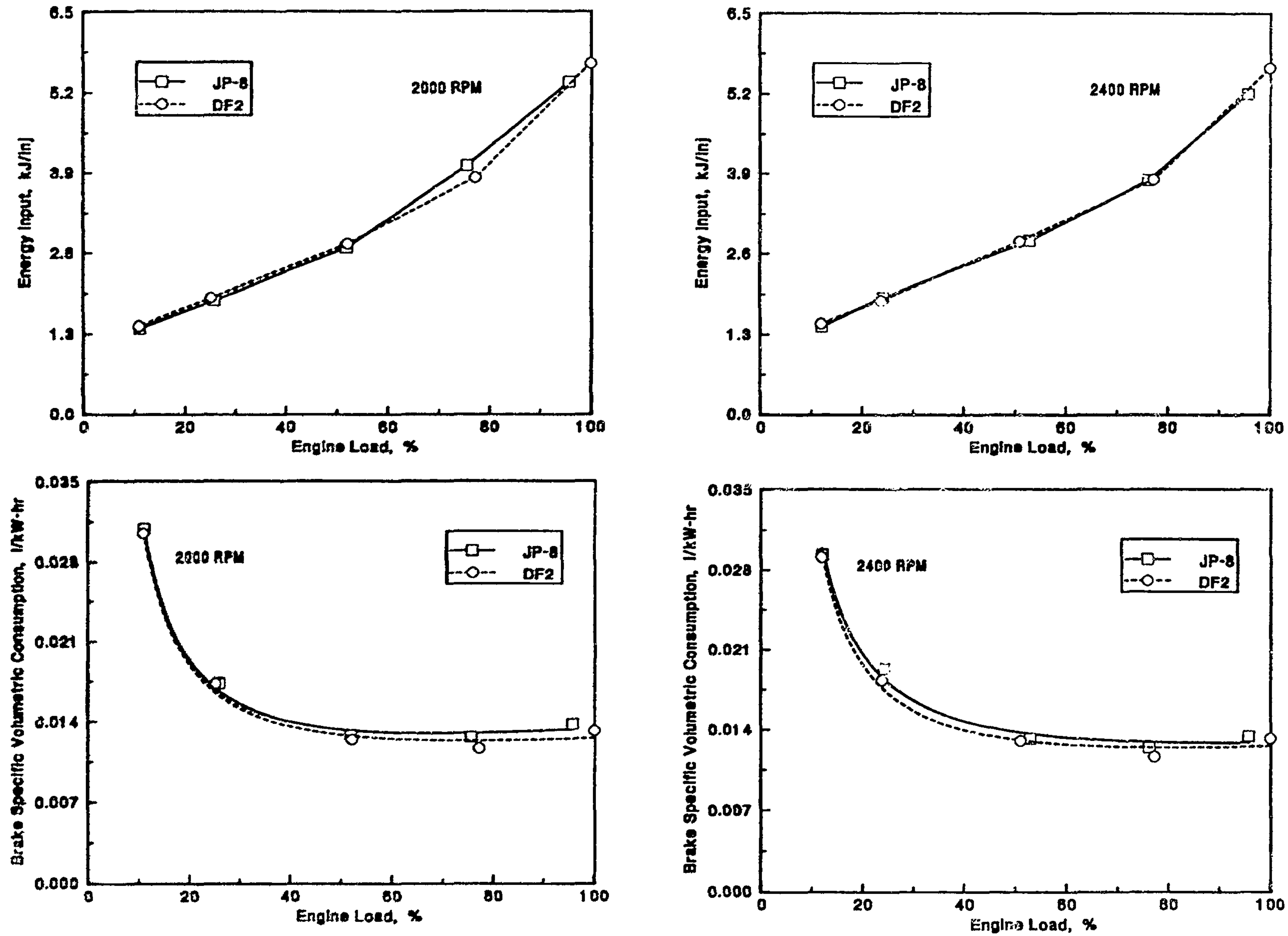

Figure 14. Isuzu C-240 engine energy input and brake specific volumetric fuel consumption response

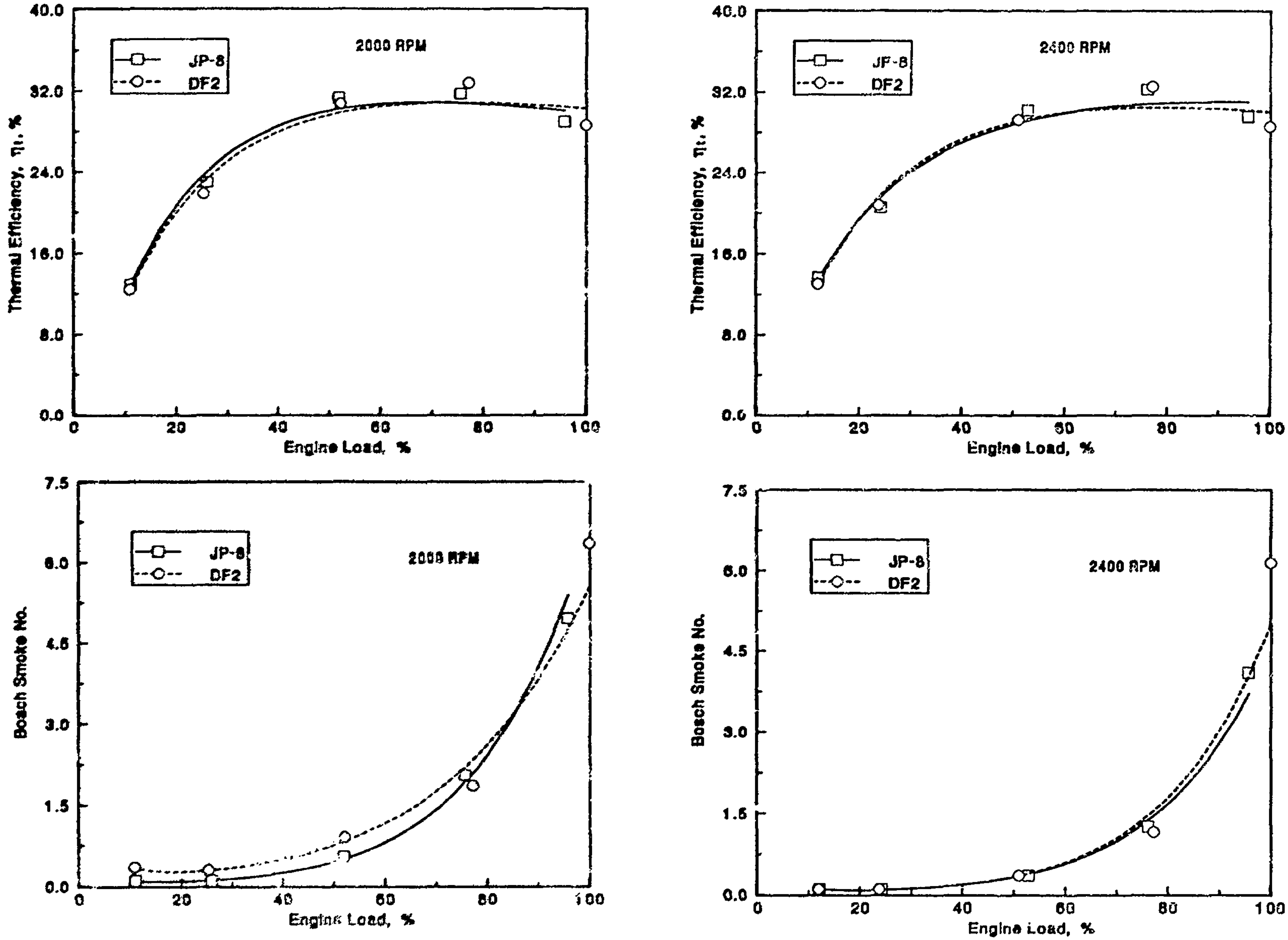

Figure 15. Isuzu C-240 engine thermal efficiency and Bosch smoke number response

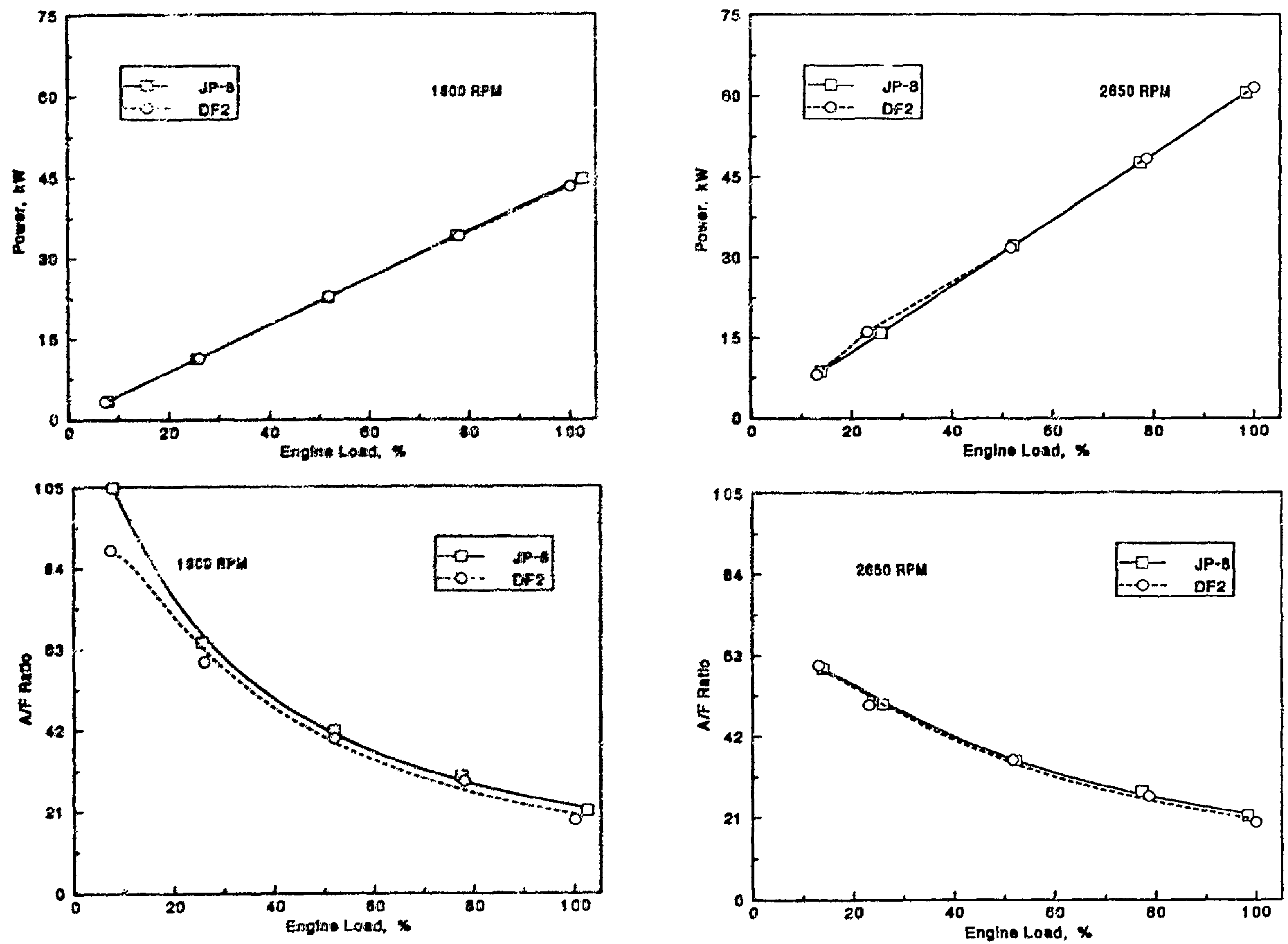

Figure 16. Deutz F3L912W engine brake horsepower and air/fuel ratio response

on JP-8. The peak power at 2650 rpm is slightly less with JP-8. At 1600 rpm, the air/fuel ratios for JP-8 are leaner than for the referee DF-2 and similar at 2650 rpm. Overall, the Deutz F3L912W engine operates at leaner air/fuel ratios than the Isuzu C-240 engine.

Fig. 17 is a record of the fuel energy input into the engine and the brake specific volumetric fuel consumption. The energy input values for 1600 rpm are lower across the load range with JP-8, especially at full rack. At 2650 rpm, the energy input is similar with JP-8 except at the full-rack condition. The differences at full rack are due to injection system pumping losses and lower fuel energy content. The results at 1600 rpm indicate no increase in fuel consumption when utilizing JP-8 at the peak torque speed. At 2650 rpm, there appears to be light-load fuel-consumption increase, which reduces to no change at full rack.

Engine thermal efficiency and Bosch smoke number are displayed in Fig. 18 for both speeds. The Deutz F3L912W engine shows improvements in thermal efficiencies at 1600 rpm at all loads. This improvement accounts for the ability of the engine to produce equivalent power with lower energy input when utilizing JP-8. The thermal efficiency at 2650 rpm explains the variation in the BSVC from light to full loads. The F3L912W engine reveals higher thermal efficiencies at the maximum torque speed. The smoke numbers indicate equivalent or lower concentration of soot in the exhaust when utilizing JP-8. The smoke number is higher at peak torque, which is consistent with the particulate emission results.

c. Deutz F4L912W Engine

The brake horsepower and air/fuel ratio at both speeds are shown in Fig. 19 for the Deutz F4L912W engine. The constant engine power evaluations at part loads appear consistent at both speeds. There is a maximum power decrement when operating on JP-8 at both speeds. Except for 25-percent load at 1500 rpm, the air/fuel ratios with JP-8 and DF-2 were similar. The engine was operating at a richer air/fuel ratio with JP-8 at this load. The 25-percent load point coincides with variations seen in the engine NO_x and particulate response at this load and speed. At 2300 rpm, the air/fuel ratios for JP-8 are slightly leaner than for the referee DF-2. Overall, this engine operates at leaner air/fuel ratios than any of the other engines evaluated.

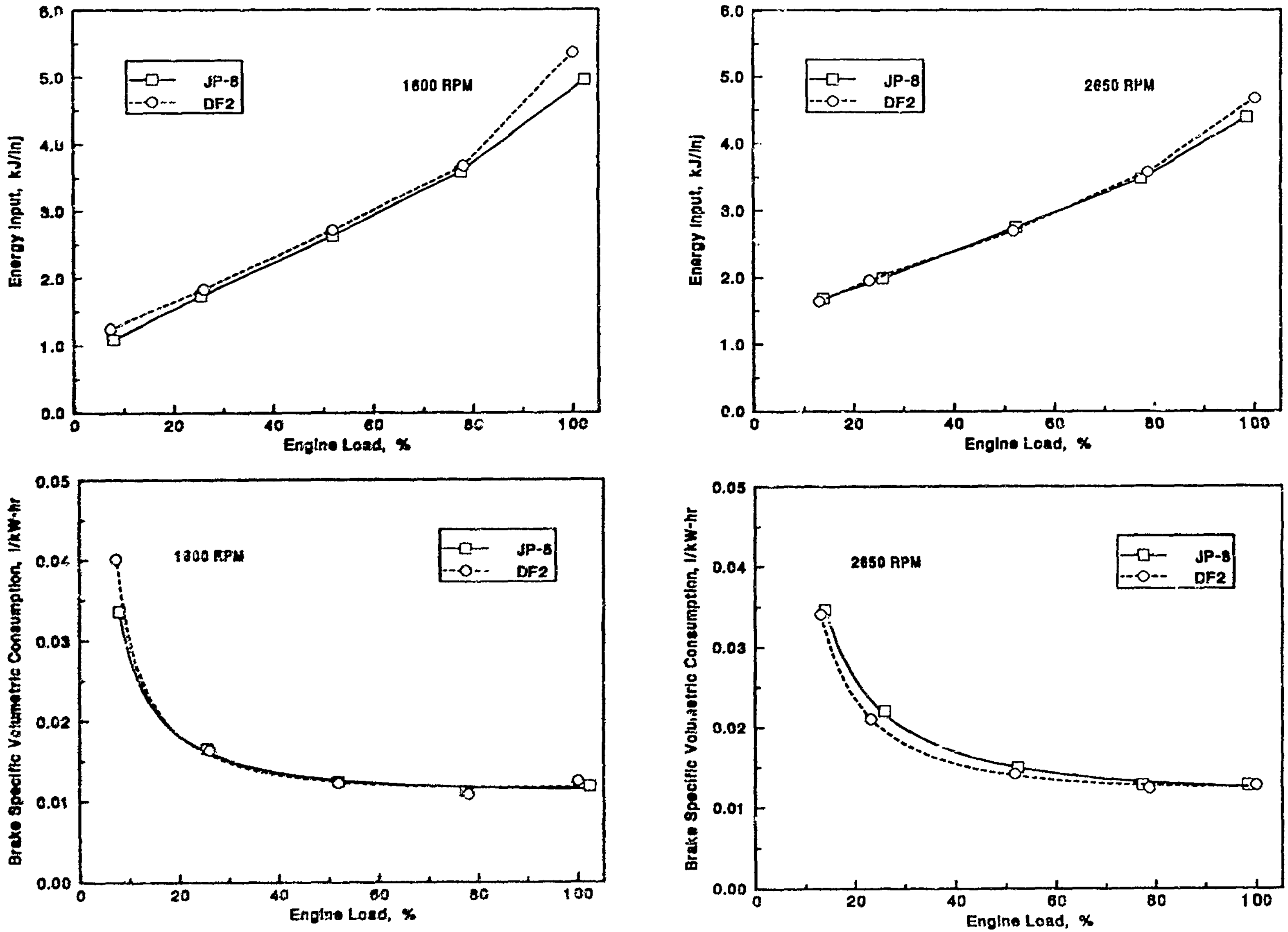

Figure 17. Deutz F3L912W engine energy input and brake specific volumetric fuel consumption response

