FINAL REVIEW OF
U.S. ARMY FIRE-RESISTANT
FUEL PROGRAM

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INTERIM REPORT
BFLRF No. 244

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Extensive research has been conducted by the U.S. Army on means for making hydrocarbon fuels resistant to unwanted fire. An approach to developing a fire-resistant fuel (FRF) for use with diesel- and gas turbine-powered armored combat vehicles has been identified. This approach comprises the addition of water and emulsifier to diesel fuel with simple mixing. The resulting FRF is a clear-to-hazy microemulsion. The fuel enhances fuel fire safety by decreasing ignition susceptibility, by retarding flame spread rates, and by self-extinguishing if ignited when spilled. However, it burns readily when atomized, and diesel engines and turbine combustors start, idle, and run satisfactorily on FRF.

The thrust of this program was to address the problems associated with utilization of the current formula in the field. The main problem areas addressed included the production and storage of

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FRF at reduced temperatures; the vehicular fuel systems effects, e.g., fuel filter plugging, resulting from the use of the water-containing emulsions; and the effects of transportability and possible fuel-handling system contamination by the FRF constituents.

As a result of this program, additional work was not recommended because of several requirements that could not easily be solved in field applications.

FOREWORD

This work was conducted at the Belvoir Fuels and Lubricants Research Facility (SwRI) located at Southwest Research Institute (SwRI), San Antonio, TX under Contract Nos. DAAK70-85-C-0007 and DAAK70-87-C-0043 during the period October 1984 through December 1987. The work was funded by the U.S. Army Belvoir Research, Development and Engineering Center, Ft. Belvoir, VA, with Mr. F.W. Schaekel (STRBE-VF), as the Contracting Officer's Representative and Mr. M.E. LePera, Chief of Fuels and Lubricants Division (STRBE-VF), as the project technical monitor.

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I. INTRODUCTION

Extensive research has been conducted by the U.S. Army on means for making hydrocarbon fuels resistant to unwanted fire. An approach to developing a fire-resistant fuel (FRF) for use with diesel-powered armored combat vehicles has been identified. This approach comprises the addition of water and emulsifier to diesel fuel with simple mixing.(1-6)* The resulting FRF is a clear-to-hazy microemulsion. The fuel enhances fuel fire safety by decreasing ignition susceptibility, by retarding flame spread rates, and by self-extinguishing if ignited when spilled. However, it burns readily when atomized, and diesel engines and turbine combustors start, idle, and run satisfactorily on FRF. The viscosity of FRF is somewhat greater than that of its base fuel, especially at low temperatures. It may be possible to be pumped at temperatures down to the base fuel pour point; however, it has been shown to cause filter plugging below 0°C in continuous-flow systems. FRF is normally stable for more than 30 days, and is not degraded by ambient temperature cycling above 0°C. It can be mixed with other diesel fuels or exposed to normal fuel contaminants without adverse effects on the phase stability. The selected approach involved the addition to diesel fuel of 10-vol% water and 12-vol% emulsifier premix to form a stable water-in-fuel microemulsion. The premix contains equal volumes of surfactant and aromatic concentrate. Stable FRF formulations have been made with some diesel fuels using water containing more than 500 ppm of total dissolved solids. However, purified water, containing less than 50 ppm of dissolved solids, is required if stable formulations are to be made with the majority of diesel fuels that may be encountered. For the same reason, it has been found necessary to include in the formulation the additional 6 vol% of an aromatic hydrocarbon concentrate to serve as a combination microemulsion promoter and emulsifier solvent/thinner. This additional concentrate is premixed with the emulsifier before FRF blending.

II. OBJECTIVE

The objective of this program was to assess the problems associated with fielding the current formulated fire-resistant fuel (FRF) and develop specific data required to assist in making a decision on the feasibility of using such a fuel in armored combat vehicles.

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

These problems relate to blending, storage, engine power and performance, and utilization of the water-containing emulsion at reduced temperatures.

III. APPROACH

The thrust of this program was to address the problems associated with utilization of the current FRF formula in the field. The main problem areas to be addressed include the production and storage of FRF at reduced temperatures; the vehicular fuel systems effects, e.g., fuel filter plugging, resulting from the use of the water-containing emulsions; and the effects of transportability and possible fuel-handling system contamination by the FRF constituents. This report describes the experiments conducted to address these issues. The initial laboratory phase includes production of "hand-stirred" batches at reduced temperatures as well as rheological evaluations at similar temperatures. The second phase was partially conducted in a specially-designed low-temperature chamber measuring approximately 16 by 18 feet (4.9 x 5.5 m) with controlled temperature ranges between approximately -30° to 10°C (-20° to 50°F). This facility was utilized for the small-scale continuous blending studies, as well as the vehicular fuel system and heater adaptations for low-temperature evaluations. The third phase, consisting of full-scale vehicular and blending system field testing, was conducted at Yuma Proving Ground and is reported in a separate document from that facility.(7)

IV. DISCUSSION

A.   Laboratory Evaluations of FRF Properties

1. Low-Temperature Fire-Resistant Fuel Production and Analysis

It is commonly known that reaction rates are greatly affected by temperature. In some reaction mechanisms, temperature is the most critical parameter. It is, therefore imperative to determine if the solubilizing/blending of FRF components that occur at ambient temperature also occur at the lower temperatures required for fielding-type applications. Also of importance is the temperature-viscosity relationships of the fuel

components, especially the surfactant-aromatic concentrate fraction. The viscosity of the components could affect the proper proportioning by the pumping systems. Tests were conducted to evaluate the effect of temperature on blending rates of FRF and the resulting stability and performance of such a blend. The guide for determining the lowest temperature was based on the specification cloud point of the test fuel.

Laboratory scale blending was conducted to define the temperature parameters of blending FRF before establishing full-scale blending facilities. In this effort, FRF was prepared at ambient temperatures, and the temperature was lowered until the blend could not be prepared. Although the component percentage remained the same in all the fuels, the individual components were varied to establish different blends.

12-percent premix — composed of 50-percent surfactant with total acid numbers of approximately 15, 17, and 19, and 50-percent aromatic concentrate/solvent.

10-percent water — containing approximately 50-, 150-, 300-, and 500-ppm total dissolved solids (TDS), NaCl.

78-percent diesel fuel — MIL-F-46162B was used as base fuel. JP-8 was also used since it is being evaluated as a replacement for DF-2/F-54 in Europe. In addition to these two fuels, two different OCONUS diesel fuels from the Patriot program were included in the matrix for laboratory-scale blending studies.

Analyses conducted on the blended fuel include determining viscosity-temperature relationship as well as stability and compositional verification. Therefore, this blending matrix consisted of three different acid numbers, four TDS levels, and four fuels for a matrix totaling 48 samples at each temperature.

2.   FRF Water Purity Requirements

Correlation between the total acid number of the FRF emulsifying agent and the sodium chloride content of the water was established using two NATO F-54 diesel fuels, a JP-8

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turbine fuel, and a MIL-F-46162B referee grade diesel fuel. Analytical data on these fuels are given in TABLES 1, 2 and 3 for referee grade diesel fuel, JP-8 and CCONUS diesel fuel, respectively.

TABLE 1. Properties of Referee Grade Diesel Fuel No. 14619

Property	Method	MIL-F-46162B Requirement	Value
Gravity, °API at 15°C	D 1298	NR*	30.4
Density, kg/L at 15°C	D 1298	Report	0.8735
Flash Point, PMCC, °C	D 93	Report	66
Cloud Point, °C	D 2500	-13 max	-19
Pour Point, °C	D 97	-18 max	-25
Kinematic Viscosity, cSt, at 40°C	D 445	1.9-4.1	3.08
Distillation, °C	D 86		
IBP		Report	168
10% Recovered		Report	202
50% Recovered		245-285	283
90% Recovered		330-357	340
EP		385 max	364
Recovered, vol%		NR	98.5
Residue, vol%		NR	1.5
Ash, wt%	D 482	0.02 max	0.00
Carbon Residue, 10% Bottoms, wt%	D 524	0.20 max	0.13
Particulate Contamination, mg/L	D 2276	10 max	2.2
Accelerated Stability, mg/100 mL	D 2274	1.5 max	0.36
Neutralization No., mg KOH/g	D 664	0.2 max	0.02
Copper Strip Corrosion	D 130	1 max	1A
Carbon, wt%		NR	86.45
Hydrogen, wt%		NR	12.40
Sulfur, wt%		0.95-1.05	1.00
Water, ppm	D 1744	NR	--
Aromatics, vol%	D 1319	Report	--
Olefins, vol%	D 1319	NR	--
Aromatic Ring Carbon, wt%	UV	NR	
Mononuclear			14.0
Dinuclear			5.3
Trinuclear			0.6
Total			19.9
Heat of Combustion, net	D 240		
Btu/lb		Report	18,100
MJ/kg		NR	42.10
Cetane Number	D 613	40-45	43.2
Cetane Index		40-45	44.4

* NR = No Requirement.

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TABLE 2. Properties of JP-8 No. 14216

Property	Method	MIL-T-83133 Requirement	Value
Gravity, °API at 15°C	D 1298	37-51	40.3
Density, kg/L at 15°C	D 1298	0.775-0.840	0.8232
Flash Point, PMCC, °C	D 93	38 min	56
Freezing Point, °C	D 2386	-50 max	-55
Smoke Point, mm	D 1322	19 min	22.2
Kinematic Viscosity, cSt, at 40°C	D 445	80 max	4.14
Distillation, °C	D 2887		
IBP		Report	136
10% Recovered		186 max	169
50% Recovered		Report	206
90% Recovered		Report	237
EP		330 max	263
Particulate Contamination, mg/L	D 2276	1.0 max	1.1
Existent Gum, mg/100 mL	D 381	7.0 max	0.2
Thermal Stability, JFTOT,	D 3241		
Δ P, mm Hg		25 max	0
Copper Strip Corrosion	D 130	13 max	1A
Electrical Conductivity, pS/m	D 2624	200-600	170,90
Hydrogen, wt%		13.5 min	13.69
Sulfur, wt%	D 2622	0.3	<0.01
Mercaptan Sulfur, wt%	D 3227	0.001 max	0.0002
Aromatics, vol%	D 1319	25.0 max	19.0
Olefins, vol%	D 1319	5.0 max	0
Aromatic Ring Carbon, wt%	UV	NR*	
Mononuclear			10.0
Dinuclear			2.7
Trinuclear			0.0
Total			12.7
Heat of Combustion, net	D 240		
Btu/lb		18,400 min	18,532
MJ/kg		42.8 min	43.11
Cetane Number	D 613	NR	41

* NR = No Requirement.

Three Kritchevsky amide-type emulsifying agents, synthesized from oleic acid and diethanolamine, were used having total acid numbers of 15.0, 17.3, and 19.3 mg KOH/g of sample. Each of the emulsifying agents was dissolved in equal volume of Exxon's Aromatic 150 to produce an emulsifying agent/premix. (Analysis of the Aromatic 150 shows that it contains 52.2 wt% of mononuclear and 18.1 wt% dinuclear aromatic ring

TABLE 3. Properties of OCONUS Diesel Fuel

Property	Method	VV-F-800C DF-2 OCONUS Requirement	Fuel No. 14028	Fuel No. 14029
Density, kg/L at 15°C	D 1298	0.815-0.860	0.8383	0.8276
Flash Point, PMCC, °C	D 93	56 min	70	65
Cloud Point, °C	D 2500	-13 max	-17	-15
Pour Point, °C	D 97	-18 max	-20	-21
Kinematic Viscosity, cSt,				
at 20°C	D 445	1.8-9.5	4.06	3.24
at 40°C	D 445	NR*	2.60	2.17
Distillation, °C	D 86			
IBP		NR	191	183
10% Recovered		NR	222	204
50% Recovered		Report	262	242
90% Recovered		357 max	311	312
EP		370 max	347	349
Residue, vol%		3 max	1.5	1.0
Ash, wt%	D 482	0.02 max	<0.01	<0.01
Carbon Residue, 10% Bottoms, wt%	D 524	0.20 max	0.10	0.07
Particulate Contamination, mg/L	D 2276	10 max	2.6	2.3
Accelerated Stability, mg/100 mL	D 2274	1.5 max	0.6	0.1
Neutralization No., mg KOH/g	D 664	0.10 max	0.07	0.04
Copper Strip Corrosion	D 130	1 max	1A	1A
Carbon, wt%		NR	86.10	86.01
Hydrogen, wt%		NR	13.28	13.57
Sulfur, wt%		0.70 max	0.30	0.18
Water, ppm	D 1744	NR	82	73
Aromatic Ring Carbon, wt%	UV	NR		
Mononuclear			6.9	8.2
Dinuclear			5.2	3.2
Trinuclear			0.6	0.3
Total			12.7	11.7
Heat of Combustion, net	D 240			
Btu/lb		NR	18,390	18,436
MJ/kg		NR	42.7	42.88
Cetane Number	D 613	45 min	50	49

* NR = No Requirement.

carbons, for a total aromatic ring carbon content of 70.3 wt%.) Blends were prepared at room temperature (23°C) using 78 vol% of base fuel, 12 vol% of the emulsifying agent/aromatic solvent premix, and 10 vol% of water containing between 50 and 2000

ppm of NaCl. To also study reduced temperature phase behavior, those compositions that yielded translucent microemulsions at room temperature were stored for up to 10 days in a chamber in which the temperature was held at $5^\circ \pm 1^\circ C$. Daily visual observations were made to assess phase stability.

Fig. 1 graphically illustrates the results observed at $23^\circ C$. On these charts, the solid circles represent the acceptable translucent microemulsions. The triangles depict emulsions that contain up to 2 vol% of cream, and phase separation is shown by squares. Additionally, the numbers that follow the solid circles give the number of days that the emulsions remained homogeneous, i.e., good, at $5^\circ \pm 1^\circ C$. The number zero means that the emulsion underwent phase separation within the first 24 hours, while the number 10 indicates that the emulsion survived the entire test duration without apparent change.

It should be further noted that the phase separations caused by the low temperature were reversible. When these emulsions were shaken after they were allowed to warm to room temperature, they became homogeneous translucent microemulsions.

Comparing the emulsifiability of the three diesel fuels and the JP-8 turbine fuel reveals that the behavior of referee grade diesel fuel is similar to that of the JP-8, instead of the other diesel fuels. The different emulsification tendencies of the various fuels remain essentially unexplained. Examination of the specification-type test results of the four fuels in TABLES 1, 2, and 3 does not provide for the rationalization of the emulsification data.

It was expected that a more detailed analysis of the composition of the various fuels would lead to a better understanding of the surfactant requirements to emulsify water, containing various concentrations of electrolyte, in the fuel of choice.

Since each of these four fuels is a petroleum-derived middle distillate fuel, any observed gross differences of their behavior should be due to either additives or trace quantities of polar compound. Identification of these components, therefore, should yield to a better understanding and regulation of emulsification through which fire-resistant fuel is made.

LEGEND:

● TRANSLUCENT EMULSION

▼ TRANSLUCENT EMULSION WITH <2 VOL% CREAM

■ PHASE SEPARATION (>2 VOL%)

( ) NO. OF DAYS EMULSION REMAINS GOOD AT 5°C

FUEL NO. 14216 (JP-8)

FUEL NO. 14619 (MIL-F-46162B)

FUEL NO. 14028 (NATO F-54)

FUEL NO. 14029 (NATO F-54)

SODIUM CHLORIDE CONC. IN WATER, PPM

TOTAL ACID NO. OF SURFACTANT, mg kOH/g
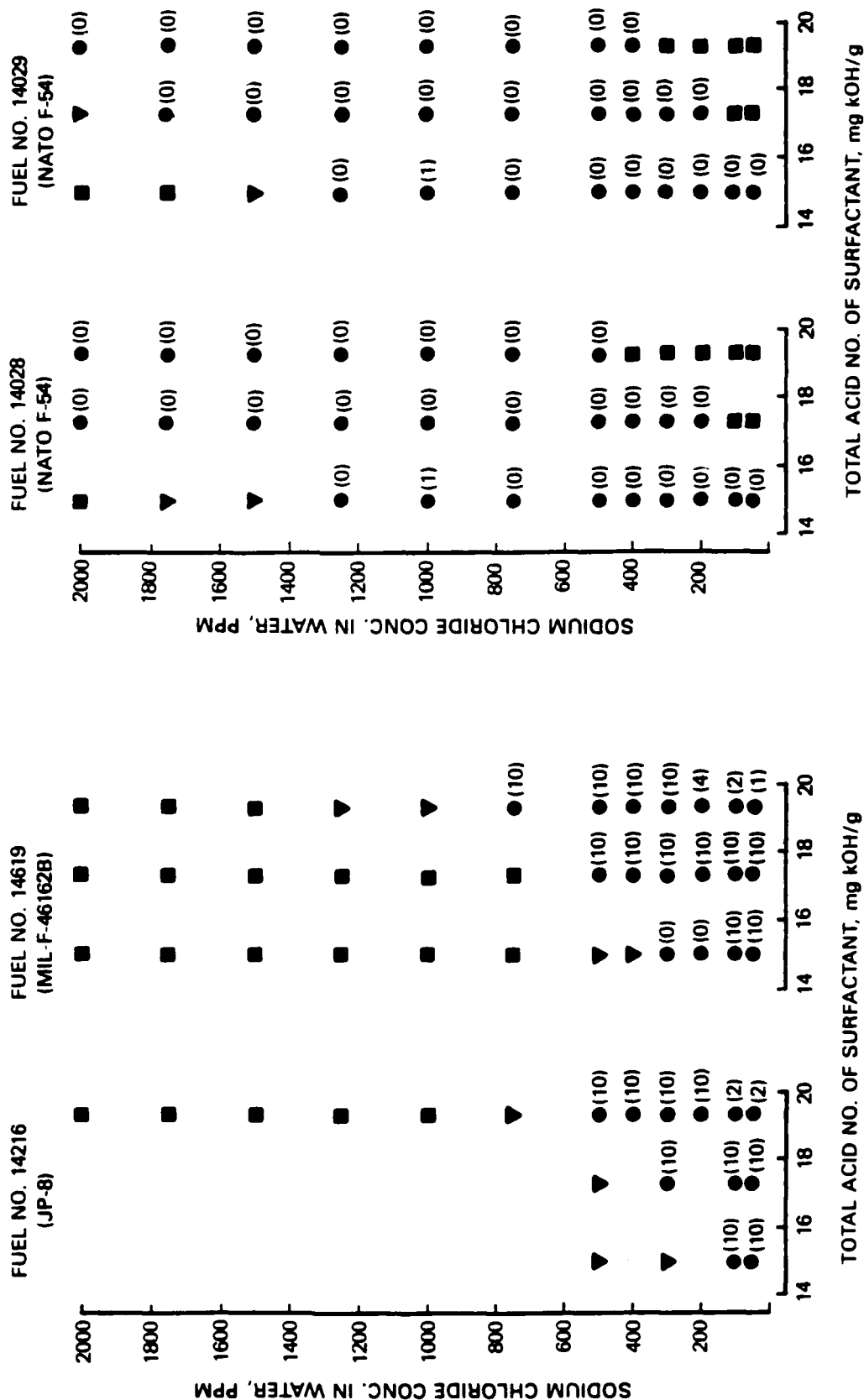
Figure 1. Interaction of sodium chloride concentration and surfactant total acid number on emulsion stability

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Direct identification and measurement of trace quantities of large numbers of compounds may be exceedingly difficult. Attempts were made in the past to concentrate these components by various means, e.g., by chromatography prior to identification and measurement. Most of these procedures met only limited success. It was proposed, therefore, to solve this problem through an indirect route, as outlined below.

Within the limits of the experiments that yielded Fig. 1, the emulsification tendencies of these four fuels are known. It was proposed that on a combination adsorbent bed of silica gel/florisil, the majority of the trace components and the most polar compounds be removed.

Emulsification of electrolyte (NaCl) containing water was made with the adsorbent-treated fuels in the same manner that yielded Fig. 1, and the data were compared. As expected, the four fuels gave the same results since their composition is more nearly similar.

Each of the four fuels was analyzed before and after the adsorbent treatment by capillary gas chromatography using flame ionization detector, as well as nitrogen and sulfur specific detectors. Additionally, on each sample, a gas chromatogram was run using a mass spectrometer as the detector. Each of these chromatograms was stored in a computer that will allow the generation of differential chromatograms. The appropriate chromatogram of the treated fuel was subtracted from that of the untreated fuel. It was the hypothesis that the differential chromatogram/spectrogram represented compounds are (at least partially) responsible for the different behavior of the four fuels. Identification of these compounds was attempted through the use of mass spectrometer's built-in and external library, which now contains over 38,000 compounds. Unfortunately, the results of this investigation were insufficient to allow an understanding and thus an accurate prediction of whether or not a fuel would produce a stable emulsion. Although general trends, such as aromatic content, were developed, trace components identification, in general, was not considered successful.