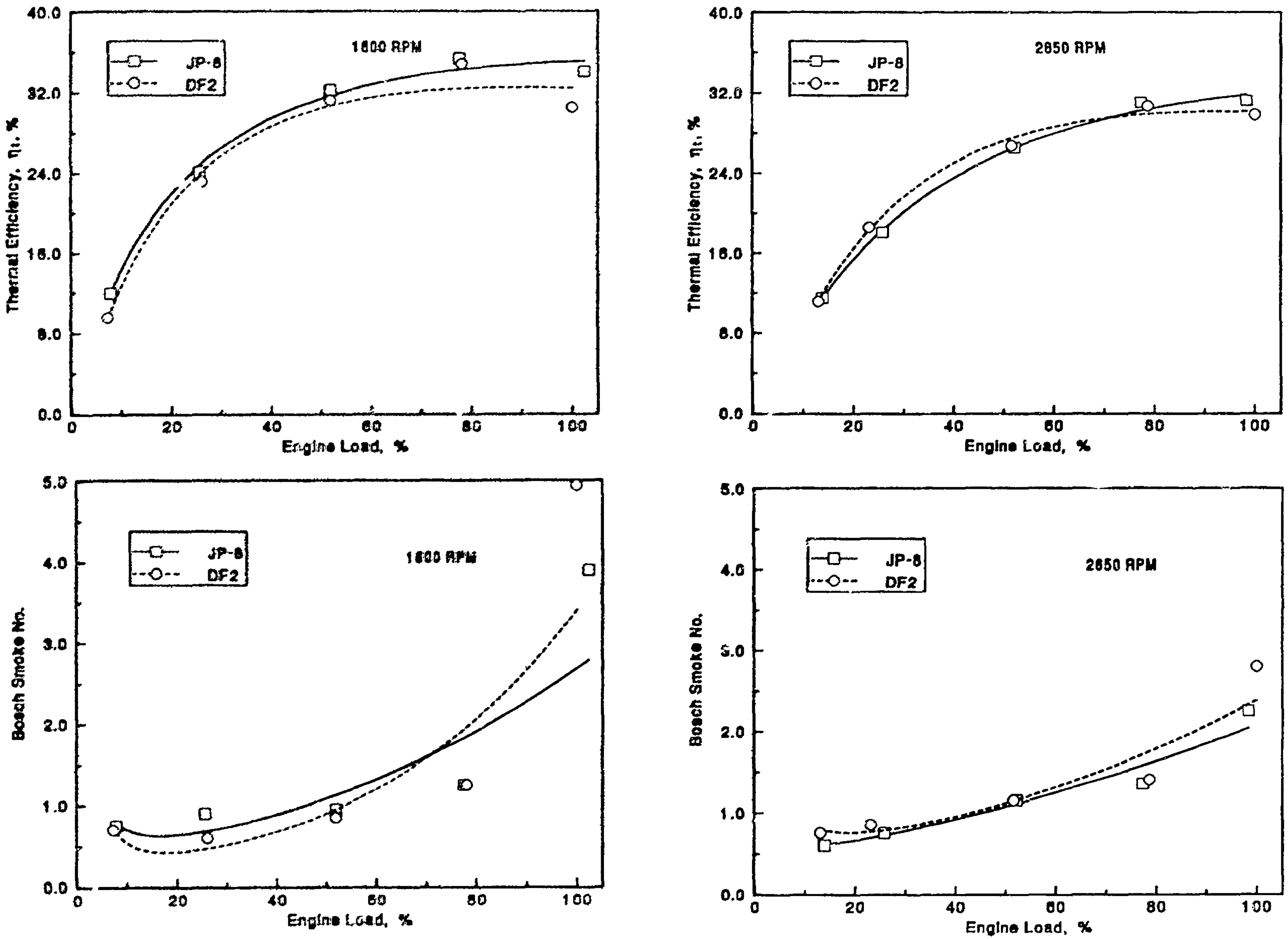

Figure 18. Deutz F3L912W engine thermal efficiency and Bosch smoke number response

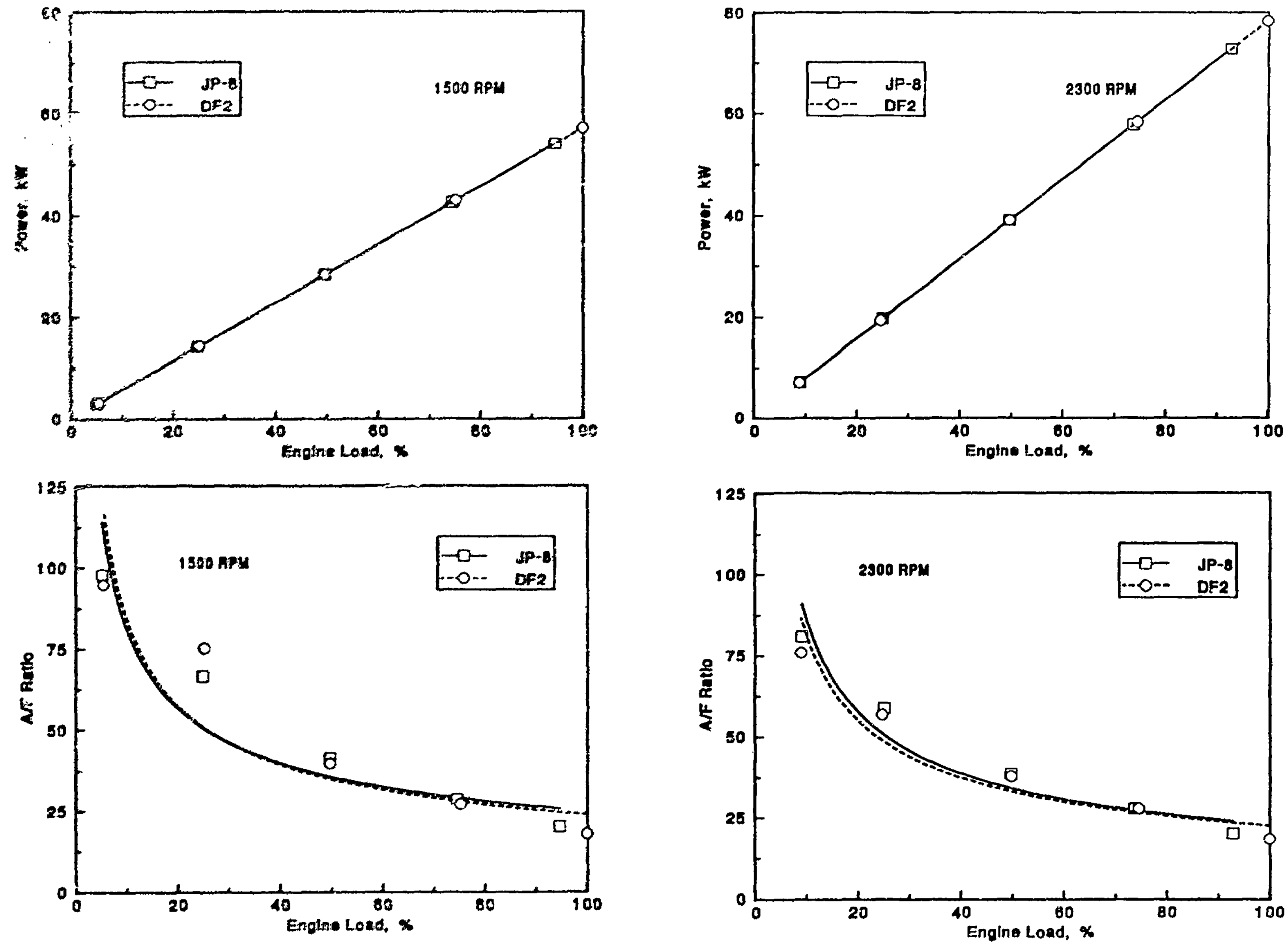

Figure 19. Deutz F4L912W engine brake horsepower and air/fuel ratio response

Fig. 20 is a record of the fuel energy input into the engine and the brake specific volumetric fuel consumption. The energy input while operating on JP-8 at 1500 rpm is slightly lower than with DF-2. The energy input curves at 2300 rpm show similar values for both fuels. At 1500 rpm, a fuel-consumption penalty for using JP-8 is absent. The results indicate an increase in fuel consumption when utilizing JP-8 at heavier loads and 2300 rpm.

Engine thermal efficiency and Bosch smoke number are displayed in Fig. 21 for both speeds. The engine shows improvements in thermal efficiencies at 1500 rpm at all but the lightest load. This improvement accounts for the ability of the engine to produce equivalent power with lower energy input when utilizing JP-8. The thermal efficiencies at 2300 rpm reveal little variation between the test fuels. Like the F3L912W engine, the F4L912W engine reveals higher thermal efficiencies at the maximum torque speed. The smoke numbers indicate equivalent or lower concentration of soot in the exhaust when utilizing JP-8. The higher smoke number at peak torque is consistent with the particulate emission results.

d. Perkins 4.154 Engine

The brake horsepower and air/fuel ratio at both speeds are shown in Fig. 22 for the Perkins 4.154 engine. The partial-load points indicate consistent constant power operation except at 75-percent load, 2600 rpm with JP-8. Lower maximum power and maximum torque at full rack are realized when this engine is operated on JP-8. This engine showed the greatest power decrement with JP-8, which indicates the rotary fuel injection pump installed in this engine is more sensitive to fuel viscosity and density variations. The part load air/fuel ratios for JP-8 are leaner at 1800 rpm and similar at 2600 rpm. The full-rack air/fuel ratios with JP-8 are leaner than the referee DF-2 at both speeds.

Fig. 23 is a record of the fuel energy input into the engine and the brake specific volumetric fuel consumption. The fuel energy input at 1800 rpm are lower for partial loads with JP-8 and significantly reduced at full rack. At 2600 rpm, the energy input is similar with JP-8 at part load, with a sizable reduction at the full-rack condition. The differences at full rack are due to fuel

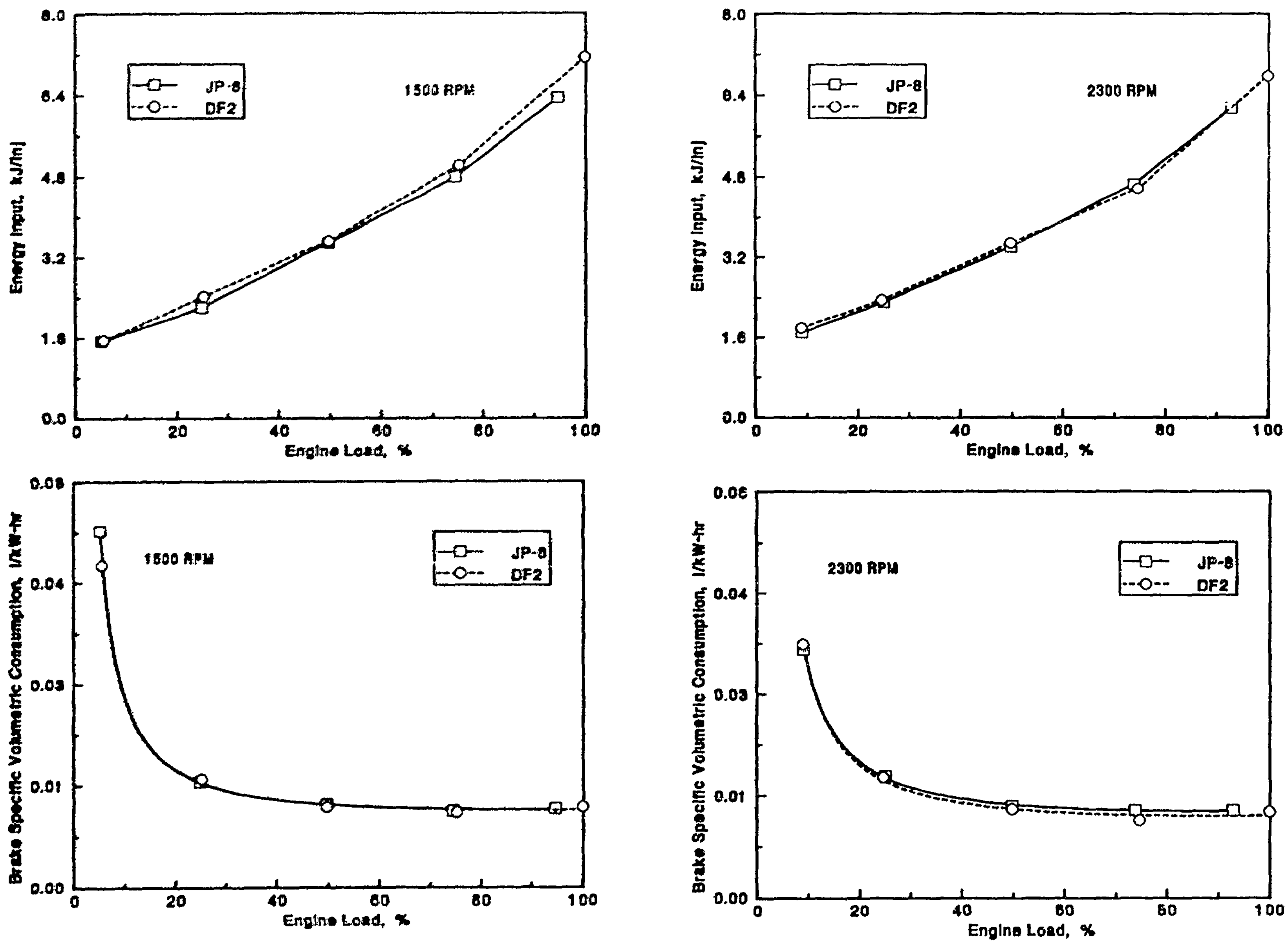

Figure 20. Deutz F4L912W engine energy input and brake specific volumetric fuel consumption response