3.   Analysis of Separated Fractions (Bottom Cream)

In an effort to understand the factors involved in preparing a stable emulsion, chemical analyses were conducted on the separated fractions from unstable emulsion. The

fraction was the bottom layer, whitish in appearance, and thus referred to as the cream fraction.

Preliminary analyses were performed of the white cream formed upon addition of 10-percent water containing 300-ppm NaCl to a mixture of referee grade diesel fuel and an emulsifier premix. Diesel fuel No. 14683 was purchased under Specification MIL-F-46162B, and the emulsifier premix had a Total Acid Number of approximately 15 mg KOH/g.

The separation method used was centrifugation followed by filtering or decanting the supernatant. The FRF was allowed to stand undisturbed for approximately one week, which permitted the cream to settle to the bottom of a 125-mL separating funnel. The fuel and surfactant mixture was then pipetted from the vessel, leaving approximately 0.5 mL of cream. Approximately 5 mL of the pipetted referee fuel were saved for analysis.

Compositional differences between the base fuel, cream, and a reference FRF (free of cream) containing 100-ppm NaCl aqueous solution were determined using a Hewlett-Packard 5880A gas chromatograph. Chromatographic conditions are listed in TABLE 4. Chromatograms for each of the individual components used in the formulation of the

TABLE 4. Chromatographic Conditions
(Using HP 5880A Model GC)

Temperature

Injection Port	350°C
Detector	400°C

Oven Temperature Program

Initial	50°C
Rate	10°C/min
Final	320°C

Carrier Gas Flow	1 mL/min
Carrier Gas	Helium
Split	400:1
Sample Size	0.5 µL
Column	OV-101

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emulsifying agent were also obtained under the same conditions. The cream is a white macroemulsion with particle size possibly 10 microns or larger, and a 2-in. (5.1 cm) 22-gauge x 0.18 in. (0.46 cm) ID needle was used to introduce this sample into the chromatograph. Retention times were noted for all injected samples. The detector used for this analysis (FIA) was not sensitive to water.

Both the FRF sample mixture and reference FRF yield similar chromatograms, each indicating the presence of base fuel, the Aromatic 150 solvent, and the surfactant. TABLE 5 shows the approximate concentrations based on the peak heights for each of these components. Similarly, the chromatogram of the cream not only indicates the presence of these components but also appreciable amounts of oleyl diethanolamine, one of the components of the surfactant. Unfortunately, an approximate concentration of diethanolamine within the cream could not be obtained since this peak was severely distorted, characteristic of amines, and unresolved from the fuel and Aromatic 150 solvent. However, the broad peak observed is attributed to this component of the surfactant as is evident by the chromatogram for an authentic sample of diethanolamine.

TABLE 5. Concentrations of Material of Interest

Name	Retention Time	Height	Percent
AL-14683-F FRF Sample Mixture			
(300-ppm NaCl)	10.99	162.22	63.04
Oleyl Diethanolamide	24.55	16.55	6.43
Aromatic 150 Solvent	6.21	78.54	30.52
AL-14683-F FRF Reference Sample			
(100-ppm NaCl)	10.99	176.47	61.80
Oleyl Diethanolamide	24.55	20.23	7.09
Aromatic 150 Solvent	6.21	88.82	31.11
White Macroemulsion "Cream"	10.99	161.85	62.89
Oleyl Diethanolamide	24.57	37.92	14.73
Aromatic 150 Solvent	6.22	57.58	22.37
Diethanolamine	ND*	ND	ND

* ND = Not Determined.

The chromatograms suggest that the presence of oleyl diethanolamine is partly responsible for cream formation, precipitated by the addition of 200 ppm or greater of NaCl solution. The creaming effect observed upon addition of higher concentrations of NaCl aqueous solution (10-percent water) suggested that the product distribution in the formulation of the surfactant (approximately 70-percent oleyl diethanolamide, 22-percent diethanolamine, and 8-percent diethanolamine oleic acid soap) is shifted in favor of the amine component. On purely speculative grounds, this increase in diethanolamine content may be accounted for by the reaction of excess dissolved NaCl ions and the 8-percent soap content of the surfactant to yield free diethanolamine and the corresponding sodium salt of oleic acid. This, in turn, may account for the observed creaming effect.

Since the detector used in the chromatographic separation was insensitive to water, coulemetric Karl Fischer titrations were used to determine the water content of the cream fractions.

Analysis was performed on the white precipitate. For comparison, quantitative measurements were also performed on a stable FRF made with water containing 100-ppm NaCl.

Compositional differences between the stable, translucent microemulsion, the micro-emulsion phase of unstable FRF, the separated precipitate, and the base fuel were determined using a Hewlett-Packard 5880A gas chromatograph. These results are reported in TABLE 6.

Based on the normalized data, oleyl diethanolamide, diethanolamine, and water concentrations in the separated precipitate have increased relative to their initial concentrations. This increase is presumably attributed to an upset in the product distribution of the surfactant in the unstable emulsion, which, in turn, may account for the observed phase instability.

Results of this study can be interpreted as having very little effects on fire safety due to reduced water content. Even though 5 vol% cream produces an unacceptable FRF

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TABLE 6. Composition of FRF Emulsions

Sample	Composition, wt%
AL-14683-F FRF Translucent Emulsion (100-ppm NaCl)	
Fuel and Aromatic 150	81.2
Oleyl Diethanolamide	7.0
Diethanolamine	1.5
Water	10.3
	100.0
AL-14683-F Microemulsion of the Unstable FRF (300-ppm NaCl)	
Fuel and Aromatic 150	82.3
Oleyl Diethanolamide	6.4
Diethanolamine	1.4
Water	9.9
	100.0
Precipitate From Unstable FRF	
Fuel and Aromatic 150	67.1
Oleyl Diethanolamide	13.1
Diethanolamine	6.8
Water	13.0
	100.0

from a stability standpoint, the balance of the emulsion would still contain greater than 9 vol% water. Results of flammability tests have shown that this amount of water is still adequate to provide the required margin of fire safety. The potential effect of the precipitate on engine performance was not determined.

B. Laboratory Low-Temperature Studies

It was expected that low-temperature operation (15° to 30°F) (-9° to -1°C) would cause fuel system filter plugging, line freeze, and/or reduced pumping efficiency. The work was conducted to define the problem and develop alternatives for reducing the impact of low temperature on fuel system-related deficiencies in the fuel systems of the DDA 6V-53 and Cummins VTA-903 engines, cold starting and generator set operation.

1. Fuel System Heaters

The fuel system heater evaluations were carried out in a low-temperature test chamber at BFLRF. These evaluations for low-temperature performance were made using fuel-system mockups designed to simulate the DDA 6V-53T and Cummins VTA-903T engines fuel systems and using commercially available diesel fuel heaters.

The DDA 6V-53T engine fuel system mockup consisted of a 50-gallon (189-liter) fuel cell with gravity feed to a primary (sock-type) filter. A gear pump was installed on the discharge side of the sock filter and inlet side of the secondary (pleated paper type) filter. The outlet of the fuel pump was connected to a tee joint. One leg of the tee was connected to an injector and another leg to a return line into the fuel cell.

The Cummins VTA-903T engine fuel system mockup consisted of the real engine fuel pump and injector. The system consisted of a 30-gallon (114-liter) fuel cell with gravity feed to a fleet guard FS 1212 filter. The discharge side of the filter was connected to the suction side of Cummins pressure-time fuel pump. The outlet of the fuel was connected to a cylindrical P7 (D) injector. The system was calibrated for idle rpm flow at 30°C temperature.

The simulated engine fuel system tests were conducted with referee grade DF-2 based FRF at 15°F (-10°C). The fuel system was filled with FRF at room temperature and the fuel circulated throughout the filters and the injector with the pump running at idle speed conditions. The injector was activated to ascertain the spray flow. The system was then allowed to cold soak at the low temperature for 24 hours. The cold soak invariably resulted in severe phase separation and ice crystal formation in the fuel lines. The filter surfaces were deposited with solidified surfactant and ice crystals and the fuel flow stopped within a few seconds of pump turning.

TABLE 7 shows the engine types, their maximum fuel consumption rates, and estimated electrical power required for heaters to raise the temperature of the fuel by 15°F. The available commercial heaters of canister heat exchanger type (Davco®), heated fuel outlet (Davco®, Hot Joint®) and line hose heaters (Hot-line®) with various wattage ranges were procured.

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TABLE 7. Estimated Heater Power Requirement to Raise Temperature of Fuel by 15°F

Vehicle	Engine	Estimated Max Fuel Consumption		Est. Total Fuel Flow*	Estimated Heater Capacity to Raise Temp of Fuel by 15°F			Heater Wattage Range
		lb/hr	GP	lb/hr	Btu/hr	Watts	Amps at 24V	
HMMWV	6.2L	74	10	104	780	228	9.5	200-250
M113	6V-53T	120	17	168	1260	369	15.4	350-400
M-2	VT-903	168	24	235	1762	516	21.5	500-600
M-60	AVDS-1790	317	45	444	3330	975	40.6	1000
M-1	AGT-1500	600	86	840	6300	1845	76.9	1500-2000

* 1.4X Max

Repeated trials with various configuration of the heaters provided the following conclusions:

1. It is possible to flow the FRF at 15°F (-10°C) temperature through the system up to the inlet of injectors. However, the frozen passages in the injectors will not allow fuel spray, thus preventing an engine from starting.

2. The most critical areas that required heat were the fuel cell outlet and the individual filter elements. The fuel line heaters were not adequate without the filter heaters. The frozen fuel on the filters had to be completely melted before turning on the fuel pump.

3. The power requirement for fuel cell outlet heater (Davco®, Hot Joint®) was 150 W. The heater was turned on 3 minutes before engine start-up.

4. Each filter element of the DD 6V-53 engine system required 3- to 5-minute preheating with a 300-W heater.

5. The VT-903 engine fuel filter element required 3 to 5 minutes of preheating with 650 watts.

Thus, approximately 800 watts of heater power were required for 5 minutes before start-up trials in both types of engine systems tested. It was possible to sustain an unplugged recirculating flow with continued power input to the heaters. The injector passages, however, remained frozen, indicating that the fuel spray into the combustion chamber will not be possible.

2. Generator Set Operation

A 45-kW generator set (PU-703/G) with a DDA 3-71 engine was set up in the cold room, and baseline operation with a load bank were carried out with DF-2 fuel. This particular generator set has a Woodward governor to maintain the engine speed at 1800 rpm for generation of 60-Hz, 210-VAC current. The governor actuator uses the diesel fuel supplied by the engine fuel pump to hydraulically position the rack. The generator set was operated satisfactorily within specifications at various loads up to 40 kW on DF-2 and FRF down to 32°F (0°C). The engine cold start assist with ether was required at this temperature with both base fuel and FRF. It was not possible to start the generator set at 15°F (-10°C) with FRF.

3. Low-Temperature Blending of FRF

The objective of this set of experiments was to learn what may happen if an FRF has to be prepared at temperatures between 0° and 5°C. It was shown previously that at room temperature, FRF could be prepared from four selected middle-distillate fuels (a referee grade fuel No. 14619, two NATO F-54 diesel fuel Nos. 14028 and 14029, and a JP-8 fuel No. 14216) using water that contained up to 100 ppm of sodium chloride, with the aid of the FRF surfactant having a total acid number (TAN) of about 15 mg KOH/g. Similarly, FRF was made from each of these four fuels with water that contained 500 ppm of sodium chloride, provided that the TAN of the surfactant was raised to about 19.

It was also shown that when these microemulsions were placed in a refrigerator at 5 ± 1°C, the FRF's made from the referee grade diesel fuel and the JP-8 remained stable for at least 10 days, while those made from the two NATO F-54 fuels underwent reversible phase separation. (When these later emulsions were allowed to warm to room temperature and were subjected to mild agitation, they again microemulsified.)

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During the current experiments, FRF blends were made from each of these same four fuels with all blending component temperatures between 0° and $5^\circ C$. In these experiments, 10 vol% water, containing 100 ppm of NaCl, was microemulsified using an emulsifying agent premix made by blending equivolume quantities of an aromatic solvent (Exxon's Aromatic 150) and the surfactant having a TAN of about 15. Similar blends of FRF were made using 500-ppm aqueous NaCl solutions, but with the surfactant having a TAN of about 19 mg KOH/g. In each case, the FRF contained 78 vol% of base fuel, 12 vol% of emulsifying agent premix, and 10 vol% of the dilute NaCl solution.

The test protocol may be described as follows:

Into an ice-water cooled, three-neck round bottom flask, equipped with a mechanical stirrer, a thermometer, and a nitrogen inlet tube (to exclude moisture condensation) was placed 300 mL of precooled base fuel. At equilibrium temperature, the precooled surfactant premix was dissolved in the fuel, followed by addition of the water. Stirring was continued in the cold bath for 20 minutes, then the blend was transferred into 4-oz. sample tubes, and their physical appearance was recorded while still at a temperature below $5^\circ C$. The samples were allowed to warm to room temperature in 3 to 4 hours, when another visual observation of the emulsion was made. One to three days later, similar observations were made. Results of these observations are given in TABLE 8.

Each of the FRF blends prepared cold using 100-ppm NaCl solution yielded microemulsions when allowed to stand at room temperature for 24 hours.

Data in TABLE 8 show that FRF samples prepared cold using 500 ppm of NaCl solution were unacceptable even after the blends were allowed to warm to room temperature of about $22^\circ C$. However, when aliquots of these samples were warmed in a stream of warm water at about $40^\circ C$ for 2 to 3 minutes, each of the blends became a transparent microemulsion that remained as such when cooled back to room temperature. These observations are also shown in TABLE 8.

Results of the low-temperature blending operations are consistent with those of the earlier blending of FRF. While each of the four fuels produced microemulsions at ambient temperatures, cooling the emulsions overnight to about $5^\circ C$ resulted in phase

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TABLE 8. Low-Temperature Blending of FRF

VISUAL RATINGS

Fuel No.	TAN of EA	NaCl, ppm	While Cold	3 Hr at Room Temp	24 Hr at Room Temp	72 Hr at Room Temp	Temp, °C To Clear	Cooled to R.T.
14028	15	100	4	3	1	1	–	–
14029	15	100	4	3	1	1	–	–
14216	15	100	3	1	1	1	–	–
14619	15	100	2	1	1	1	–	–
14028	19	500	4	6	–	5	31	1
14029	19	500	4	6	–	5	26	1
14216	19	500	4	4	–	1	32	1
14619	19	500	3	3	–	1	40	1

Visual Rating:

1 Transparent Microemulsion
2 Translucent Microemulsion
3 Opaque (Borderline)
4 White Macroemulsion
5 Emulsion (Mirco or Macro) with 0.5 vol% < cream ≤2 vol%
6 Phase Separation
7 Trace of Cream (≤ 0.5 vol%)

Composition of FRF:

78 vol% of Base Fuel
12 vol% Emulsifier Premix
10 vol% Sodium Chloride Solution

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separation for the two NATO F-54 diesel fuels, but the other two FRF's remained visually unchanged. Similarly, low-temperature blending of the NATO fuels with 100-ppm NaCl solution required overnight room temperature storage to produce a translucent microemulsion. Using the 500-ppm NaCl solutions, the two NATO fuels again required more attention to microemulsify. In summary, microemulsification and phase stability of FRF's from the JP-8 and the referee grade diesel fuel were superior to those of the NATO F-54 fuels.

4. In-Line Low-Temperature Blending

The 100-gallon-per-hour (378-liter/hr) in-line blender was used for this series of experiments. This blender, as shown schematically in Fig. 2, consists of four positive displacement metering pumps, static mixture, and a totalizing meter. The sequence to accomplish the normal blending procedure follows:

1. The base fuel, accounting for approximately 78 vol% of the blend, is introduced into static mixer No. 1.

FUEL   WATER   FUEL
~78 GPH   ~10 GPH   ~12 GPH

1-1/2 HP
220/440
VAC
1725 RPM

POSITIVE
DISPLACEMENT
METERING
PUMPS

M
I
X
E
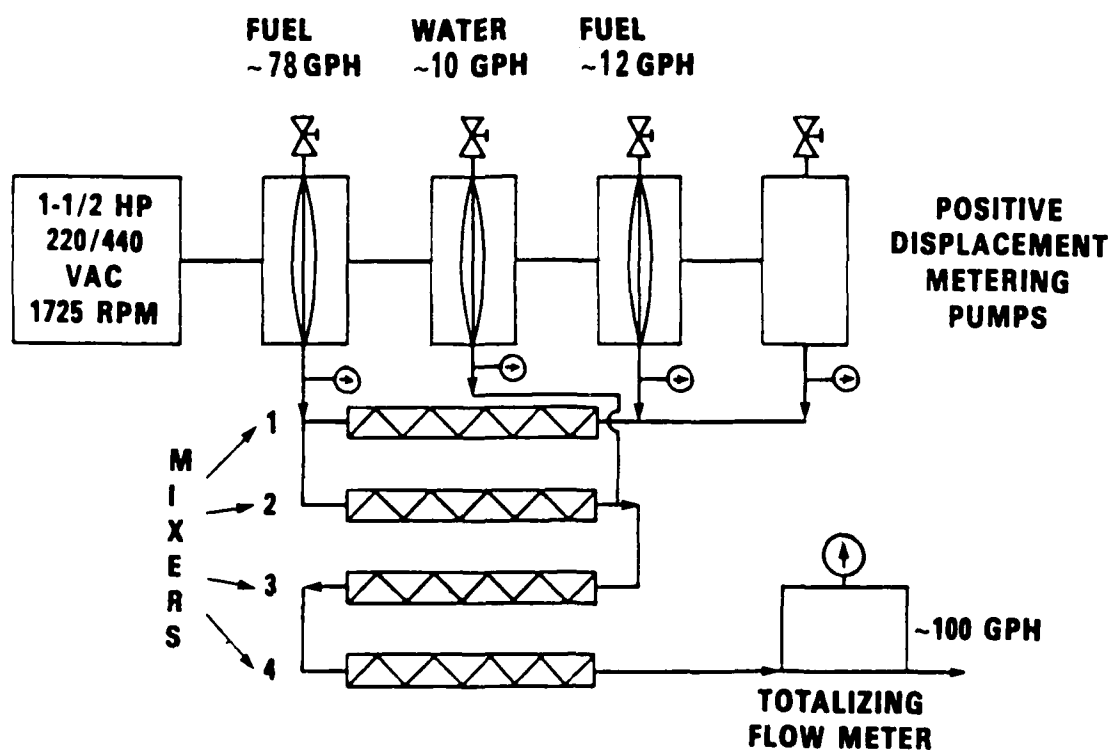R
S

1
2
3
4

~100 GPH

TOTALIZING
FLOW METER

Figure 2. Prototype FRF continuous blending system

2. The surfactant premix is also introduced into the stream entering mixer No. 1.

3. The fuel-premix accounting for 12 vol% of the blend is supplied at a mixing pressure of approximately 60 psi and flows through mixer No. 1 and then sequentially through mixer No. 2 to assume proper mixing.

4. Water is added to the fuel-premix between mixers No. 2 and 3, and this mixture flows through mixers No. 3 and 4. The pressure in the system remains at 60 to 70 psi and has been shown to provide adequate agitation/homogenization to provide a stable emulsion using the geometrically designed motionless mixing elements.

5. Total flow is measured through a totalizing flow meter.

The blending system as well as the blending components were equilibrated overnight to ensure proper temperature conditioning. The following results were obtained:

1. $16^{\circ}C$ ($60^{\circ}F$) to $2^{\circ}C$ ($35^{\circ}F$) blending was accomplished at $0^{\circ}C$ with no problems either from stability or proper proportioning of blending components. The fuel used in this blending test was MIL-F-46162 with a cloud point below $-10^{\circ}C$. Therefore, no problems were expected from the fuel in terms of pumping or in-line plugging. Although the water was near freezing, no ice crystals were allowed to form. The surfactant premix does thicken somewhat at $0^{\circ}C$; however, the proportioning pumps had no trouble supplying the proper proportion to the FRF blend. TABLE 9 illustrates some typical kinematic viscosities of blending components as well as blended FRF.