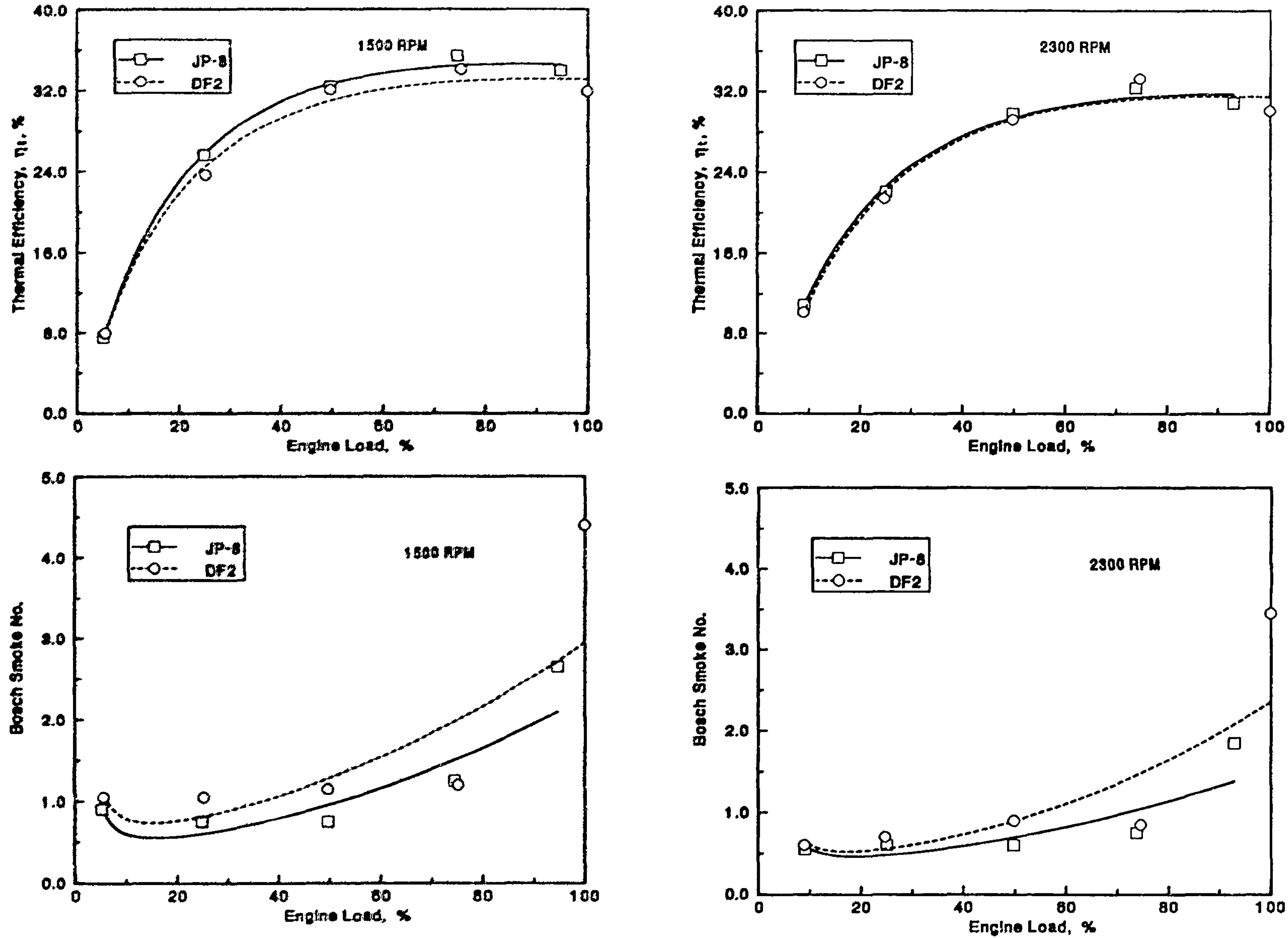

Figure 21. Deutz F4L912W engine engine thermal efficiency and Bosch smoke number response

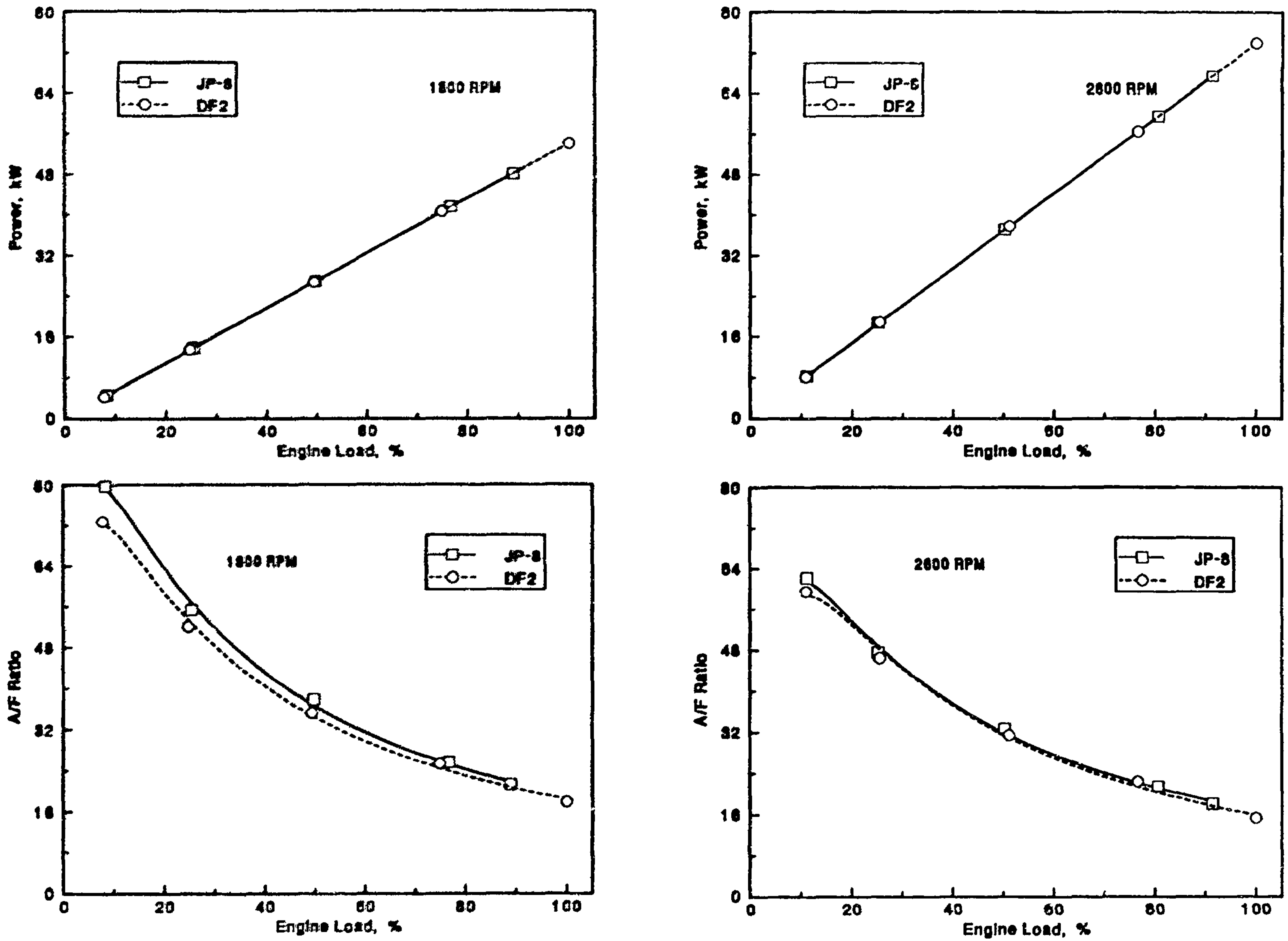

Figure 22. Perkins 4.154 engine brake horsepower and air/fuel ratio response

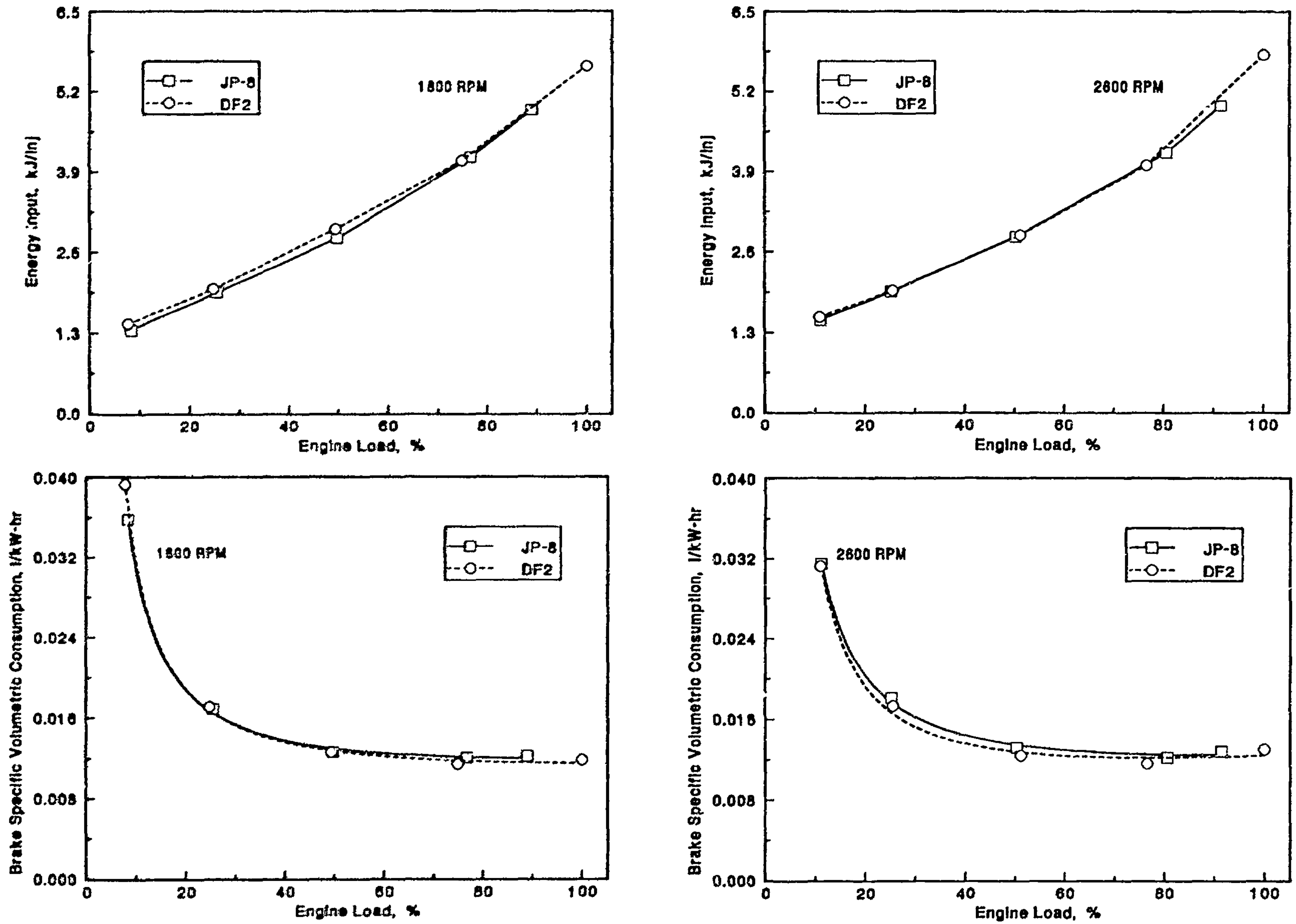

Figure 23. Perkins 4.154 engine energy input and brake specific volumetric fuel consumption response

injection system pumping losses and lower fuel energy content. The BSVC results indicate similar fuel consumption at 1800 rpm, at all loads. A fuel-consumption increase is seen at the lighter loads at 2600 rpm when utilizing JP-8.

Engine thermal efficiency and Bosch smoke number are displayed in Fig. 24 for both speeds. The engine shows improvements in thermal efficiencies at 1800 rpm at all loads. This improvement offsets the lower energy input when utilizing JP-8 and allows the engine to produce equivalent power at part loads. The thermal efficiencies at 2600 rpm reveal little variation between the test fuels except at full rack with JP-8. Lower concentrations of soot in the exhaust when utilizing JP-8 are evident from the smoke numbers. The lower maximum load smoke numbers reveal the effect of the leaner full-rack air/fuel ratios with JP-8.

Overall, clean-burn diesel engines performance is satisfactory with JP-8. Equipment operators may notice slight power loss at full rack, but will not lose any part-rack performance. Some fuel-consumption increase should accompany the use of JP-8. However, as seen in the JP-8 demonstration program (19), duty cycles can affect fuel usage as much as differences in fuel properties. The benefit of reduced black smoke seems to compensate for any performance decrement.

3. Durability

The Isuzu C-240 engine was operated to determine engine durability when functioning on JP-8, with respect to the 1% S referee diesel fuel. The 1% S referee diesel fuel is utilized to qualify engine durability by the U.S. Army Tank-Automotive Command (TACOM) in a 400-hour North Atlantic Treaty Organization (NATO) cycle evaluation. The 210-hour test chosen for these evaluations consists of repeating 14-hour segments of modes of 2 hours at full power and 1 hour at idle, with the segment ending with a 2-hour full-power mode. The resulting evaluation consists of 150 hours of full-power operation and 60 hours at idle. The engine oil used for these evaluations was an SAE 15W-40 lubricant. A fresh charge was used at the beginning of each evaluation, and only makeup oil was added during the testing.

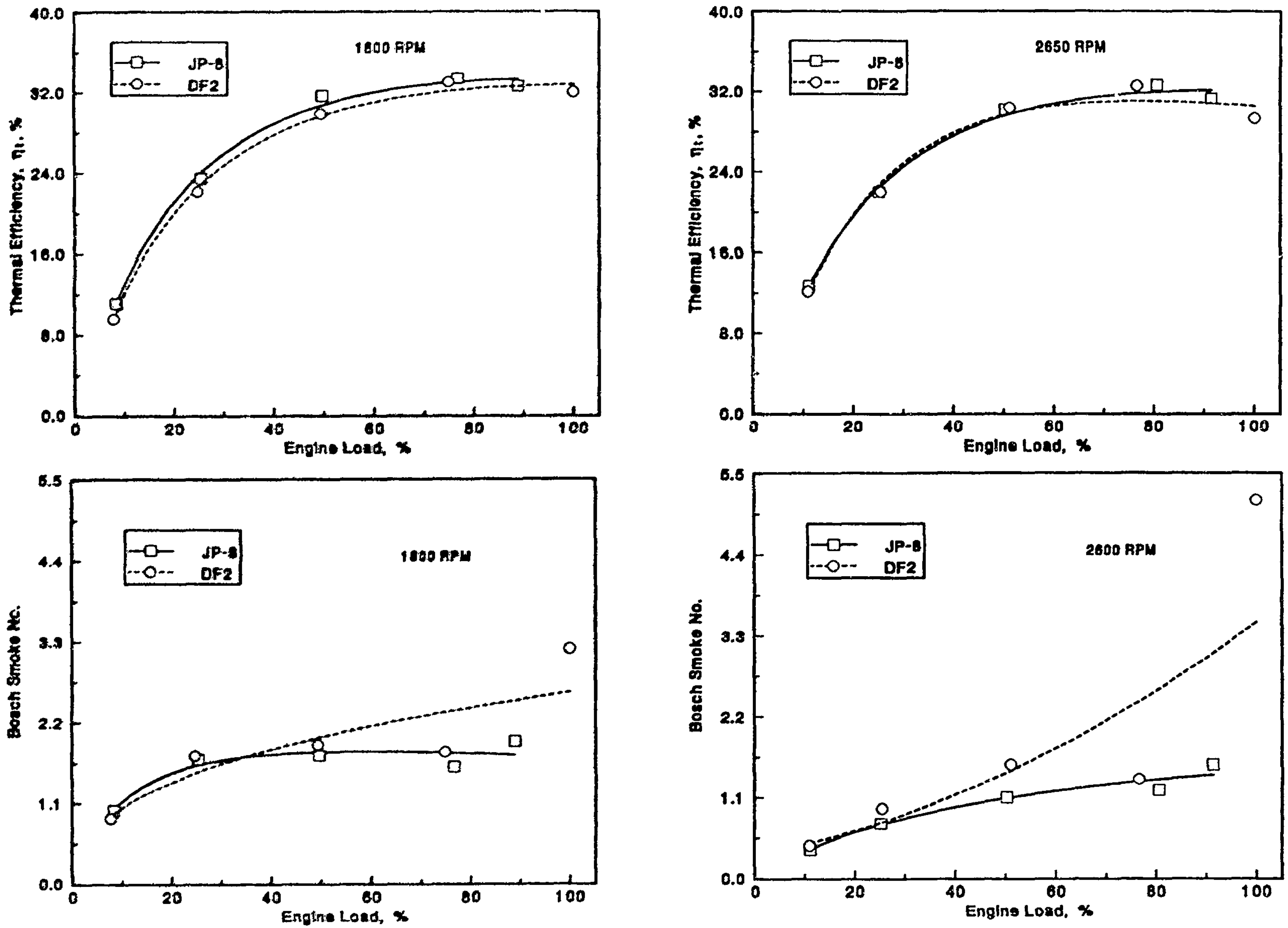

Figure 24. Perkins 4.154 engine thermal efficiency and Bosch smoke number response

a. <u>Rebuild Measurements</u>

Before each endurance evaluation, the engine was disassembled and the wear critical components were measured. If any parts exceeded the worn limits, they were replaced. TABLE 17 shows the engine part measurements taken before the JP-8 evaluation. The measurements indicate that the cylinder liners were within the new part limits for diameter, out-of-round, and taper, and well within the worn limits for diameter. The pistons were also within the new limits for the smaller sized piston available for this engine. When the liner-to-piston clearance is checked, the clearance indicates the larger of the two piston sizes available should have been used for this build. Since these were the original parts for this engine, it was decided to perform the evaluation with the slightly enlarged piston-to-liner clearance. It was expected this larger clearance would increase blowby, effect oil degradation, and establish a worst-case evaluation. The piston ring end gaps are slightly greater than the new limits, but well within the worn limits. The piston pin bushing measurements were checked to ensure that excessive piston secondary motion would not occur due to sloppy piston pin fits. Excessive piston secondary motion can lead to piston/liner contact and increase risk of scuffing. All main bearings, connecting rod bearings, and camshaft bearings were well within specifications. All valves and valve guides in the cylinder head were replaced prior to the JP-8 evaluation.