2. $-9^{\circ}C$ ($15^{\circ}F$) blending studies were conducted in the cold room after equilibrating overnight to ensure proper temperature conditioning. A heated blanket was used to prevent the water from freezing. Two methods were used to evaluate blending at this low temperature.

   a. Hand-mixing - Normal laboratory blending procedures can be accomplished by simply stirring the blending components together in the

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TABLE 9. Temperature Dependence of Viscosity of FRF Components

Composition, volume parts						Oleic Acid	Water, volume parts		Kinematic Viscosity, cSt, at T, °C		
AC150	EA15	14028	14029	14216	14683		D.I.	Ca-N	20	0	-10
100	--	--	--	--	--	--	--	--	1.34	1.94	2.44
--	100	--	--	--	--	--	--	--	1,793	13,800	--
50	50	--	--	--	--	--	--	--	64.46	258	596
--	--	--	--	--	--	100	--	--	38.22	Solid	--
--	--	100	--	--	--	--	--	--	3.99	7.32	10.60
6	--	78	--	--	--	--	--	--	3.60	6.40	9.08
--	6	78	--	--	--	--	--	--	6.84	15.75	28.65
6	6	78	--	--	--	--	--	--	5.78	11.89	18.53
--	--	--	100	--	--	--	--	--	3.24	5.80	7.62
6	--	--	78	--	--	--	--	--	2.95	4.94	6.81
--	6	--	78	--	--	--	--	--	5.30	11.31	22.78
6	6	--	78	--	--	--	--	--	4.70	9.13	14.65
--	--	--	--	100	--	--	--	--	1.71	2.51	3.12
6	--	--	--	78	--	--	--	--	1.65	2.47	3.01
--	6	--	--	78	--	--	--	--	2.66	4.28	5.82
6	6	--	--	78	--	--	--	--	2.44	3.81	4.96
--	--	--	--	--	100	--	--	--	5.02	9.71	14.61
6	--	--	--	--	78	--	--	--	4.39	8.26	12.01
--	6	--	--	--	78	--	--	--	7.44	12.56	31.77
6	6	--	--	--	78	--	--	--	6.24	12.50	19.19
6	6	--	--	--	78	--	10	--	6.94	23.46	152.5
6	6	--	--	--	78	--	--	10	7.12	22.49	150.7

Notes
AC150   Aromatic 150 by Exxon
EA15   Emulsifying Agent With Total Acid No. $\simeq$ 15 mg KOH/g
14028   NATO F-54
14029   NATO F-54
14216   JP-8
14683   MIL-F-46162B Referee Grade DF-2
D.I.   Deionized Water
Ca-N   50-ppm Calcium Nitrate Solution

proper proportions and blending order. Therefore, it was decided to attempt this method of blending first in order to determine the feasibility of making a proper FRF at 15°F. The blending with hand stirring with components at 15°F did produce a milky emulsion that cleared upon standing. It should be noted that the water was maintained just above freezing and did cause the emulsion to change to a milky color upon blending.

b.   100-GPH Blender - The 100-GPH blender was also evaluated in preparing FRF at 15°F. As was mentioned before, the blender and blending components were all maintained at the desired blending temperature (15°F in this case, except the water temperature was maintained at approximately 33°F).

When blending was attempted at 15°F, the blender worked normally; however, the pumping became sluggish within a few minutes. This slowing in pumping rate was attributed to the thickening of the FRF blend upon addition of water. Several procedures were evaluated to prevent the transfer of the cold temperature to the fluid while mixing; however, due to the design of the blender, none was successful. The procedures that were tried included wrapping the Kenix mixer with heating tape, insulation, and using heating lamps. While these methods were not considered very practical from a "field use" standpoint, the intent was to demonstrate that blending could be accomplished. However, using the system available at BFLRF, attempts to blend FRF on a continuous basis were not successful.

C.   Storability and Transportability

Storability and handling of FRF could potentially cause severe problems, not only from a stability standpoint, but from the contamination of existing equipment. This contamination could cause some equipment with vital performance functions to malfunction. A good example of this is the effect of the surfactant on the filter-coalescer commonly used to treat turbine fuels. This task was conducted in two phases.

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1.   Drummed Fuel Storage Stability Tests

These storage samples included the emulsifier premix and the emulsified FRF with samples being taken for further analysis. These samples were analyzed for stability, i.e., phase separation, and other visual examinations for changes in fuel quality.

On July 5, 1986, 350 gallons of FRF were blended using the 100 GPH blending unit and stored in seven 55-gallon drums. The initial composition of the FRF under storage was 78 vol% DF-2, 12 vol% surfactant premix, and 10 vol% water. The drums were sealed and stored in vertical position for 6 months, exposed to San Antonio weather at BFLRF. The water analysis of fuel samples from top, middle, and bottom of the undisturbed drums after 6 months of storage are presented in TABLE 10. In all cases, the FRF had phase-separated to various extents. The bottom sample was always white or cream. The rest of the fuel in each drum was clear microemulsion, with water contents varying from 4 to 10 vol%.

TABLE 10. Six-Month Storage Stability of FRF
(Water content in samples drawn from three different
levels of vertical 55-gallon drums)

Drum No.	Vol% Water		
	Top	Middle	Bottom
1	9.8	9.5	49.4
2	6.4	6.7	64.4
3	7.8	7.6	31.8
4	10.0	9.4	27.3
5	7.6	7.3	12.3
6	7.9	8.5	16.3
7	3.6	4.1	62.0

Attempts were made to reblend the contents of individual drums by rolling, hand-mixing, and passing the contents through a 100 GPH blending unit. However, in each case, the phases separated upon overnight storage as was evident by the cream in the bottom phase.

2. Contamination Effects of FRF in Fuel-Handling Systems

It was not known how serious the problem of contamination of other types of fuels may be. Aside from the normal fuel hang-up in certain areas of the fuel-handling system, the surfactant, being surface active, may be very difficult to flush from the system due to wall-adhering tendencies. This factor could also be affected by the type and condition of the surface.

Experiments were conducted to determine the poisoning effects of the surfactant on the coalescer, thus affecting the water-shedding tendencies of other fuels, including JP-4. A microsep was used to make these determinations since it was planned to be used in the fuel test kit. However, it was suspected that even the base diesel fuel may not meet current specifications due to the sensitivity of the microsep that was developed for jet fuel application.

Experiments were conducted in order to determine the minimum concentration of FRF on the water-shedding characteristics of the microsep. Initially a concentration of 50-percent FRF and 50-percent JP-4 was evaluated. Then the concentration of FRF was *reduced to determine* the minimum FRF that could be tolerated by the coalescer system. Results of this study, shown in TABLE 11, show that even 50 ppm of FRF may be sufficient to poison the coalescer.

TABLE 11. Effects of Surfactant on Microsep Filter Coalescers

FRF	Microsep Reading
50% FRF	00
1% FRF	00
1000-ppm FRF	00
100-ppm FRF	46
50-ppm FRF	59

Another series of experiments was conducted in order to determine if a coalescer could be regenerated after FRF had neutralized the coalescent activity. In this series of experiments, a coalescer filter was poisoned with FRF and then successively washed with

JP-4 until the coalescent activity was restored. TABLE 12 reports the results of this series of experiments.

TABLE 12. Effects of Flushing Poisoned Filter With JP-4 Fuel

Fuel	Microsep Reading
FRF	00
JP-4 - 1st Run	56
JP-4 - 2nd Run	64
JP-4 - 3rd Run	66
JP-4 - 4th Run	70
JP-4 - 5th Run	71
JP-4 - 6th Run	74
JP-4 - 7th Run	80

The results, shown in TABLE 12, indicate that a coalescer may be cleaned up after poisoning with FRF after successive flushes with an unadulterated fuel.

Another series of tests was conducted in order to determine the effect of temperature on the response of a coalescer to FRF. This series of tests was conducted at 75°F (24°C) and at 32°F (0°C), and the results are reported in TABLE 13. The table includes not only diesel fuel filters, but also jet fuel filter as specified in the microsep procedure.

TABLE 13. Effects of FRF on Microsep Diesel and Jet Filters

Sample	Microsep, 75°F (24°C)	Microsep, 32°F (0°C)
Diesel Filter		
FRF	00	00
JP-4	92	107
Jet Filter		
FRF	0	0
JP-4	53	53

Results of this phase of testing indicates that even a very dilute solution of FRF (50 ppm) may poison a coalescer filter, but the effectiveness of the filter could possibly be restored after repeated flushings with the desired fuel. One concern is the correlation of the microsep application to field correlation using the diesel filters.

D. Powerplant Performance

1. Diesel Engines

Quantification of power loss has been accomplished both with engine dynamometer testing and with full-scale vehicular tests. The results of these tests, shown partially in TABLES 14 and 15, indicate a nominal 10-percent loss in maximum speed and acceleration rates. Data shown in TABLES 14 and 15 were generated in the indicated vehicles at Yuma Proving Grounds and were not published in a report. Actual power loss is somewhat dependent upon the engine configuration and operating parameters but correlates somewhat with the energy content of the fuels, i.e., 10 percent less energy in FRF.