TABLE 18 records the engine part measurements taken before the first MIL-F-46162C evaluation. The cylinder liners were within the new part limits for diameter, out-of-round, and taper, and well within the worn limits for diameter. The pistons were still within the new limits for the smaller sized piston, even after the 210-hour JP-8 evaluation. It was decided to continue with the original build and perform the evaluation with the slightly enlarged piston-to-liner clearance. Again it was expected blowby would increase and establish a worst-case evaluation. The piston ring end gaps are slightly greater than the new limits, but well within the worn limits. The piston pin bushing measurements were within limits. All main bearings and connecting rod bearings were within specifications. The camshaft bearings were screened after the first evaluation, and revealed no change, which is typical of steady-state operating conditions.

TABLE 17. Isuzu C-240 Engine Rebuild Measurements for JP-8 Evaluation

Test: 1 Fuel: JP-8 Model Number: C-240

	Min		Max		Avg		Min		Max	Worn Limit
	in.	mm	in.	mm	in.	mm	in. (mm)		in. (mm)	in. (mm)
Cylinder										
Inside Diameter	3.3875	86.04	3.3882	86.06	3.3879	86.05	3.3868 (86.02)	-	3.3883 (86.06)	3.3898 (86.10)
Out-of-Round	0.0000	0.000	0.0014	0.036	0.0008	0.022		-	0.0015 (0.038)	
Taper	0.0001	0.003	0.0014	0.036	0.0004	0.009		-	0.0015 (0.038)	
Piston Diameter (at Skirt)	3.3815	85.887	3.3820	85.899	3.3818	85.894	3.3815 (85.888)	-	3.3822 (85.907)	
Piston Skirt to Cylinder Liner Clearance	0.0050	0.127	0.0070	0.178	0.0055	0.138	0.0048 (0.123)	-	0.0056 (0.143)	
Compression Rings										
Gap No. 1	0.015	0.38	0.016	0.41	0.016	0.40	0.008 (0.20)	-	0.015 (0.40)	0.079 (2.0)
Gap Nos. 2 and 3	0.014	0.36	0.014	0.36	0.014	0.36	0.008 (0.20)	-	0.015 (0.40)	0.079 (2.0)
Oil Control Ring										
Gap No. 4	0.015	0.38	0.017	0.43	0.016	0.41	0.004 (0.10)	-	0.012 (0.30)	0.079 (2.0)
Piston Pin										
Pin-to-Piston Bushing Interference	-0.0003	-0.008	-0.0001	-0.003	-0.0002	-0.006	0.0 (0.0)	-	0.0002 (0.005)	
Pin-to-Connecting Rod Bushing Clearance	0.0005	0.013	0.0007	0.018	0.0007	0.017	0.0003 (0.008)	-	0.0008 (0.02)	0.002 (0.05)
Connecting Rod Bearing-to-Journal Clearance	0.0025	0.063	0.0025	0.063	0.0025	0.063	0.0007 (0.018)	-	0.0026 (0.065)	0.0047 (0.12)
Main Bearing-to-Journal Clearance	0.0030	0.076	0.0035	0.089	0.0032	0.082	0.0007 (0.018)	-	0.0026 (0.065)	0.0047 (0.12)
Camshaft Bearing-to-Journal Clearance	0.0019	0.048	0.0020	0.051	0.0020	0.050	0.0020 (0.05)	-	0.0047 (0.12)	0.0047 (0.12)

TABLE 18. Isuzu C-240 Engine Rebuild Measurements for First 1% S DF-2 Evaluation

Test: 2 Fuel: 1% S DF-2 Model Number: C-240

Cylinder	Min in.	Min mm	Max in.	Max mm	Avg in.	Avg mm	Min in. (mm)	Max in. (mm)	Worn Limit in. (mm)
Inside Diameter	3.3873	86.03	3.3879	86.05	3.3876	86.04	3.3868 (86.02)	- 3.3883 (86.06)	3.3898 (86.10)
Out-of-Round	0.0000	0.000	0.0015	0.038	0.0008	0.021		- 0.0015 (0.038)	
Taper	0.0000	0.000	0.0012	0.030	0.0006	0.016		- 0.0015 (0.038)	
Piston Diameter (at Skirt)	3.3815	85.887	3.3819	85.897	3.3818	85.893	3.3815 (85.888)	- 3.3822 (85.907)	
Piston Skirt to Cylinder Liner Clearance	0.0052	0.132	0.0069	0.175	0.0060	0.153	0.0048 (0.123)	- 0.0056 (0.143)	
Compression Rings									
Gap No. 1	0.015	0.38	0.017	0.43	0.016	0.41	0.008 (0.20)	- 0.015 (0.40)	0.079 (2.0)
Gap Nos. 2 and 3	0.014	0.36	0.015	0.38	0.015	0.38	0.008 (0.20)	- 0.015 (0.40)	0.079 (2.0)
Oil Control Ring									
Gap No. 4	0.017	0.43	0.019	0.48	0.019	0.47	0.004 (0.10)	- 0.012 (0.30)	0.079 (2.0)
Piston Pin									
Pin-to-Piston Bushing Interference	-0.0003	-0.008	-0.0002	-0.005	-0.0003	-0.007	0.0 (0.0)	- 0.0002 (0.005)	
Pin-to-Connecting Rod Bushing Clearance	0.0007	0.018	0.0008	0.020	0.0007	0.018	0.0003 (0.008)	- 0.0008 (0.02)	0.002 (0.05)
Connecting Rod Bearing-to-Journal Clearance	0.0025	0.063	0.0026	0.066	0.0025	0.064	0.0007 (0.018)	- 0.0026 (0.065)	0.0047 (0.12)
Main Bearing-to-Journal Clearance	0.0025	0.063	0.0035	0.089	0.0031	0.079	0.0007 (0.018)	- 0.0026 (0.065)	0.0047 (0.12)

TABLE 19 records the engine part measurements taken before the second of the MIL-F-46162C evaluations. The cylinder liners were within the new part limits for diameter, out-of-round, and taper, and well within the worn limits for diameter. New pistons were installed for this test, due to the stuck rings in the previous evaluation. The new pistons were within specifications for the smaller sized pistons. The evaluations were performed with a slightly enlarged piston-to-liner clearance. Again it was expected blowby would increase and establish a worst-case evaluation. The new piston ring end gaps were slightly greater than the new limits, but well within the worn limits. The ring end gaps are measured by installing the rings at the top of the cylinder bores. Some wear in the bore at this location may have accounted for the wider end gap measurements. The piston pin bushing measurements were within limits. All main bearings and connecting rod bearings were within specifications.

b. Wear Measurements

The wear measurements for the Isuzu C-240 engine upon completion of the 210-hour JP-8 evaluation are shown in TABLE 20. The measurements shown are for the cylinder bores, ring end gaps, and valves. These areas are considered to be the most wear prone of the engine and the most critical for engine performance. Individual and average bore measurements indicate little, if any, measurable wear occurred during the evaluation. The presence of negative values indicate bore wear was probably less than the measurement accuracy. The ring end gap wear results reveal the oil control ring, Ring No. 4, has the greatest end gap increase. The overall average wear rate for the rings would be on the order of 132 micrometer/hour for the JP-8 evaluation. The valve to guide clearance wear was low for the evaluation. The valve depth change, or valve recession, reveals a 1040 micrometer/hour intake valve recession and a 315 micrometer/hour exhaust valve recession.

The wear measurements for the Isuzu C-240 engine upon completion of the initial 70-hour MIL-F-46162C evaluation are shown in TABLE 21. Individual and average bore measurements indicate little, if any, measurable wear occurred during the evaluation, which is not unexpected after only 70 hours of operation. Again, the presence of negative values indicate bore wear was

TABLE 19. Isuzu C-240 Engine Rebuild Measurements for Second 1% S DF-2 Evaluation

Test: 3 Fuel: 1% S DF-2 Model Number: C-240

Cylinder	Min		Max		Avg		Min		Max	Worn Limit
	in.	mm	in.	mm	in.	mm	in. (mm)		in. (mm)	in. (mm)
Inside Diameter	3.3876	86.04	3.3881	86.06	3.3875	86.05	3.3868 (86.02)	-	3.3883 (86.06)	3.3898 (86.10)
Out-of-Round	0.0002	0.005	0.0013	0.033	0.0008	0.020		-	0.0015 (0.038)	
Taper	0.0000	0.000	0.0012	0.030	0.0005	0.013		-	0.0015 (0.038)	
Piston Diameter (at Skirt)	3.3812	85.879	3.3819	85.897	3.3816	85.889	3.3815 (85.888)	-	3.3822 (85.907)	
Piston Skirt to Cylinder Liner Clearance	0.0057	0.146	0.0069	0.176	0.0063	0.161	0.0048 (0.123)	-	0.0056 (0.143)	
Compression Rings										
Gap No. 1	0.021	0.53	0.023	0.58	0.022	0.55	0.008 (0.20)	-	0.015 (0.40)	0.079 (2.0)
Gap Nos. 2 and 3	0.020	0.51	0.022	0.56	0.021	0.54	0.008 (0.20)	-	0.015 (0.40)	0.079 (2.0)
Oil Control Ring										
Gap No. 4	0.014	0.36	0.017	0.43	0.016	0.39	0.004 (0.10)	-	0.012 (0.30)	0.079 (2.0)
Piston Pin										
Pin-to-Piston Bushing Interference	-0.0002	-0.005	0.0000	0.000	-0.0001	-0.003	0.0 (0.0)	-	0.0002 (0.005)	
Pin-to-Connecting Rod Bushing Clearance	0.0007	0.018	0.0009	0.023	0.0008	0.019	0.0003 (0.008)	-	0.0008 (0.02)	0.002 (0.05)
Connecting Rod Bearing-to-Journal Clearance	0.0029	0.074	0.0031	0.079	0.0030	0.076	0.0007 (0.018)	-	0.0026 (0.065)	0.0047 (0.12)
Main Bearing-to-Journal Clearance	0.0023	0.058	0.0033	0.084	0.0033	0.084	0.0007 (0.018)	-	0.0026 (0.065)	0.0047 (0.12)

TABLE 20. Isuzu C-240 Engine Wear Measurements After JP-8 Evaluation

Test: 1 Lubricant: 18750 Fuel: JP-8

Cylinder Bore Diameter Changes

Cylinder No.	1				2			
	T-AT*		F-B		T-AT		F-B	
	in.	mm	in.	mm	in.	mm	in.	mm
Top	0.0000	0.000	-0.0013	-0.033	0.0003	0.008	-0.0001	-0.003
Middle	-0.0002	-0.005	0.0000	0.000	0.0001	0.003	-0.0003	-0.008
Bottom	-0.0004	-0.010	0.0000	0.000	-0.0008	-0.020	-0.0001	-0.003

Cylinder No.	3				4			
	T-AT		F-B		T-AT		F-B	
	in.	mm	in.	mm	in.	mm	in.	mm
Top	0.0001	0.003	-0.0001	-0.003	0.0001	0.003	-0.0001	-0.003
Middle	0.0000	0.000	-0.0001	-0.003	0.0000	0.000	-0.0003	-0.008
Bottom	-0.0008	-0.020	-0.0003	-0.008	-0.0014	-0.036	-0.0001	-0.003

Average Change

	T-AT		F-B	
	in.	mm	in.	mm
Top	0.0001	0.003	-0.0004	-0.010
Middle	-0.0000	-0.001	-0.0002	-0.004
Bottom	-0.0008	-0.022	-0.0001	-0.003

Piston Ring End Gap Change

Cylinder No.	1		2		3		4		Average	
Ring No	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
1	0.0000	0.000	0.0010	0.025	0.0000	0.000	0.0000	0.000	0.0003	0.006
2	0.0010	0.025	0.0010	0.025	0.0010	0.025	0.0000	0.000	0.0007	0.019
3	0.0010	0.025	0.0010	0.025	0.0010	0.025	0.0010	0.025	0.0010	0.025
4	0.0020	0.051	0.0030	0.076	0.0020	0.051	0.0030	0.076	0.0025	0.063

Overall Average Change: 0.0011 in. 0.029 mm

Valve Clearance Change

Cylinder No.	1		2		3		4		Average	
Valve	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
Intake	0.0001	0.003	0.0000	0.000	0.0004	0.010	0.0004	0.010	0.0002	0.006
Exhaust	0.0001	0.003	0.0004	0.010	0.0000	0.000	0.0000	0.000	0.0001	0.003

Valve Depth Change

Cylinder No.	1		2		3		4		Average	
Valve	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
Intake	0.0147	0.373	0.0002	0.005	0.0087	0.221	0.0106	0.269	0.0086	0.217
Exhaust	-0.0016	-0.041	0.0029	0.074	0.0085	0.216	0.0005	0.013	0.0026	0.065

* T-AT = Thrust-Antithrust Direction; F-B = Front-Back Direction.

TABLE 21. Isuzu C-240 Engine Wear Measurements After First 1% S DF-2 Evaluation

Test: 2 Lubricant: 18750 Fuel: 1% S DF-2

Cylinder Bore Diameter Changes

Cylinder No.	1				2			
	T-AT*		F-B		T-AT		F-B	
	in.	mm	in.	mm	in.	mm	in.	mm
Top	0.0000	0.000	-0.0001	-0.003	-0.0001	-0.003	0.0000	0.000
Middle	0.0001	0.003	-0.0001	-0.003	0.0000	0.000	0.0002	0.005
Bottom	-0.0001	-0.003	-0.0001	-0.003	0.0000	0.000	0.0001	0.003

Cylinder No.	3				4			
	T-AT		F-B		T-AT		F-B	
	in.	mm	in.	mm	in.	mm	in.	mm
Top	0.0000	0.000	0.0000	0.000	-0.0001	-0.003	0.0000	0.000
Middle	0.0002	0.005	0.0003	0.008	0.0003	0.008	0.0004	0.010
Bottom	0.0011	0.028	-0.0001	-0.003	0.0000	0.000	0.0001	0.003

Average Change

	T-AT		F-B	
	in.	mm	in.	mm
Top	-0.0000	-0.001	-0.0000	-0.001
Middle	0.0002	0.004	0.0002	0.005
Bottom	0.0003	0.006	0.0000	0.000

Piston Ring End Gap Change

Cylinder No.	1		2		3		4		Average	
Ring No.	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
1	0.0040	0.102	0.0080	0.203	Stuck	--	0.0060	0.152	0.0060	0.152
2	0.0070	0.178	0.0080	0.203	Stuck	--	0.0070	0.178	0.0073	0.186
3	0.0080	0.203	0.0070	0.178	Stuck	--	0.0070	0.178	0.0073	0.186
4	0.0050	0.127	0.0090	0.229	0.0100	0.254	0.0040	0.102	0.0070	0.178

Overall Average Change: 0.0069 in. 0.176 mm

Valve Clearance Change

Cylinder No.	1		2		3		4		Average	
Valve	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
Intake	0.0005	0.013	0.0007	0.018	0.0003	0.008	-0.0002	-0.005	0.0003	0.008
Exhaust	0.0000	0.000	0.0003	0.008	-0.0008	-0.020	-0.0003	-0.008	-0.0002	-0.005

Valve Depth Change

Cylinder No.	1		2		3		4		Average	
Valve	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
Intake	0.0010	0.025	0.0010	0.025	0.0003	0.008	0.0032	0.081	0.0014	0.035
Exhaust	0.0030	0.076	0.0002	0.005	0.0005	0.013	-0.0005	-0.013	0.0008	0.020

* T-AT = Thrust-Antithrust Direction; F-B = Front-Back Direction.

probably less than the measurement accuracy. The ring end gap wear results indicate sizable end gap increase on all rings, with the top three rings on Piston No. 3 being stuck. The overall average wear rate for the rings would be approximately 2504 micrometer/hour for the 1% S referee diesel fuel evaluation. Valve-to-guide clearance wear was low for the evaluation. The valve depth change, or valve recession, reveals a 508 micrometer/hour intake valve recession and a 290 micrometer/hour exhaust valve recession for the 70-hour evaluation.