TABLE 14. Comparison of Maximum Vehicle Speeds

| Vehicle | Maximum Speed (mph) | | Loss | % Loss |
	Base Fuel	FRF		
M113A1	39.0	34.6	4.4	11
M60A3	31.4	30.7	0.7	2

TABLE 15. Comparison of Vehicle Acceleration Rates

| Vehicle | Time to Accelerate From 0 to 20 mph (sec) | | Loss | % Loss |
	Base Fuel	FRF		
M113A1	10.0	13.2	3.2	32
M60A3	14.7	17.5	2.8	19

It has been theorized that the full speed/power decrement could be recovered by simple rack adjustment to allow more fuel blend to enter the engine. To accomplish this rack adjustment, full power would be recovered, but the total range and specific fuel consumption of the vehicle would be reduced. A Cummins NHC-250 engine was operated on base fuel DF-2, on FRF from the same base fuel, and then on FRF with rack adjustment to provide the same power. The results of these tests are shown in Figs. 3, 4, and 5.
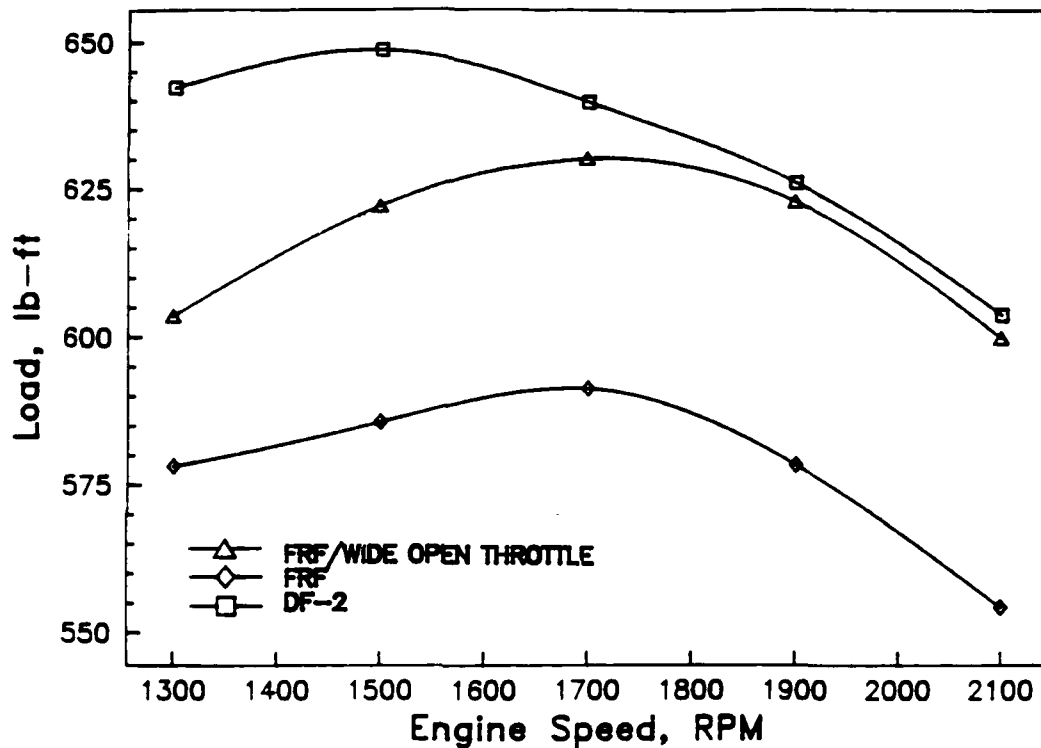

Figure 3. Observed engine load of the Cummins NHC-250 engine

The results of these tests confirm that the fuel pump can be adjusted to provide sufficient fuel to regain full power from the fuel containing 10-percent water, especially at higher speeds.

2.   Gas Turbines

In evaluating the effect of FRF on a gas turbine engine system, one important criterion to look at is the stability of the fuel under high-temperature conditions. Tests were initiated to study this stability on the "Hot Fuel Nozzle Fouling Apparatus," (8) which was recently assembled on programs funded by the U.S. Navy.
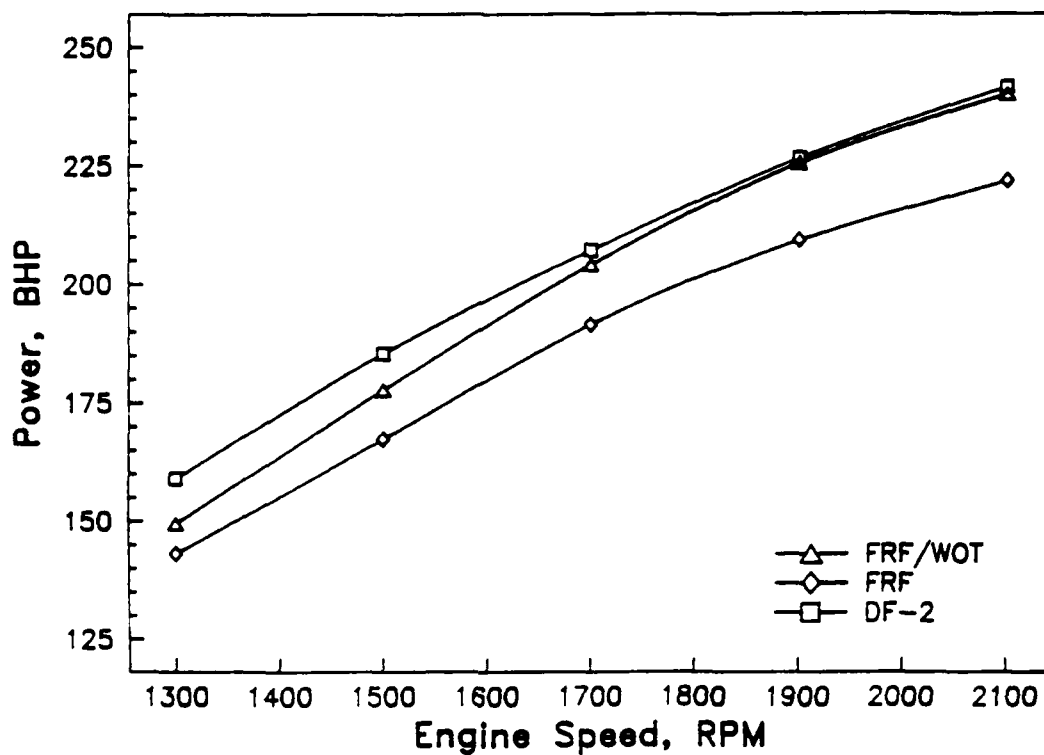
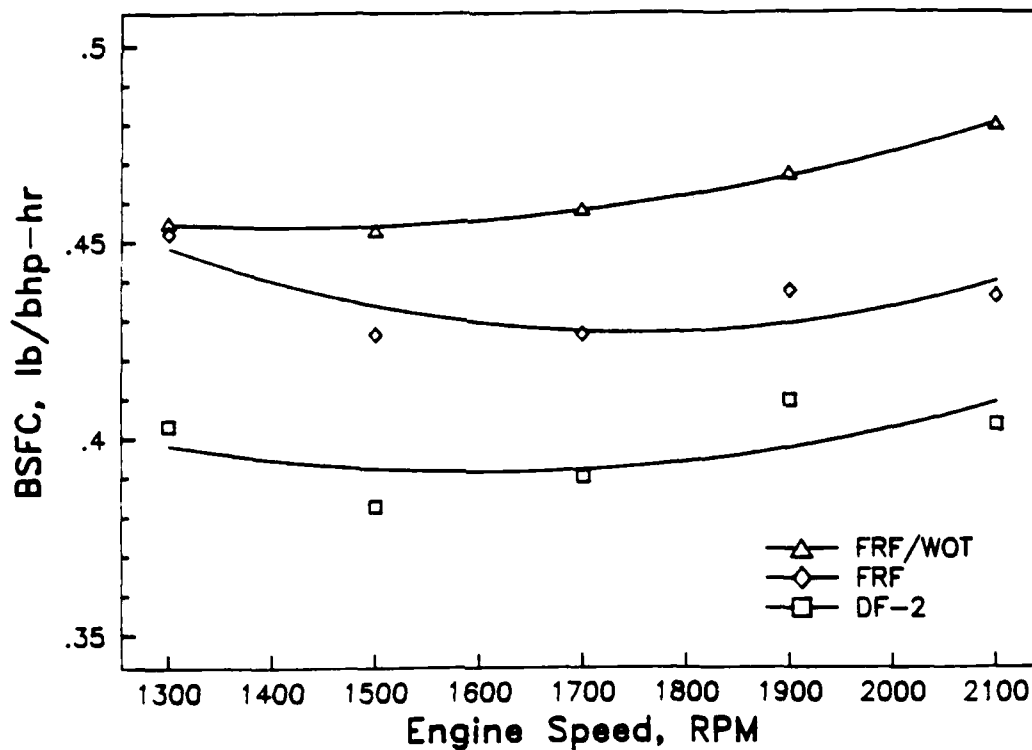Figure 4. Observed power of the Cummins NHC-250 engine

Figure 5. Brake specific fuel consumption of the
Cummins NHC-250 engine

The apparatus evaluates the nozzle fouling/flow divider valve sticking tendencies of a fuel when operating in an environment similar to turbine engine operation. Nozzle fouling is measured by pressure/flow differentials after the specified test hours. Fuel flow divider valve sticking is evaluated by flow hysteresis. For this program, nozzle/flow divider valve failure is defined as a 10-percent reduction in primary flow, a 5-percent reduction in secondary flow, or a 10-percent increase in valve hysteresis.

The first full duration 75-hr test performed during this program employed MIL-F-46162B referee fuel using a nonspecific fuel atomizer nozzle. The second 75-hr test, for back-to-back comparisons, utilized FRF formulated from the same base fuel and an identical unused nonspecific nozzle. Since the fuels for these tests were heated to 380° to 410°F (193° to 210°C), the instability/deposits may be best attributed to fuel thermal stability characteristics. The nozzles used for these tests were of the simplex swirl type with no internal flow divider valve. Therefore, the only failure criterion that applied was the 10-percent reduction in flow. Also, nonspecific nozzles were employed because AGT-1500 atomizers were not available for testing when the "baseline" test was initiated.

A preliminary test using MIL-F-46162B referee fuel and a nonspecific nozzle was initially performed to determine appropriate test conditions. Based on a JFTOT thermal stability breakpoint temperature of 505°F (262°C) $\pm$ 5°, as determined for the fuel, the fuel temperature selected at the inlet to the nozzle for this test was 410°F (210°C). After 5 hours of testing at this fuel temperature, the nozzle was fouling at a faster rate than desired. Therefore, the test was discontinued and another test was initiated with a new nozzle and employing a lower fuel-in temperature of 380°F (193°C). This test proceeded for 75 hours with slight nozzle fouling, as measured by pressure/flow differentials. Subsequent to this test, the referee fuel and an emulsifying agent/aromatic solvent premix was blended to produce a FRF for comparison testing. The FRF test also had a duration of 75 hours and a fuel-in temperature of 380°F (193°C).

The calibration test data at rated pressure (80 psig) for the nozzle are shown in Fig. 6. The data for a previously tested nozzle of the same design and size and employing the "baseline" referee fuel without the fire-resistant treatment are also presented in Fig. 6. As shown in the plot of data, the baseline referee fuel, designated by circles, had much more erratic performance during testing. It appeared that the nozzle orifice and fuel passages would begin to have deposit buildup at a fairly rapid rate. After reaching a 3-

29

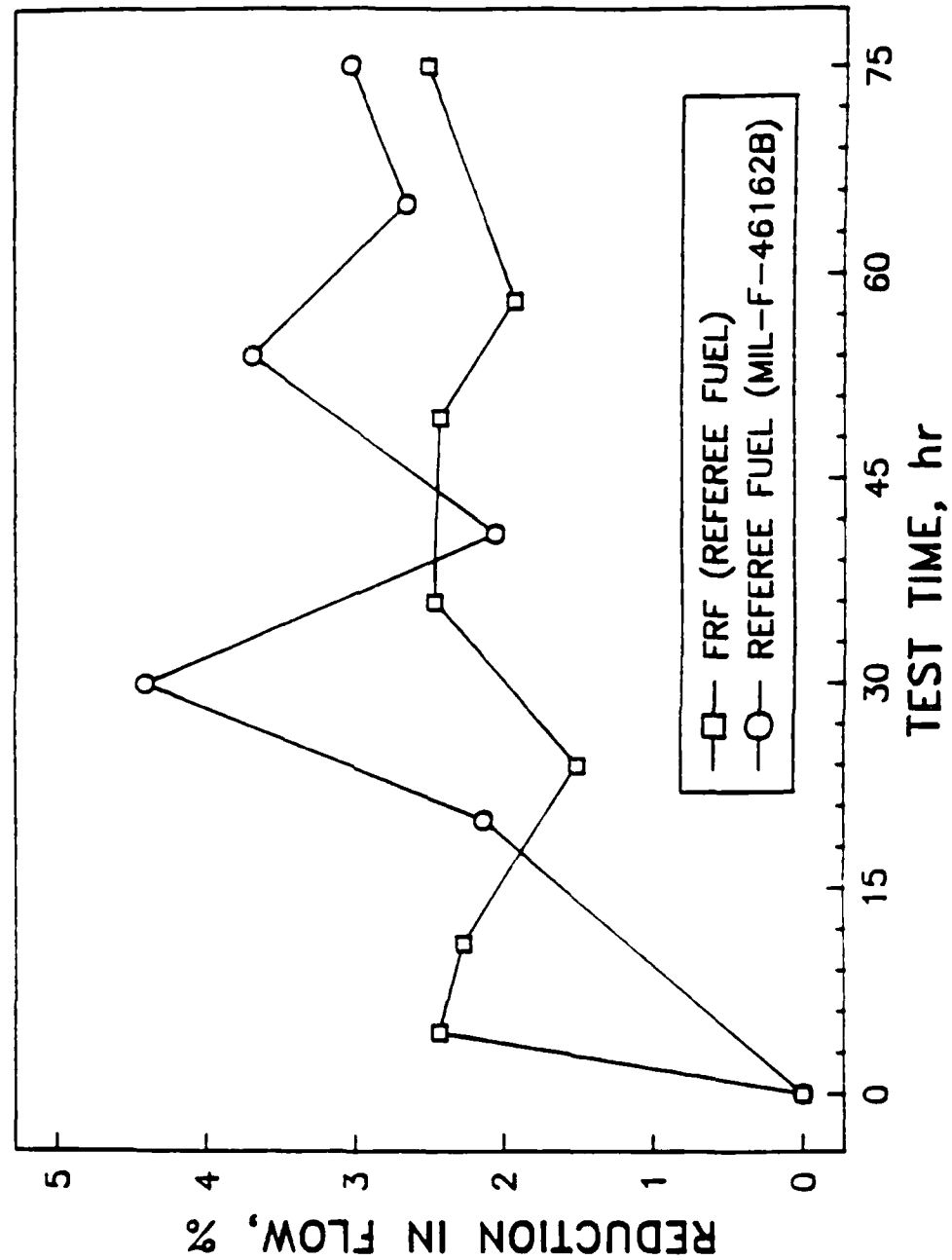380 °F FUEL-IN TEMP; 520 °F NOZZLE STEM TEMP; 60 LB/HR FUEL FLOW RATE

Figure 6. Simplex nozzle flow characteristics using baseline referee fuel and FRF (blended from baseline fuel) under similar test conditions

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to 4-percent reduction in flow, the nozzle would "clean" itself back to approximately 2- to 2.5-percent flow reduction. Then, increased fouling would again occur before the nozzle would again display the cleaning effect. On the other hand, the FRF displayed an initial rapid reduction in flow of about 2.4 percent in the first 4.5 hours of testing and remained at that level for the remainder of the 75-hour test. There was some evidence of this fuel displaying the cleaning effect on the nozzle twice during the test, but not nearly as dramatically as observed with the baseline fuel. It was observed during testing that the FRF displayed very erratic flows through the test facility and nozzle, as compared to the baseline fuel. As a result, the speed of the pump was continuously being adjusted to maintain the constant 60 lb/hr fuel flow rate. This erratic flow is attributed to the fact that FRF is probably not as homogeneous as the baseline fuel, and the mass flow meter was distinguishing this inconsistency.

Nozzle failure is considered to be a 10-percent reduction in flow rate at rated pressure. As shown by the data in Fig. 6, neither of these tests approached nozzle failure at these testing conditions. It must be realized that these tests were performed using nonspecific nozzles, which are quite different from AGT-1500 combustor atomizers (nozzles). Also the exact operational temperatures of the fuel-in and nozzle stem were not known for the AGT-1500 and were approximated. Therefore, these data can be used for comparative purposes for the two fuels under the similar test conditions employed, which may or may not be representative of performance in a more realistic operational condition using the AGT-1500.

3. FRF Atomization Tests in AGT-1500 Atomizer

The atomization performance of a fire-resistant diesel fuel (water/diesel fuel microemulsion) was compared to that of a standard reference diesel fuel using an atomizer from an AGT-1500 gas-turbine engine, which powers the M1 tank. Atomization tests were also performed with aircraft fuel system calibration fluid MIL-C-7024 II. Three engine conditions were simulated -- two for start-up and one for idle. Spray tests have not been performed for higher power conditions.

Because of its higher viscosity and density, the fire-resistant fuel degraded atomization at a constant mass flow rate by an average of about 23 percent at 32°C (90°F) and 43 percent at 4°C (40°F). These increased drop sizes for the fire-resistant fuel may

somewhat adversely affect start-up and idle performance. Alternatively, if fuel flow rates are increased to compensate for displacement of fuel by water, the atomization of the fire-resistant fuel should be improved by about 10 percent relative to that reported here. For purposes of completeness, these data and discussion of results are presented in Appendix A.

V. SUMMARY AND CONCLUSIONS

1.   Chemical analysis of base fuels were not successful in providing guidance to predict emulsion stability. General trends such as aromatic content of the fuel and acid number of the surfactant were observed to be important, but not controlling factors that were infallible. Fractions taken from the separated layers in FRF consisted of increased concentrations of water and emulsifying agent components.

2.   Studies did confirm that the fuel could be emulsified at temperatures below the freezing point of water, if the water was kept from freezing. However, due to the rapid transfer of cold from the fuel and surfactant, the emulsion soon thickened. Continuous blending at lower temperatures would require a system that could supply heat to the blending tubes.

3.   Low-temperature fuel system studies evaluated various heating elements for fuel system components such as fuel lines and fuel filters. These studies utilized mock-up systems of the DDA 6V-53 and the Cummins VTA-903T, and a Cummins VTA-903T engine installed in a cold box. Results of these studies showed that the components did keep the fuel warm enough to provide fuel to the engine. The problem occurred in the fuel tank and inside of the engine. Low temperatures caused the fuel in the tank to solidify and could not be pumped out of the tank. The fuel system inside of the engine (injectors) solidified and fuel could not be pumped through the engine. These problems could not be resolved.

4.   Engine power and performance evaluations were conducted both in engine/dynamometer and in full-scale vehicles, as well as a generator. Results of this testing showed that power loss of approximately 10 percent (lower heating value) could be measured in an engine/dynamometer test device. However, the power could be

recovered by rack adjustment. The 45-kW generator maintained proper frequency output using FRF, since the fuel supply was being controlled by a governor.

5.   Thermal stability tests were conducted to evaluate the fuel's thermal stability characteristics in a turbine fuel system-nozzle test procedure. Results of these tests indicated that the thermal stability (relating to the surfactant system) should not cause problems such as nozzle fouling.

6.   Turbine atomization tests conducted at low-engine-power conditions (start-up and idle) indicated a degraded atomization as high as 43 percent at 4°C (40°F). This reduction in atomization (increased drop sizes) could adversely affect start-up and idle conditions.

7.   Six-month drum storage tests indicated that FRF has a tendency to stratify into layers, with higher water contents settling to the bottom. Microsep evaluations of coalescer poisoning indicate that the surfactant used in this formulation caused reduced water separation efficiency.

VI. RECOMMENDATIONS

1.   Further work on this formulation should not be initiated. While most problems could be resolved by some engineering modifications, the two underlying factors that could not be resolved are:

- The requirement of "pure" water is not reasonable for field applications.

- Low-temperature related problems in the fuel system, blending, and storage prevent the use of this fuel at temperatures much below 0°C.

2.   The development of a different surfactant system is recommended to eliminate the "pure" water requirement.

3.   The demonstrated effectiveness of FRF to eliminate fires in armored vehicles should be incorporated into a scenario of limited, high-risk application, such as armored vehicular conflicts in warm climates.

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APPENDIX

Studies on Atomization of Fire-Resistant
Fuel in an AGT-1500 Atomizer

INTRODUCTION

Aqueous microemulsions with diesel fuel (i.e., diesel fuel/water/surfactant blends) have been shown to be self-extinguishing for pool burning under many conditions (1)*. These same fuels exhibit combustion characteristics similar to specification fuels in diesel engines and gas turbine combustors (2). Three mechanisms have been suggested by which the presence of water may lead to self-extinguishment of burning pools of aqueous microemulsions with diesel fuel: (1) liquid surface blanketing with water vapor which acts as a diluent and heat sink, (2) evaporative cooling of the liquid surface stemming from the high volatility and heat of vaporization of water relative to those of the base fuels, or (3) "phase-rule" maximum liquid surface temperature restriction stemming from presence of coexisting immiscible water and base fuel phases (1). The dominant mechanism for fire-resistant diesel fuel (FRF) has been shown to be the liquid surface blanketing with water vapor (1).

Although FRF has the potential of significantly increasing survivability of tank equipment and personnel under hostile conditions, it has disadvantages such as loss of range and possible loss of combustion performance. Previous tests of water/jet-fuel microemulsions in a T-63 gas turbine combustor showed insignificant reductions in combustion efficiency (based on emissions) at high power conditions, and a 2 percent reduction at idle conditions for a 10 percent water microemulsion (2). These slight reductions in combustion efficiency may have been due to degraded atomization or some other factors.