The wear measurements for the Isuzu C-240 engine upon completion of the second MIL-F-46162C evaluation, which lasted 30 hours, are shown in TABLE 22. The individual and average bore measurements exhibit a relatively large amount of bore wear for such a short evaluation. The increased bore wear could be attributed to the new rings running in on the bores, and the increased wear due to the stuck fire control rings. The ring end gap wear results indicate negligible end gap increase except for the oil control ring. All fire control rings were stuck, with the second and third rings stuck on Cylinder No. 3 also. The overall average wear rate for the rings would be on the order of 170 micrometer/hour for the second 1% S referee diesel fuel evaluation. Valve-to-guide clearance and valve depth change were not determined due to the brevity of this evaluation.

c. Overall Results

Before each endurance evaluation, a power curve was performed on the Isuzu C-240 engine with the test fuel. The plan then was to perform a post-test power curve to determine the extent of power loss due to wear in the engine. Due to the high oil oxidation rates and stuck rings during the MIL-F-46162C evaluations, post-test results could not be performed. The results of the initial power curves for the three evaluations are exhibited in Fig. 25. Also included with the figure is the post-test evaluation for JP-8. The evaluation with JP-8 indicates only a slight decrease in power after 210 hours of operation. The curve for the first DF-2 evaluation indicates the engine was slightly down on power after rebuild, compared to the initial and post-test JP-8 run. This slight decrease may have occurred as a result of the worn cylinder components. The second

TABLE 22. Isuzu C-240 Engine Wear Measurements After Second 1% S DF-2 Evaluation

Test: 3　　Lubricant: 18750　　Fuel: 1% S DF-2

Cylinder Bore Diameter Changes

Cylinder No.	1				2			
	T-AT*		F-B		T-AT		F-B	
	in.	mm	in.	mm	in.	mm	in.	mm
Top	0.0050	0.127	0.0051	0.130	0.0051	0.130	0.0051	0.130
Middle	0.0051	0.130	0.0052	0.132	0.0052	0.132	0.0052	0.132
Bottom	0.0058	0.147	0.0054	0.137	0.0067	0.170	0.0049	0.124

Cylinder No.	3				4			
	T-AT		F-B		T-AT		F-B	
	in.	mm	in.	mm	in.	mm	in.	mm
Top	0.0051	0.130	0.0051	0.130	0.0052	0.132	0.0053	0.135
Middle	0.0050	0.127	0.0051	0.130	0.0051	0.130	0.0051	0.130
Bottom	0.0057	0.145	0.0054	0.137	0.0066	0.168	0.0055	0.140

Average Change

	T-AT		F-B	
	in.	mm	in.	mm
Top	0.0051	0.130	0.0051	0.131
Middle	0.0051	0.130	0.0051	0.131
Bottom	0.0062	0.157	0.0053	0.135

Piston Ring End Gap Change

Cylinder No.	1		2		3		4		Average	
Ring No.	in.	mm	in.	mm	in.	mm	in.	mm	in.	mm
1	Stuck	--	Stuck	--	Stuck	--	Stuck	--	--	--
2	0.0010	0.025	-0.0020	-0.051	Stuck	--	0.0000	0.000	-0.0002	-0.006
3	0.0000	0.000	-0.0010	-0.025	Stuck	--	-0.0010	-0.025	-0.0005	-0.013
4	0.0010	0.025	0.0010	0.025	0.0020	0.051	0.0030	0.076	0.0017	0.044

Overall Average Change: 0.0002 in. 0.006 mm

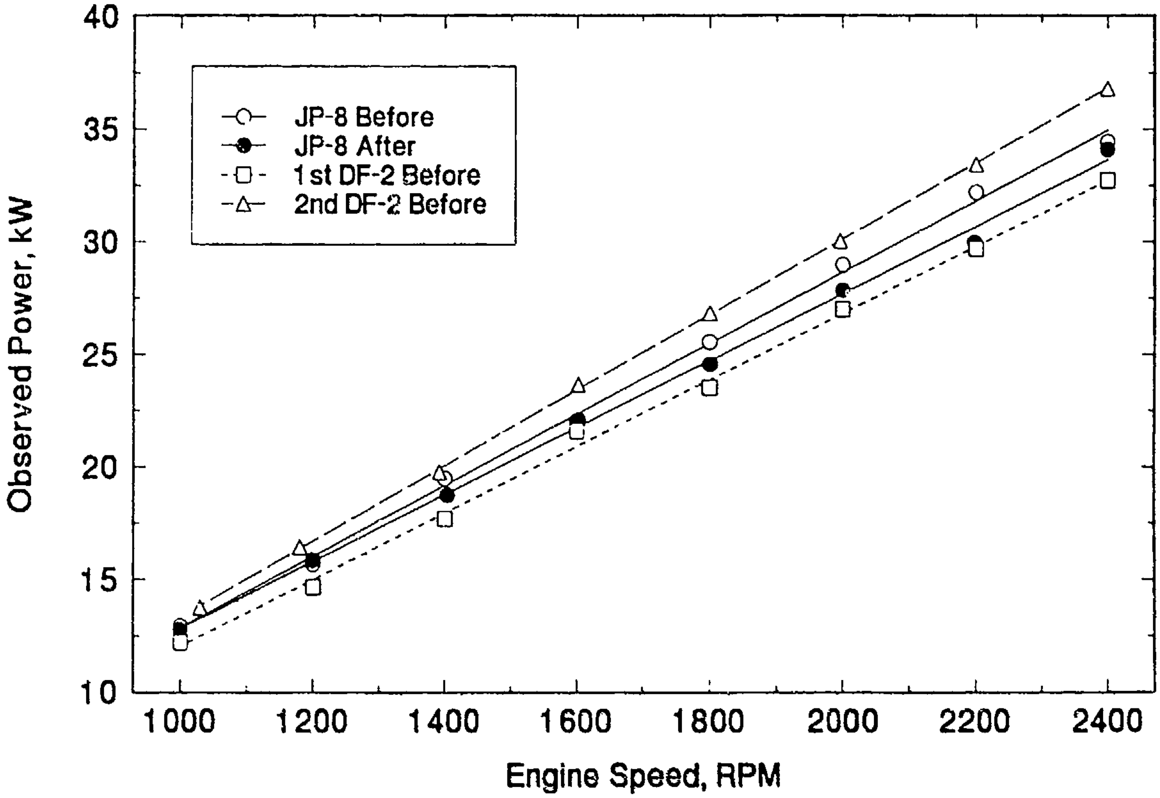

Figure 25. Isuzu C-240 engine durability power curves

DF-2 power curve displays expected results based on the heating value difference between the JP-8 and the MIL-F-46162C fuel. This build did include new pistons and rings, although, as seen earlier, the piston-to-liner clearances were slightly large.

The fuel injection pump was calibrated to factory settings by factory technicians before each evaluation. The check before the JP-8 run showed the pump was performing according to specification, which indicates it was properly functioning during the emission evaluations. The post-test evaluation indicated the pump met performance specifications, although the pump appeared to be sluggish when returning to idle from full rack. The injection pump barrel and plungers were replaced, and the original sets were inspected. When inspected, there was no indication of wear, scuffing, or scratching of the barrel and plungers. The inspections after the 1% S DF-2 evaluations indicated no performance change in the fuel injection pump.

The used oil analysis is one of the best tools for indicating how the engine is performing with different fuels. The oxidation of the engine oil and soot buildup in the oil led to the termination of the MIL-F-46162C evaluations. The iron accumulation results displayed in Fig. 26 are indicative of cylinder liner and piston ring wear. These data suggest slightly lower iron accumulation rates with MIL-T-83133C grade JP-8 fuel. Some of the variation in the wear metals accumulations is due to oil additions.

Engine oil usually has some acidity as measured by the Total Acid Number (TAN) and some reserve alkalinity measured by the Total Base Number (TBN). The TBN is present to neutralize the acids formed by both oil degradation and combustion by-products. The increase of TAN usually follows a decrease of the TBN. In other words, when the reserve alkalinity is expended, the acidity of the lubricant tends to increase. The rate at which these events occur is a known function of the fuel sulfur content. Fig. 27 illustrates the TAN and TBN histories of the three durability evaluations. The results with JP-8 follow a typical trend of base number depletion and acid number increase. The referee grade 1% S DF-2 results show rapid TBN depletion, corresponding to a TAN increase.

One measure of oil oxidation is the lubricant viscosity increase as a function of time. Rapid oil oxidation rates were not expected for these evaluations, so the viscosity was scheduled to be measured every 70 hours of testing. The DF-2 evaluations had high oil oxidation and oil thickening, and the time for the oil to exceed the viscosity range for a 15W-40 grade lubricant was not accurately determined. Fig. 28 represents the extent of the oil viscosity data, but clearly shows the rapid oxidation of the lubricant with the 1% S DF-2. The oxidation of the lubricant can also be catalyzed by soot and, to some extent, wear metals. Emissions results indicate soot should be greater with the DF-2 fuel. The oil thickening and soot led to the formation of deposits, which stuck the rings during the DF-2 evaluations.

The durability results indicate JP-8 was not detrimental to the durability of the engine. The use of MIL-F-46162C appears to affect durability substantially. Such a wide difference in engine durability with these fuels was not expected at the onset of the program.

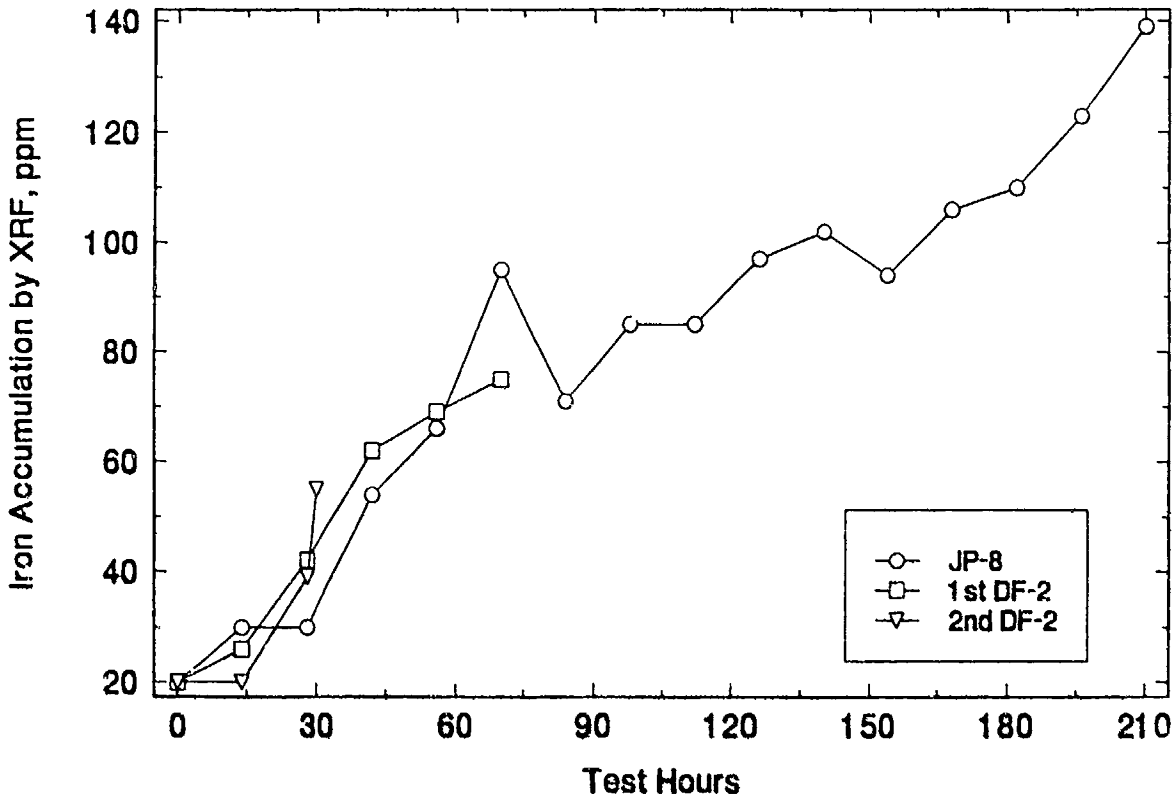

Figure 26. Used oil analysis — iron wear metals accumulation

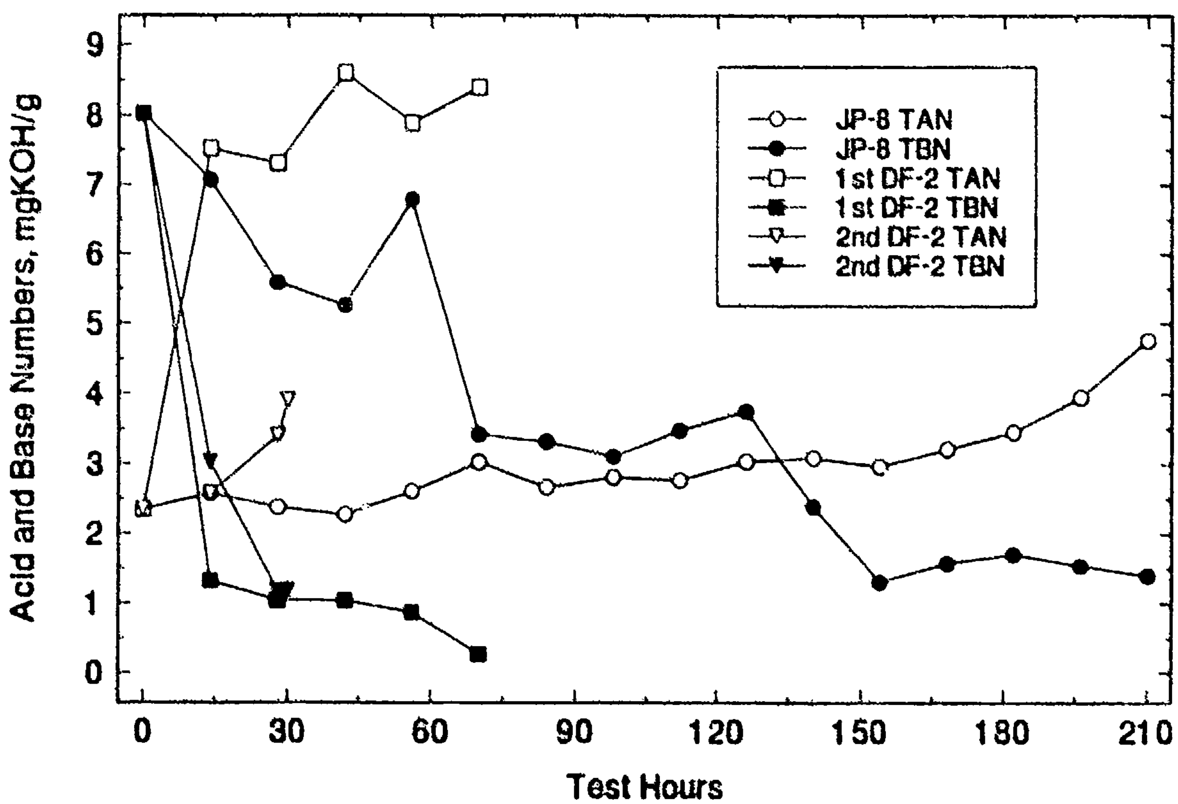

Figure 27. Used oil analysis — lubricant acidity trend

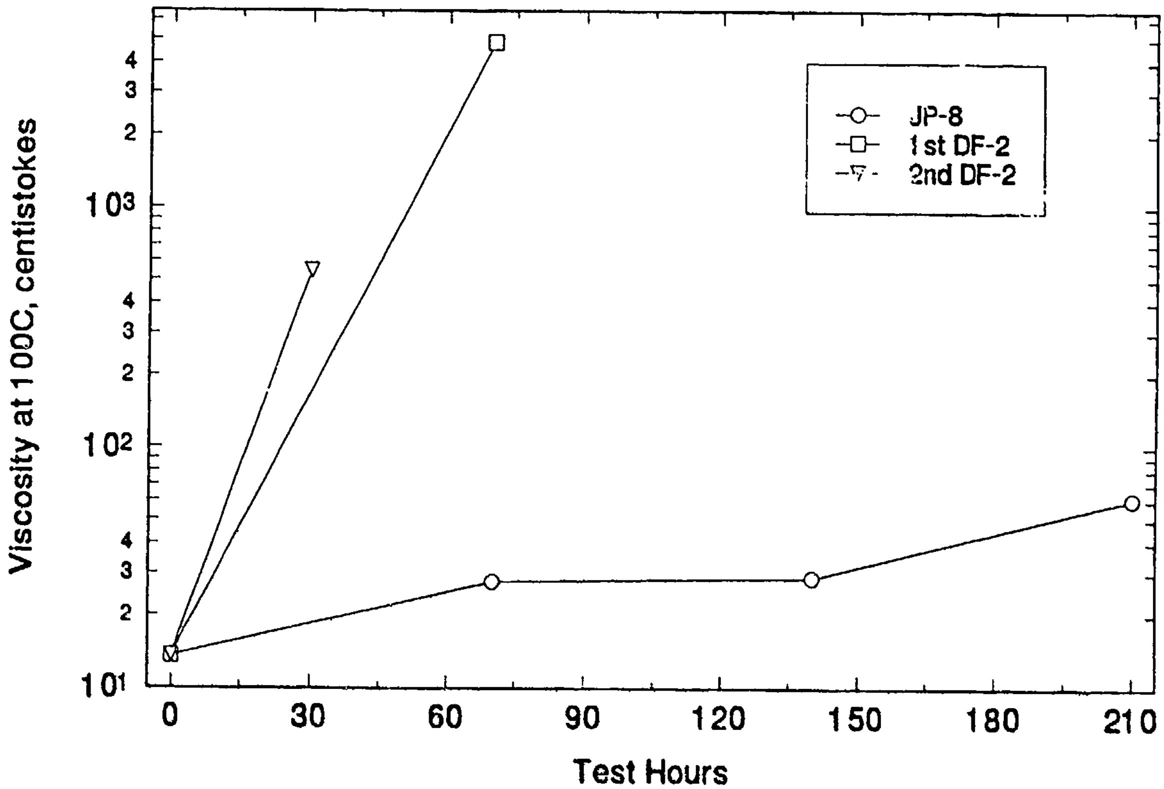

Figure 28. Used oil analysis -- viscosity increase

B. Rough-Terrain Forklifts

The rough-terrain forklift evaluations with JP-8 were in two performance categories: fuel consumption and power availability. The fuel consumption was estimated by the load-placement evaluations and the steady-speed measurements. The power availability was determined by employing time-to-distance accelerations and the speed-on-grade on a 45-percent slope.

1. Fuel Consumption

The fuel consumption and fuel economy deviations for the rough-terrain forklifts are shown in Fig. 29, along with the deviation between the volumetric heat of combustion of the two test fuels. For these evaluations, the volumetric heating value for the JP-8 was approximately 3 percent lower than the reference DF-2. The fuel consumption data, in liters per hour (gallons per hour), were generated during the load-placement tests. The fuel economy data, km per liter (miles per gallon), were generated during the steady-speed measurements.

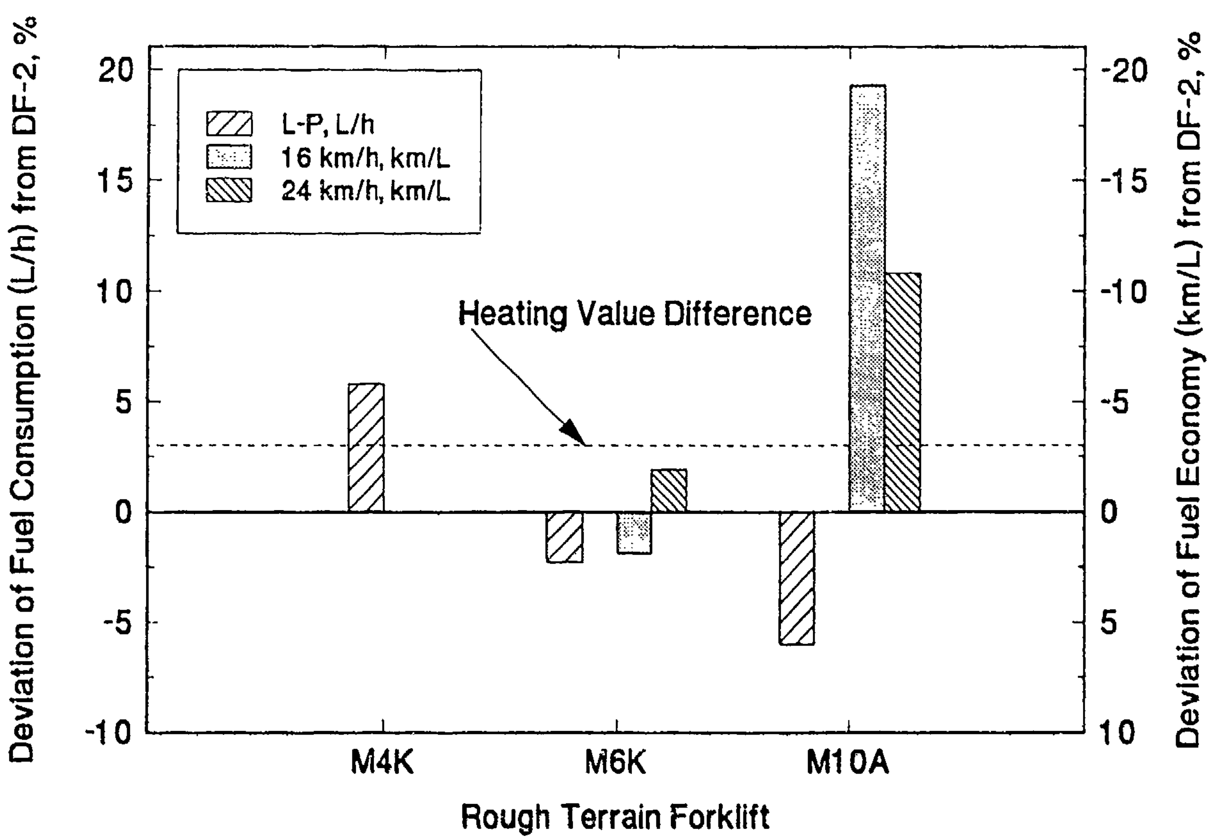

Figure 29. Fuel consumption and economy for rough-terrain forklifts

The M4K RTFLT was evaluated for fuel consumption (liters/hr) utilizing the load-placement test only. The data indicate the typical fuel consumption increase for the M4K would be approximately 5.8 percent. While utilizing JP-8 during the load-placement tests, the M4K did not display any operational problems. The operator felt that the vehicle performed satisfactorily with JP-8.

The M6K VRRTFLT was evaluated for fuel usage utilizing both load-placement and steady-speed tests. The load-placement test was performed twice with JP-8 and once with DF-2. The average fuel consumption (liters/hr) decrease for the M6K with JP-8 was approximately 2.4 percent. While utilizing JP-8 during the load-placement test, idle roughness and stalling were noted, particularly after the vehicle and fuel reached operating temperatures. The M6K VRRTFLT has parasitic hydraulic loads while idling. The lower viscosity of heated JP-8 and the ensuing increased injection pump leakage resulted in lower injected fuel quantities at idle. The combination of the parasitic loads and the lower injection quantities with JP-8 resulted in the idle roughness and stalling. An adjustment of the idle speed or idle fuel flow would eliminate the hot-idle stalling problem with JP-8 in the M6K vehicle.

The M6K VRRTFLT was evaluated for fuel economy (km/liter) at two speeds, while carrying a capacity load. The operator was able to maintain the average speed targets around the BEPG test track, which did include a graded section. At a test speed of 18 km/hr (10 mph), the M6K revealed an approximate 2-percent improvement in fuel economy while utilizing JP-8. At the 28-km/hr (15-mph) test speed, the M6K indicated an approximate 2-percent decrement in fuel economy while utilizing JP-8. All fuel usage measurements for the M6K revealed fuel consumption differences less than would be predicted from the volumetric heat of combustion difference of the test fuels. Overall, the fuel usage deviations with JP-8 in the M6K is on the order of a 1-percent decrease with respect to DF-2.

The M10A RTFLT was also evaluated for fuel usage using both the load-placement and steady-speed tests. The fuel consumption (liters/hr) decrease for the M10A with JP-8 was on the order of 5.9 percent. While utilizing JP-8 during the load-placement tests, the M10A did not display any operational problems. The operator felt that the vehicle performed satisfactorily with JP-8.

The M10A RTFLT was evaluated for fuel economy (km/liter) at two speeds, while carrying a capacity load. Again, the operator was able to maintain the average speed targets around the BEPG test track. At a test speed of 18 km/hr (10 mph), the M10A revealed a decrement in fuel economy, with respect to DF-2, on the order of 19.3 percent while utilizing JP-8. At the 15-mph test speed, the M10A indicated an approximate 10.9-percent decrement in fuel economy while utilizing JP-8. The fuel usage measurements for the M10A revealed fuel consumption differences, which vary significantly from the values predicted from the volumetric heat of combustion difference of the test fuels. It is not known why these large fuel consumption deviations exist with the M10A. An overall average of the fuel usage deviations with JP-8 in the M10A reveals an approximate increase in fuel usage of 8.1 percent with respect to DF-2.

2. Power Availability

Acceleration time-to-distance was measured for all vehicles both with and without their respective capacity loads. Fig. 30 represents the acceleration times for the unloaded rough-terrain forklifts at each of the two measured distances. Similarly, Fig. 31 displays the results for the loaded forklifts.

From Fig. 30, it can be seen that the unloaded M4K has 2.1 percent longer times to 46 meters (151 feet) and equivalent times to 92 meters (302 feet) while consuming JP-8. From Fig. 31, the loaded vehicle acceleration times for the M4K were roughly equivalent at 46 meters and 4.2 percent longer at 92 meters. The overall average increase in acceleration times for the M4K was approximately 1.4 percent when JP-8 was consumed. This value is lower than the energy content difference between the test fuels.

The unloaded M6K reveals 1.8 percent longer times to 46 meters (151 feet) and 1.6 percent longer times to 92 meters (302 feet) when consuming JP-8. The loaded vehicle acceleration times for the M6K were 4.9 percent longer at 46 meters and 5.0 percent longer at 92 meters. The overall average increase in acceleration times for the M6K was on the order of 3.3 percent when JP-8 was consumed. This value reflects the energy content difference between the test fuels.

The unladen M10A reveals 3.1 percent longer times to 46 meters and 3.3 percent longer times to 92 meters while JP-8 is consumed. The acceleration times for the M10A while carrying a capacity load were 1.1 percent longer at 46 meters and 1.1 percent longer at 92 meters. The averaged increase in acceleration times for the M10A was on the order of 2.2 percent when JP-8 was being consumed. This value is slightly lower than the energy content difference between the test fuels.

All vehicles performed satisfactorily during the acceleration tests with JP-8. One observation noted during the testing was the reduced exhaust smoke signature when JP-8 was used in all vehicles.

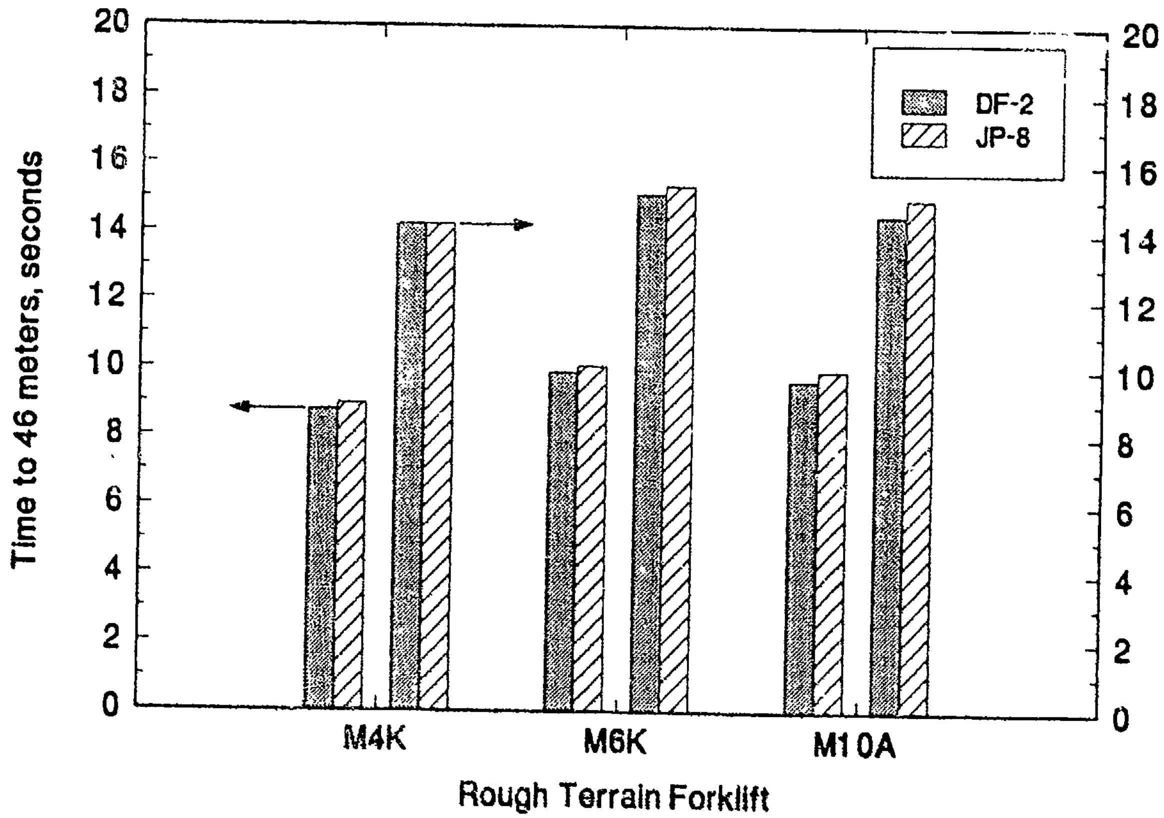

Figure 30. Time-to-distance for accelerating unloaded rough-terrain forklifts

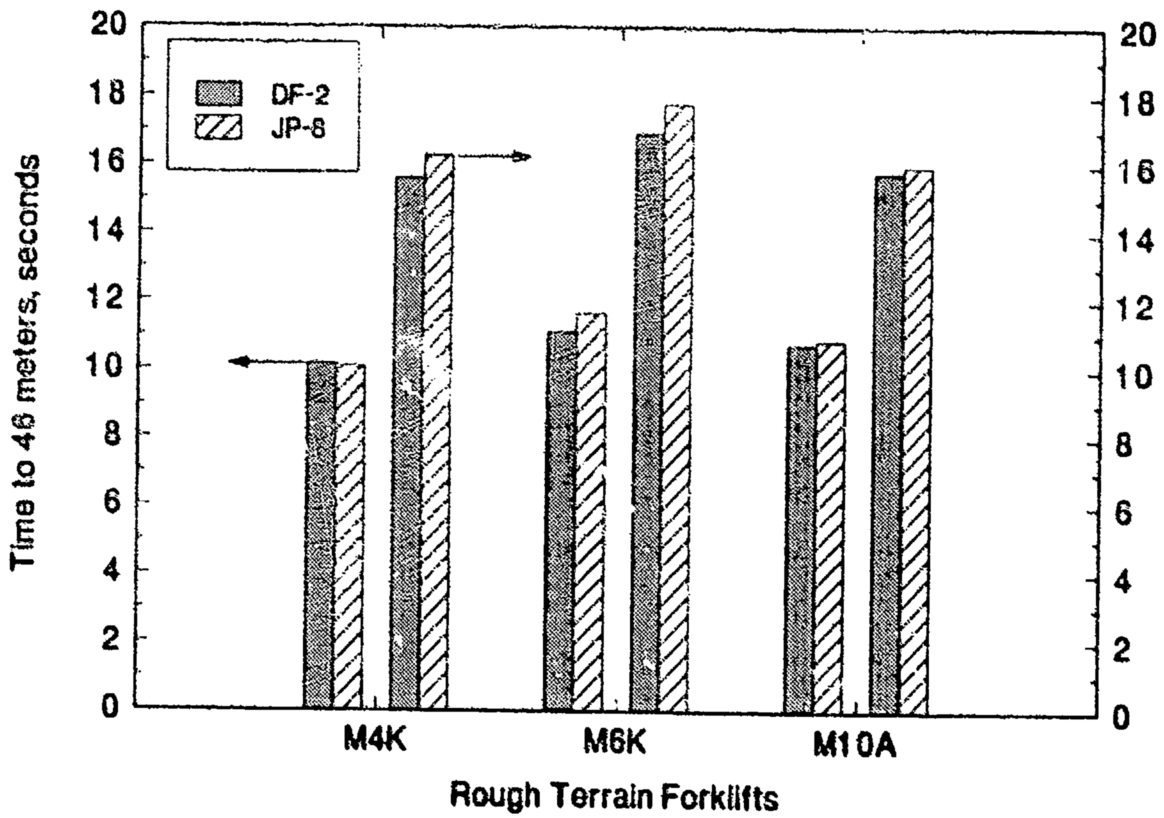

Figure 31. Time-to-distance for accelerating capacity-loaded rough-terrain forklifts

A 45-percent slope was used to observe the speed-on-grade of the rough-terrain forklifts. The vehicle speeds were calculated from the elapsed time through a 10.7-meter (35-foot) constant slope test section. All evaluations were performed with the vehicle carrying a capacity load. The speeds obtained on the grade for both fuels are shown in Fig. 32 for all three test vehicles. All results shown are the average of six timed climbs. The grade-climbing ability of the M4K was not affected by the use of JP-8. The M10A showed a slight increase in grade speed when JP-8 was combusted. The operator felt the performances of these vehicles with JP-8 were satisfactory.

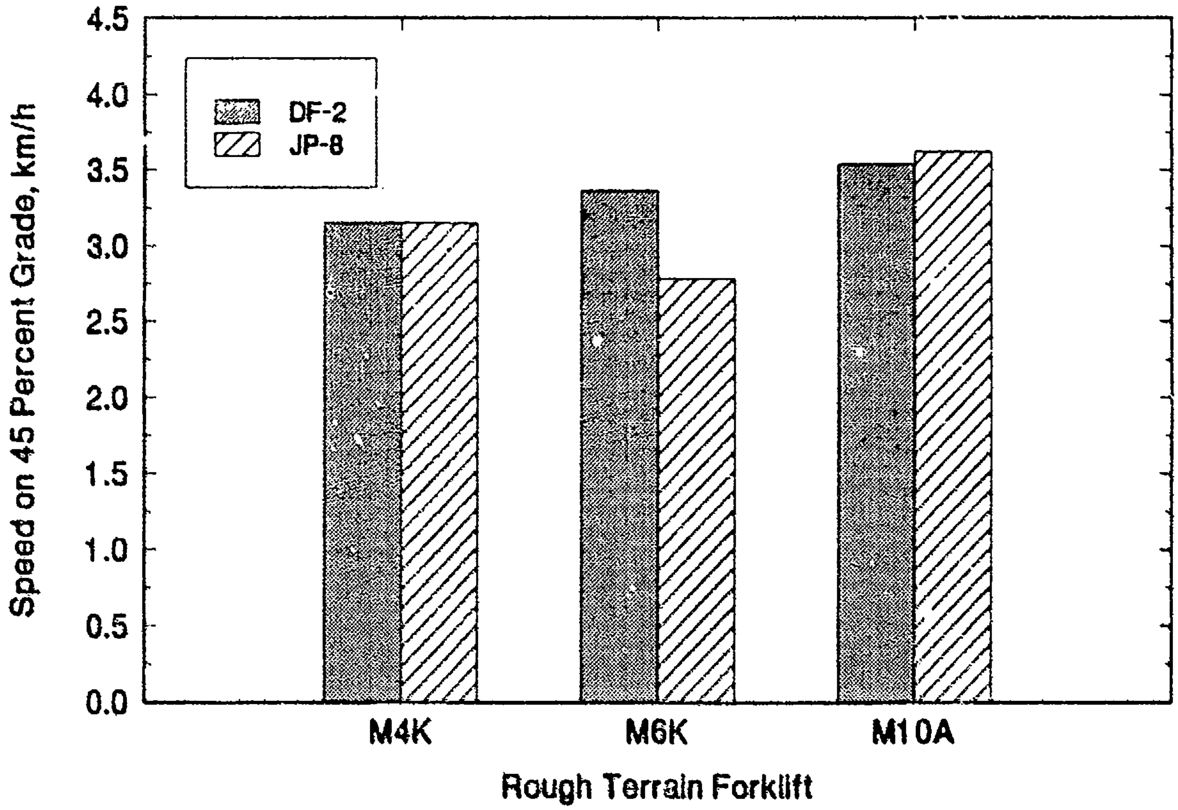

Figure 32. Speed on 45-percent grade for capacity-loaded rough-terrain forklifts

The M6K revealed a 17.4-percent reduction in grade speed, much greater than would have been expected from the energy content of the fuels. It is interesting that the M6K uses the same design fuel injection pump as the Perkins 4.154 engine discussed earlier. As noted during the discussion of the Perkins 4.154 performance data, the Perkins engine had suffered a performance loss greater than experienced by the other engines evaluated. The performance of the M6K seems to confirm the speculation that particular design of fuel injection pump appears to be sensitive to fuel viscosity and density variations.

The acceleration results indicate some decrease in power availability when JP-8 is utilized in the rough-terrain forklifts. The speed-on-grade results indicate that for the M4K and M10A, the power available using JP-8 to perform their mission is adequate. The M6K, however, reveals a loss of grade climbing ability, or insufficient power availability, when JP-8 is utilized.

VII. CONCLUSIONS

A. Clean-Burn Diesel Engines

- In general, the gaseous exhaust emissions of the four clean-burn diesel engines evaluated were lower with MIL-T-83133C grade JP-8 than with the MIL-F-46162C referee grade diesel fuel. The Deutz F3L912W engine revealed higher unburned hydrocarbon emissions with JP-8.

- All engines revealed substantial reductions in particulate mass emissions when utilizing JP-8.

- The three engines with in-line injection pumps revealed performance decrements with JP-8 that were on the order of the difference in heating values of the test fuels. The engine that utilizes a rotary injection pump displayed a performance decrement larger than expected from the heating value of the fuels.

- A 210-hour evaluation with the Isuzu C-240 engine operating on JP-8 indicates that the use of JP-8 would not affect the durability of the engine. The same evaluations indicate substantial improvements in durability with JP-8 are realized when compared to the MIL-F-46162C referee grade diesel fuel.

B. Rough-Terrain Forklifts

- The M4K RTFLT in load-placement testing revealed a 5.8-percent increase in fuel consumption with JP-8. The M4K performance during the accelerations and grade climbing indicate adequate power is available when consuming JP-8.

- The M6K VRRTFLT in load-placement and steady-speed evaluations revealed an overall 1-percent decrease in fuel usage during JP-8 utilization. The M6K displayed acceleration time increases with JP-8 on the order of the heating value differences of the test fuels. The grade-climbing ability was decreased with the use of JP-8.

- The M6K revealed a hot-idle and stalling problem when JP-8 was utilized, particularly when the engine and fuel reach operating temperatures.

- The M10A RTFLT in load-placement and steady-speed evaluations displayed an overall 8.1-percent increase in fuel usage when JP-8 was utilized. The M10A performance during the acceleration trials and grade climbs indicated the power availability when utilizing JP-8 was adequate for the vehicle to perform its mission.

VIII. RECOMMENDATIONS

The following recommendations are made as a result of this study:

- The required idle speed and fuel flow settings for the M6K to eliminate the hot-idle and stalling concerns when JP-8 is utilized should be determined.

- The required fuel injection pump adjustments for the M6K to recover the grade climbing performance loss when JP-8 is utilized should be determined.

- The reason for the unexpectedly large increase in fuel usage with JP-8 of the M10A during the steady-speed evaluations should be determined.

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APPENDIX

Gaseous and Particulate Exhaust Emissions

GASEOUS and PARTICULATE EXHAUST EMISSIONS

Engine Model: Perkins 4.154

Test Date : 08/29/90
Fuel : MIL-T-83133C grade JP-8

	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 8	MODE 9	MODE 10	MODE 11	MODE 12	IDLE AVG.
SPEED, RPM	1790	1809	1802	1808	1800	2600	2600	2600	2600	2600	601
TORQUE, lb-ft	10.40	30.00	59.90	93.00	102.00	100.00	94.00	55.00	28.00	12.00	3.50
EMISSION RESULTS											
gr/hp-hr											
HC	4.699	0.821	0.318	0.106	0.091	0.053	0.062	0.231	1.102	6.835	16.001
CO	26.173	5.983	2.009	1.053	1.082	0.713	0.721	1.566	7.934	33.595	62.337
NOX	3.175	2.209	2.185	2.162	1.822	1.744	1.803	2.296	2.465	3.547	10.536
NOX,CORR	5.051	3.514	3.166	2.873	2.344	2.140	2.292	3.171	3.761	5.436	17.663
CO2	1263	651	483	466	470	493	467	510	686	1190	2692
PARTICULATE CONC.		0.808	0.411		0.225	0.170		0.168	0.486		
O2 %	16.88	15.28	12.92	8.72	6.97	5.34	3.89	12.29	14.90	17.13	17.05

Test Date : 09/12/90
Fuel : MIL-T-83133C grade JP-8

	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 8	MODE 9	MODE 10	MODE 11	MODE 12	IDLE AVG.
SPEED, RPM	1804	1803	1808	1796	1801	2606	2601	2600	2620	2590	599
TORQUE, lb-ft	9.10	29.80	57.80	87.40	107.00	103.00	85.00	56.70	28.00	12.70	2.80
EMISSION RESULTS											
gr/hp-hr											
HC	10.266	1.511	0.505	0.324	0.148	0.054	0.104	0.265	1.315	0.568	32.786
CO	39.346	8.367	2.239	1.127	0.766	0.903	0.892	1.835	8.859	7.357	99.297
NOX	3.745	2.161	2.009	1.860	1.634	1.576	1.958	2.226	2.498	1.418	23.456
NOX,CORR	6.164	3.336	2.951	2.447	2.008	1.850	2.475	3.068	3.710	2.231	38.789
CO2	1438	642	484	453	470	490	476	505	687	1176	4447
PARTICULATE CONC.		1.560	0.696		0.295	0.178		0.196	0.410		
O2 %	16.88	15.40	12.67	8.85	5.19	4.10	7.52	11.54	14.66	16.14	17.51

GASEOUS and PARTICULATE EXHAUST EMISSIONS

Engine Model: Perkins 4.154

Test Date : 08/30/90
Fuel : MIL-F-46162C DF-2 (1% S)

	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 8	MODE 9	MODE 10	MODE 11	MODE 12	IDLE AVG.
SPEED, RPM	1809	1808	1800	1800	1800	2606	2604	2607	2600	2595	609
TORQUE, lb-ft	9.00	29.00	58.00	88.00	115.00	109.00	86.00	57.00	27.00	13.30	2.33
EMISSION RESULTS											
gr/hp-hr											
HC	7.896	1.059	0.274	0.109	0.109	0.037	0.069	0.262	1.168	8.138	69.822
CO	36.606	8.010	1.964	1.001	1.588	9.211	0.762	1.690	11.135	42.538	187.187
NOX	3.625	2.351	3.024	2.553	1.828	1.808	2.390	3.145	2.889	2.872	20.189
NOX,CORR	6.418	6.764	4.545	3.538	2.283	2.095	3.186	4.539	4.337	4.444	34.572
CO2	1591	702	518	471	485	527	475	510	716	1078	6480
PARTICULATE CONC.		0.897	0.608		0.492	1.514		0.494	0.845		
O2 %	16.64	15.40	12.54	8.95	3.73	1.15	7.47	8.93	14.41	16.14	12.25

Test Date : 09/13/90
Fuel : MIL-F-46162C DF-2 (1% S)

	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 8	MODE 9	MODE 10	MODE 11	MODE 12	IDLE AVG.
SPEED, RPM	1807	1820	1807	1813	1801	2614	2600	2600	2600	2590	613
TORQUE, lb-ft	9.10	29.10	58.00	88.00	120.00	113.00	84.00	56.50	29.70	11.00	2.57
EMISSION RESULTS											
gr/hp-hr											
HC	12.062	2.198	0.617	0.340	0.128	0.022	0.061	0.169	0.984	4.213	76.201
CO	45.346	9.540	2.606	1.040	1.499	8.367	0.649	1.552	10.339	61.857	193.980
NOX	14.770	2.253	2.249	2.127	1.733	1.981	2.773	2.623	2.629	3.057	14.205
NOX,CORR	25.098	3.625	3.258	2.801	2.013	2.176	3.512	3.702	2.524	4.768	24.174
CO2	1535	679	520	471	488	520	484	516	676	1381	6053
PARTICULATE CONC.		1.379	0.815		0.754	1.692		0.463	0.773		
O2 %	16.88	15.03	12.42	7.68	3.16	1.42	7.83	11.66	14.53	15.89	17.38

GASEOUS and PARTICULATE EXHAUST EMISSIONS

Engine Model: Isuzu C-240

Test Date : 11/02/90
Fuel : MIL-T-83133C grade JP-8

	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 8	MODE 9	MODE 10	MODE 11	MODE 12	IDLE AVG.
SPEED, RPM	2000	2000	2009	2000	2000	2400	2400	2400	2396	2380	677
TORQUE, lb-ft	11.30	28.00	55.00	84.50	101.00	100.00	80.00	59.00	24.00	13.00	4.10
EMISSION RESULTS											
gr/hp-hr											
HC	4.289	1.169	0.377	0.136	0.112	0.057	0.261	1.195	0.690	1.807	3.304
CO	13.406	2.737	1.294	0.695	3.914	2.385	1.358	3.151	4.251	11.010	26.633
NOX	8.417	5.869	4.485	2.843	2.240	2.244	2.908	3.794	5.100	6.732	32.360
NOX,CORR	10.395	7.035	5.176	2.988	2.332	2.351	3.115	4.138	5.685	7.544	37.721
CO2	1166	643	480	474	523	510	468	490	747	1043	3458
PARTICULATE CONC.		0.576	0.422		1.061	1.760		0.290	1.016		
O2 %	16.51	14.90	11.91	7.29	2.17	6.25	19.92	11.16	15.03	16.14	17.34

Test Date : 11/06/90
Fuel : MIL-T-83133C grade JP-8

	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 8	MODE 9	MODE 10	MODE 11	MODE 12	IDLE AVG.
SPEED, RPM	1996	2000	2000	2000	2000	2400	2400	2400	2400	2400	668
TORQUE, lb-ft	12.00	27.00	55.00	82.00	102.00	101.00	80.00	52.00	26.90	12.30	4.20
EMISSION RESULTS											
gr/hp-hr											
HC	6.401	1.699	0.675	0.311	0.192	0.080	0.350	2.406	0.765	1.724	3.672
CO	13.584	3.478	2.045	0.846	3.893	3.041	1.207	2.294	3.812	13.463	29.048
NOX	12.984	8.460	6.131	3.251	2.340	2.355	3.521	5.194	5.540	10.633	24.444
NOX,CORR	14.251	9.339	6.656	3.337	2.301	2.336	3.660	5.562	6.090	11.847	27.177
CO2	1166	686	497	495	532	525	483	517	738	1190	3986
PARTICULATE CONC.		0.379	0.625		5.625	3.407		0.440	1.032		
O2 %	16.76	15.28	14.78	7.81	5.99	2.44	7.22	12.04	14.53	15.77	17.12

GASEOUS and PARTICULATE EXHAUST EMISSIONS

Engine Model: Isuzu C-240

Test Date : 11/01/90
Fuel : MIL-F-46162C DF-2 (1% S)

	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 8	MODE 9	MODE 10	MODE 11	MODE 12	IDLE AVG.
SPEED, RPM	2000	2000	2000	2005	2000	2400	2400	2400	2362	2346	674
TORQUE, lb-ft	12.10	26.50	55.00	81.60	105.00	103.00	82.00	54.00	26.00	13.00	4.50
EMISSION RESULTS											
gr/hp-hr											
HC	2.082	1.402	0.534	0.216	0.210	0.146	0.163	0.510	1.381	1.672	4.363
CO	14.184	2.535	1.349	0.835	16.578	22.408	1.331	1.087	4.846	14.525	44.919
NOX	9.258	7.770	5.452	4.118	2.225	2.393	3.955	3.759	6.864	8.948	23.988
NOX,CORR	10.555	8.951	6.013	4.409	2.290	2.450	4.211	4.129	7.779	9.967	27.653
CO2	1139	701	503	471	529	525	480	313	706	1092	2600
PARTICULATE CONC.		1.498	0.631		5.711	4.478		0.378	1.700		
O2 %	16.26	14.66	11.28	7.81	1.15	0.95	6.92	11.66	14.66	15.77	13.43

Test Date : 11/08/90
Fuel : MIL-F-46162C DF-2 (1% S)

	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 8	MODE 9	MODE 10	MODE 11	MODE 12	IDLE AVG.
SPEED, RPM	1999	1992	2000	2000	2000	2402	2400	2400	2400	2400	670
TORQUE, lb-ft	10.90	27.10	55.50	82.00	107.00	107.00	80.00	53.00	24.00	12.00	3.93
EMISSION RESULTS											
gr/hp-hr											
HC	4.964	2.242	0.981	0.306	0.281	0.242	0.191	1.264	1.354	3.516	18.700
CO	25.917	3.287	1.176	0.863	7.587	16.125	1.126	1.272	4.539	22.727	121.268
NOX	11.320	9.838	7.785	5.568	3.051	2.849	5.306	6.687	7.449	10.734	44.045
NOX,CORR	12.876	10.972	8.369	5.668	2.913	2.714	5.429	7.143	8.246	12.179	49.042
CO2	1327	718	508	480	535	522	477	557	724	1267	4865
PARTICULATE CONC.		5.290	0.996			9.570		0.838	1.955		
O2 %	16.64	15.03	12.42	8.04	1.65	0.86	8.15	11.91	14.90	16.14	17.17

GASEOUS and PARTICULATE EXHAUST EMISSIONS

Engine Model: Deutz F4L912W

Test Date : 12/17/90
Fuel : MIL-T-83133C grade JP-8

	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 8	MODE 9	MODE 10	MODE 11	MODE 12	IDLE AVG.
SPEED, RPM	1501	1500	1500	1500	1500	2300	2300	2300	2300	2300	606
TORQUE, lb-ft	6.90	37.00	74.00	111.00	139.00	122.00	98.00	67.00	34.00	12.00	2.63
EMISSION RESULTS											
gr/hp-hr											
HC	3.085	0.55	0.295	0.212	0.206	0.181	0.219	0.383	0.836	3.359	14.888
CO	15.297	2.151	0.964	0.69	1.098	1.316	0.994	1.552	4.362	16.99	78.198
NOX	14.526	6.095	5.239	4.03	2.988	2.704	3.631	3.874	4.65	7.669	123.865
NOX,CORR	18.95	7.7	6.2	4.617	3.362	3.09	4.125	4.563	5.5	9.355	151.790
CO2	2012	566	468	435	451	497	469	503	682	1373	9724
PARTICULATE CONC.		0.757	0.9945		1.679	1.0875		0.416	0.983		
O2 %	17.63	16.14	13.17	10.01	5.39	5.08	9.62	13.04	15.52	17.01	18.05

Test Date : 12/19/90
Fuel : MIL-T-83133C grade JP-8

	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 8	MODE 9	MODE 10	MODE 11	MODE 12	IDLE AVG.
SPEED, RPM	1505	1500	1500	1500	1500	2300	2300	2300	2300	2300	622
TORQUE, lb-ft	8.20	37.00	74.00	111.00	143.00	126.00	99.00	66.00	33.00	12.10	3.50
EMISSION RESULTS											
gr/hp-hr											
HC	4.371	0.771	0.387	0.233	0.252	0.022	0.252	0.325	0.779	2.897	3.123
CO	23.984	2.787	1.1	0.61	0.928	0.019	1.061	1.183	4.011	17.592	19.048
NOX	19.106	9.899	6.087	4.306	3.816	0.001	5.488	4.447	6.504	9.432	53.916
NOX,CORR	20.117	10.39	6.353	4.264	3.738	0.001	5.368	4.392	6.749	9.458	54.111
CO2	2010	629	478	363	452	497	479	523	696	1405	3129
PARTICULATE CONC.		0.512	0.584		0.8075	0.6275		0.3785	1.0425		
O2 %	18.89	18.89	5.44	10.39	5.84	5.39	9.45	13.29	15.89	17.38	14.54

GASEOUS and PARTICULATE EXHAUST EMISSIONS

Engine Model: Deutz F4L912W

Test Date : 12/14/90
Fuel : MIL-F-46162C DF-2 (1%S)

	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 8	MODE 9	MODE 10	MODE 11	MODE 12	IDLE AVG.
SPEED, RPM	1500	1500	1500	1500	1500	2300	2300	2300	2300	2300	711
TORQUE, lb-ft	8.00	37.00	74.00	112.00	149.00	133.00	100.00	67.00	33.00	12.00	4.07
EMISSION RESULTS											
gr/hp-hr											
HC	3.032	0.525	0.262	0.222	0.265	0.21	0.243	0.459	1.072	6.448	7.044
CO	18.615	2.204	0.781	0.579	2.254	2.161	0.887	1.451	5.87	32.861	35.075
NOX	15.611	9.489	6.183	5.469	3.508	3.185	4.252	4.909	5.158	7.101	45.514
NOX,CORR	17.167	10.352	6.66	5.775	3.66	3.393	4.699	5.298	5.557	7.929	51.429
CO2	1927	651	469	456	487	514	472	529	716	1432	3411
PARTICULATE CONC.		0.6575	0.758		1.713	1.509		0.789	1.508		
O2 %	17.76	16.02	13.54	10.26	4.00	3.94	9.73	12.79	15.40	16.88	18.22

Test Date : 12/18/90
Fuel : MIL-F-46162C DF-2 (1%S)

	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 8	MODE 9	MODE 10	MODE 11	MODE 12	IDLE AVG.
SPEED, RPM	1502	1500	1500	1500	1500	2300	2300	2300	2300	2300	651
TORQUE, lb-ft	8.10	38.00	74.00	112.00	149.00	134.00	99.00	66.00	33.00	11.70	[illegible]
EMISSION RESULTS											
gr/hp-hr											
HC	4.041	0.666	0.381	0.259	0.274	0.202	0.26	0.428	1.229	13.798	12.254
CO	21.483	2.492	0.98	0.579	2.317	2.616	1.049	1.518	7.793	36.763	59.243
NOX	14.176	2.083	5.333	4.657	3.609	3.049	4.205	5.193	5.925	9.776	100.654
NOX,CORR	14.342	2.075	5.114	4.478	3.41	2.904	4.034	4.993	5.773	9.518	101.027
CO2	1944	664	499	459	487	517	464	534	721	1534	5277
PARTICULATE CONC.		0.522	0.959		2.607	2.067		0.8585	1.9315		
O2 %	17.26	15.52	13.04	10.14	11.28	4.10	10.52	13.42	15.77	17.01	18.09

GASEOUS and PARTICULATE EXHAUST EMISSIONS

Engine Model: Deutz F3L912W

Test Date : 01/08/91
Fuel : MIL-T-83133C grade JP-8

	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 8	MODE 9	MODE 10	MODE 11	MODE 12	IDLE AVG.
SPEED, RPM	1604	1603	1603	1607	1600	2653	2650	2654	2646	2660	596
TORQUE, lb-ft	9.60	27.40	55.90	82.70	110.00	89.00	70.00	48.00	23.00	13.00	2.90
EMISSION RESULTS											
gr/hp-hr											
HC	0.804	0.37	0.223	0.181	0.146	0.292	0.354	0.442	0.786	1.312	5.017
CO	6.205	1.694	0.882	0.756	1.235	1.312	1.258	1.635	3.192	6.678	24.241
NOX	16.619	10.823	8.088	6.081	3.85	5.656	6.673	8.83	10.803	13.712	155.617
NOX,CORR	16.36	10.702	8.027	6.025	3.791	5.513	6.589	8.841	10.898	14.015	158.434
CO2	1056	611	469	426	438	494	494	579	861	1294	6832
PARTICULATE CONC.		0.334	0.353		2.403	0.68		0.587	0.754		
O2 %	17.01	15.77	13.17	10.26	5.39	6.48	10.14	12.42	14.78	15.40	17.01

Test Date : 01/10/91
Fuel : MIL-T-83133C grade JP-8

	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 8	MODE 9	MODE 10	MODE 11	MODE 12	IDLE AVG.
SPEED, RPM	1605	1610	1601	1622	1600	2652	2652	2652	2646	2653	639
TORQUE, lb-ft	7.20	27.30	55.00	83.00	109.00	90.00	70.70	47.00	24.00	12.30	1.67
EMISSION RESULTS											
gr/hp-hr											
HC	1.323	0.38	0.181	0.123	0.145	0.262	0.339	0.494	0.707	1.166	5.177
CO	13.026	2.696	0.89	0.693	1.479	1.389	1.402	1.777	3.022	4.978	41.672
NOX	30.209	11.864	7.122	5.887	3.348	5.008	7.064	8.769	9.483	15.622	208.645
NOX,CORR	34.101	12.914	7.522	6.142	3.375	5.074	7.268	9.099	10.303	16.99	230.139
CO2	1603	663	484	443	468	489	494	580	834	1374	8971
PARTICULATE CONC.		0.348	0.297		2.83	0.807		0.623	0.801		
O2 %	17.63	16.02	13.42	10.26	13.04	6.23	9.59	12.29	14.66	14.66	17.80

GASEOUS and PARTICULATE EXHAUST EMISSIONS

Engine Model: Deutz F3L912W

Test Date : 01/09/91
Fuel : MIL-F-46162C DF-2 (1%S)

	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 8	MODE 9	MODE 10	MODE 11	MODE 12	IDLE AVG.
SPEED, RPM	1611	1600	1627	1602	1600	2648	2640	2647	2653	2647	595
TORQUE, lb-ft	8.80	27.40	55.50	83.00	109.00	92.00	70.30	47.00	22.80	12.60	2.27
EMISSION RESULTS											
gr/hp-hr											
HC	0.99	0.317	0.184	0.147	0.238	0.271	0.282	0.359	0.546	1.016	5.919
CO	12.197	2.075	0.993	0.728	3.391	1.813	1.344	1.583	3.173	10.612	36.813
NOX	21.975	11.554	8.254	6.715	3.378	5.218	7.046	8.109	11.008	15.539	123.305
NOX, CORR	23.721	12.386	8.614	6.856	3.341	5.224	7.183	8.471	11.686	16.687	132.342
CO2	1476	652	498	439	506	519	512	577	877	1355	5529
PARTICULATE CONC.		0.438	0.753		4.084	2.545		1.062	2.469		
O2 %	17.13	15.65	13.17	12.42	3.92	5.14	9.66	12.42	14.66	15.52	17.55

Test Date : 01/29/91
Fuel : MIL-F-46162C DF-2 (1%S)

	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6	MODE 8	MODE 9	MODE 10	MODE 11	MODE 12	IDLE AVG.
SPEED, RPM	1602	1608	1601	1598	1605	2653	2655	2650	2643	2643	593
TORQUE, lb-ft	6.80	28.30	55.40	83.80	104.80	90.00	72.80	47.00	24.70	11.20	0.73
EMISSION RESULTS											
gr/hp-hr											
HC	1.013	0.327	0.19	0.188	0.262	0.12	0.289	0.43	0.587	1.138	8.173
CO	10.887	1.993	1.005	0.697	4.714	2.094	1.597	2.069	3.414	6.949	58.780
NOX	29.476	12.164	9.99	7.298	3.537	5.083	7.478	8.897	10.206	19.264	246.776
NOX,CORR	36.479	14.63	11.446	8.055	3.801	5.463	8.271	10.038	11.417	21.756	294.638
CO2	1816	692	534	458	509	525	504	589	803	1435	10638
PARTICULATE CONC.		0.907	0.937		4.338	1.866		0.993	1.506		
O2 %	16.39	14.53	12.14	8.85	3.08	4.63	8.42	11.54	13.79	14.66	16.76

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STOCKTON CA 95296-0960

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US ARMY COLD REGION TEST CENTER
ATTN: STECR-TA 1
APO SEATTLE WA 98733

CDR
US ARMY RSCH, DEV & STDZN GROUP (UK)
ATTN: AMXSN-UK-RA (DR REICHENBACH) 1
BOX 65
FPO NEW YORK 09510-1500

CDR
US ARMY COMBAT SYS TEST ACTY
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US ARMY BIOMEDICAL R&D LABORATORY
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PM BFVS, ATTN: SFAE-ASM-BV 1
PM 113 FOV, ATTN: SFAE-ASM-AFAS 1
PM M9 ACE, ATTN: SFAE-ASM-FARVA 1
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US ARMY TRANSPORTATION SCHOOL
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US ARMY INFANTRY SCHOOL
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US ARMY AVIATION CTR & FT RUCKER
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FORT RUCKER AL 36362

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ATZL-CAT-A 1
FORT LEAVENWORTH KS 66027-5300

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US ARMY ENGINEER SCHOOL
ATTN: ATSE-CD 1
FORT LEONARD WOOD MO 65473-5000

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US ARMY ORDNANCE CENTER & SCHOOL
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ABERDEEN PROVING GROUND MD
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US ARMY WESTERN COMMAND
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FORT SCHAFTER HI 96858-5100

CINC
US SPECIAL OPERATIONS COMMAND
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MACDILL AFB FL 33608

CDR
US CENTRAL COMMAND
ATTN: CINCCEN/CC J4-L 1
MACDILL AFB FL 33608

HQ, EUROPEAN COMMAND
ATTN: ECJ4/LIJ (LTC CUMBERWORTH) 1
VAIHINGEN, GE
APO NEW YORK 09128

CDR
US ARMY RESEARCH LABORATORY
VEHICLE PROPULSION DIRECTORATE
ATTN: AMSRL-VP, MR ROBERT BILL 1
21000 BROOKPARK ROAD
CLEVELAND OH 44135

Department of the Navy

OFFICE OF CHIEF OF NAVAL RESEARCH
ATTN: OCNR-12E (DR ROBERTS) 1
ARLINGTON VA 22217-5000

CDR
NAVAL SEA SYSTEMS COMMAND
ATTN: CODE 05M32 (MR DEMPSEY) 1
WASHINGTON DC 20362-5101

CDR
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ANNAPOLIS MD 21402-5067

CDR
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200 STOVAL STREET
ALEXANDRIA VA 22322

CDR
NAVAL AIR WARFARE CENTER AIRCRAFT
DIVISION
ATTN: PE-33 (MR D'ORAZIO) 1
P O BOX 7176
TRENTON NJ 06828-0176

CDR
NAVAL PETROLEUM OFFICE
ATTN: CODE 40 (MR LONG) 1
CAMERON STATION
ALEXANDRIA VA 22304-6180

DEPARTMENT OF THE NAVY
HQ, US MARINE CORPS
ATTN: LPP-2 (MAJ TALLERI) 1
WASHINGTON DC 20380

OFFICE OF THE CNO
ATTN: OP-731D 1
DEPT OF NAVY
WASHINGTON DC 20350

JOINT OIL ANALYSIS PROGRAM -
TECHNICAL SUPPORT CENTER 1
BLDG 780
NAVAL AIR STATION
PENSACOLA FL 32508-5300

CDR
NAVAL AIR SYSTEMS COMMAND
ATTN: CODE 53632F (MR MEARNS) 1
WASHINGTON DC 20361-5360

CDR
NAVAL RESEARCH LABORATORY
ATTN: CODE 6180 1
WASHINGTON DC 20375-5000

US MARINE CORP LIAISON
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WARREN MI 48397-5000

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STATION
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PHILADELPHIA PA 19112-5083

DEPUTY COMMANDING GENERAL
USMC RD&A COMMAND
ATTN: PM GND WEAPONS (CB6T),
LTC VARELLA 1
SSEA (LTC PHILLIPS) 1
QUANTICO VA 22134-5080

COMMANDING GENERAL
USMC RD&A CMD
ATTN: CODE SSCMT 1
WASHINGTON DC 20380-0001

H&S BATTALION
ATTN: MCCDE (CODE WF12E1) 1
WARFIGHTING CENTER
QUANTICO VA 22134-5010

Department of the Air Force

HQ, US AIR FORCE
ATTN: LEYSF 1
WASHINGTON DC 20330

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US AIR FORCE WRIGHT AERO LAB
ATTN: POSF (MR DELANEY) 1
WRIGHT-PATTERSON AFB OH 45433-6563

CDR
SAN ANTONIO AIR LOGISTICS CTR
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SAALC/LDPE (MR ELLIOT) 1
KELLY AIR FORCE BASE TX 78241

CDR
WARNER ROBINS AIR LOGISTIC CTR
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ROBINS AIR FORCE BASE GA 31098

615 SMSQ/LGTV (MMEP) 1
BLDG 100 ROOM 234
EGLIN AIR FORCE BASE FL 32542-5000

CDR
USAF 3902 TRANSPORTATION SQUADRON
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OFFUTT AIR FORCE BASE NE 68113

CDR
DET 29
ATTN: SA-ALC/SFM 1
CAMERON STATION
ALEXANDRIA VA 22304-6179

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ADMINISTRATION 1
LEWIS RESEARCH CENTER
CLEVELAND OH 44135

DEPT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
AWS-110 1
800 INDEPENDENCE AVE, SW
WASHINGTON DC 20590

DEPARTMENT OF ENERGY
CE-151, ATTN: MR JOHN RUSSELL 1
1000 INDEPENDENCE AVE, SW
WASHINGTON DC 20585

ENVIRONMENTAL PROTECTION AGENCY
AIR POLLUTION CONTROL 1
2565 PLYMOUTH ROAD
ANN ARBOR MI 48105