The specific objective of this program was to evaluate the atomization performance of FRF when compared to baseline diesel fuel in an AGT-1500 fuel nozzle. Some degradation of atomization performance was anticipated because of the higher viscosity of FRF (compared to diesel fuel) due to the presence of surfactants required in the microemulsions. Surfactants are typically very large molecules which exhibit high viscosity. If degradation in atomization performance occurs, some degradation in start-up and combustion performance may occur.

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*Numbers in parentheses designate entries in the reference list.

EXPERIMENTAL APPARATUS

Spray Chamber and Drop-Sizing Instrumentation

The AGT-1500 atomizer (two-piece design) was mounted in a spray chamber with a cross section of 0.30 m x 0.41 m and a length of 0.53 m between honeycomb flow-straightener sections. A bellmouth inlet was used in addition to the honeycomb straightener to reduce turbulence levels. A twisted metal screen and settling chamber followed the outlet honeycomb flow-straightener to aid in mist removal. An explosion-proof fan pulled air through the system at a velocity in the test section of 1.6 m/s and a turbulence level of about 2.5 percent. The atomizer was positioned within the chamber by a two-axis, computer-controlled actuator system.

Drop size data were obtained with a Malvern Model 2200 Particle sizer based on principles of forward light scattering or Fraunhofer diffraction. When illuminated by a beam of monochromatic, coherent, collimated light from a HeNe laser, the smaller drops diffract light a larger angles to the optical axis than the larger drops, forming a diffraction pattern characteristic of the drop sizes. Detection is accomplished with a 30-annular ring set of solid-state detectors. Detector outputs are multiplexed and the data signal averaged with a Commodore PET computer. A computer routine is used to interpret the light-scattering pattern of the polydisperse drop systems and to compute the drop-size distribution. The size distributions were assumed to follow a Rosin-Rammler distribution function. A 300 mm focal length f/7.3 lens was used to collect the scattered light. The laser beam diameter was 3 mm.

The Malvern laser-diffraction particle sizer measures line-of-sight average drop sizes over the entire path length of the laser beam through the spray, as shown in Fig. A-1. In order to compute overall average particle sizes for the complete cross section of the spray, it was necessary to convert the line-of-sight averages to the drop-size distributions for each ring shown in Fig. A-1. This was accomplished by taking line-of-sight measurements through various chords of the spray as shown in Fig. A-1, and then performing a deconvolution (3) of the results to get drop-size distributions and number densities for each ring. Typically the spray was assumed to consist of about 15 rings for these tests, requiring measurements through 15 chords at each condition.

Test Conditions and Fuels

Measurements have been performed using three fuels: (1) aircraft fuel system calibration fluid, MIL-C-7024 II; (2) high-sulfur referee diesel fuel No. 2, MIL-F-46162B; and (3) fire-resistant fuel, AL-1463. The fire resistant fuel was blended from 78 vol. % high-sulfur referee diesel fuel, 10 vol. % water, and 6 vol. % surfactant, and 6 vol. % aromatic concentrate. The first fuel was heated to 27°C (80°F) corresponding to standard procedures for atomization tests in the aircraft industry. This fuel (calibration fluid) was used to establish a baseline which could be reproduced at any other atomization testing facility. Atomization tests for the diesel fuel and FRF were performed at 4°C (40°F) and 32°C (90°F), corresponding to fuel temperatures for proposed ignition tests.

Three engine conditions were simulated — two for ignition and one for idle. The ignition procedure for the AGT-1500 consists first of accelerating the compressor up to 5-percent speed; then the fuel begins flowing at 40 lbm/sec. Then the engine is speeded up to a maximum cranking speed of 20 percent of full speed, and the fuel flow is simultaneously increased at a rate of 5 lbm/hr/sec, to a maximum flow of 70 lbm/hr. Atomization measurements were made at the two extremes of ignition fuel flow rates, the 40 and 70 lbm/hr conditions. Atomization measurements were also made at low idle (40 HP) condition, with a fuel flow of 61 lbm/hr. Atomization measurements were attempted at higher power conditions, but the sprays were too dense for optical measurements of drop size. For measurements in dense sprays, it is possible to physically block part of the spray to prevent its intersection with the laser beam, and limit the drop size measurements to a small region of the spray. However, that was beyond the scope of this effort.

The two-piece nozzle in current production was used for these tests. It is a hybrid air-blast atomizer consisting of a small-capacity, pressure-swirl primary atomizer used for start-up, and a high-capacity, air-blast secondary atomizer which supplies the majority of the fuel at higher-power conditions. The fuel flow rates through the primary and secondary atomizers and air pressure drops at standard operating conditions for the AGT-1500 are given in TABLE A-1.

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	Start-up		Low Idle 40 HP	High Idle 400 HP	1050 HP	Max 1500 HP
	5% Speed	20% Speed				
Primary Fuel Flow, lbm/hr lbm/min	37 0.616	44 0.733	41 0.683	51 0.850	62 1.03	67 1.12
Primary ΔP (fuel) (approx.), psid	154	218	189	293	433	505
Secondary Fuel Flow, lbm/hr lbm/min	3 0.051	26 0.44	20 0.34	216 3.60	450 7.50	656 10.93
Total Fuel Flow, lbm/hr lbm/min	40 0.667	70 1.17	61 1.02	267 4.45	512 8.52	723 12.05
Air Pressure Drop, psid inches H_2O	0.01 0.27	0.079 2.2	0.736 20.4	1.75 48.4	2.51 69.5	3.21 88.9

RESULTS

The results of the atomization tests are summarized in TABLE A-2. Results are presented for aircraft fuel system calibration fluid at the standard fuel test temperature of 27°C (80°F) in TABLE A-2 and Fig. A-2. Atomization data for the referee diesel fuel and the fire-resistant fuel are presented for temperatures of 4°C (40°F) and 32°C (90 °F) in Table A-2 and Figs. A-3 through A-8.

Average drop sizes are represented by $\bar{D}_{32}$ or the Sauter mean diameter (SMD). Two SMD values are given in TABLE A-2 for each fuel and test condition. One value is that measured through the centerline of the spray and represents a line-of-sight average of the drops measured all along the intersection of the laser beam and the spray (i.e., measurement location 3, Fig. A-1). This has traditionally been used as a representative measurement of overall spray characteristics. However, it may be seen from Fig. A-1 that the centerline measurement weights drops near the center more heavily than drops near the edge of the spray cone if compared to an area-weighted average of the spray cross section. A procedure has been developed at this laboratory

TABLE A-2. AGT-1500 Atomization Results

Fuel	Temp, °C(°F)	Sauter Mean Diameter, micrometers					
		Ignition, 40 lb/hr		Ignition, 70 lb/hr		Idle	
		Centerline Line-of-Sight Measurement	Overall Average	Centerline Line-of-Sight Measurement	Overall Average	Centerline Line-of-Sight Measurement	Overall Average
Calibration Fluid (MIL-C-7024 II)	27 (80)	19.8	50.9	21.2	75.4	17.8	44.6
High-Sulfur Referee Diesel Fuel No. 2 (MIL-F-46162B)	32 (90)	42.5	77.4	43.4	75.4	44.5	82.1
Fire-Resistant Fuel (Diesel/Water Emulsion)	32 (90)	38.0	110	52.0	85.4	51.3	92.7
High-Sulfur Referee Diesel Fuel No. 2 (MIL-F-46162B)	4 (40)	44.8	96.5	55.8	91.0	57.4	102
Fire-Resistant Fuel (Diesel/Water Emulsion)	4 (40)	55.5	116	81.2	133	99.1	167

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for computing a cross section average of the overall spray which accounts for the area-weighting of the rings in Fig. A-1 as well as differences in number density (4). This overall average is a better representation of the spray characteristics than the centerline value. Note from TABLE A-2 that the overall average is significantly larger than the centerline value, a trend that is consistent with the spray characteristics illustrated schematically in Fig. A-1 and by actual data in Fig. A-2 through A-8.

Figures A-2 through A-8 show the average drop sizes as a function of radial location for the three fuels and the three operating conditions. Note that the results shown in Figs. A-2 through A-8 are not line-of-sight averages, but rather are the spatially resolved results from the deconvolution procedure. Thus, the centerline values are smaller than the measured line-of-sight average values shown in Table A-2, consistent with Fig. A-1. Also shown in the legend of each figure is the cross section average SMD, which represents the area-weighted average of the radial measurements. The overall atomization of the FRF is degraded (i.e., SMD is larger) relative to the diesel fuel by 13 to 42 percent for the three operating conditions at the 32°C (90°F) fuel temperature, with an average degradation of 23 percent. For the cooler fuel temperature of 4°C (40°F), the overall atomization of the FRF is degraded relative to the diesel fuel by 20 to 64 percent, with an average of 43 percent. The probable reason for the increased degradation at cooler fuel temperatures is the more rapid increase in viscosity by the FRF compared to diesel fuel as the temperature decreases as shown in Fig. A-9.

From Figs. A-3 through A-8, it may be seen that the general spray structure for the two fuels is similar. The degraded atomization of the FRF is due to two factors. First, the increased viscosity of the FRF increases the film thickness of the fuel liquid sheet leaving the atomizer, resulting in larger drops upon the breakup of the sheet. Second, the FRF is a higher density fuel, so that the same mass flow rate may be achieved at a lower volume flow rate and lower pressure drop across the atomizer. Since these tests were conducted at constant mass flow rate, and since the primary nozzle is a pressure-swirl atomizer, the reduced pressure differential leads to larger fuel droplets. In realistic applications, the atomization of the FRF at lower fuel flows used for ignition and idle would be significantly improved by the higher fuel pressures required for increased flow rates to maintain the same heat input to the combustor (to compensate for the presence of water). However atomization in the secondary nozzle

used for higher fuel flows would be slightly degraded at the higher fuel flows required to maintain the same heat input when compared with diesel fuel.

SUMMARY AND CONCLUSIONS

Because of its higher viscosity, fire-resistant fuel (FRF) exhibited degraded atomization when compared with baseline diesel fuel for the same mass flow rates at ignition and idle conditions. At a fuel temperature of 32°C (90°F), atomization was degraded by about 23 percent, and at 4°C (40°F) the degradation was about 43 percent. In realistic applications, mass flow rates of the FRF would probably be higher than diesel fuel to maintain a constant heat input to the combustor, and at ignition and idle conditions these higher flow rates would improve atomization of the FRF. Atomization tests at equivalent thermal energy input rates were not conducted.

A new method has been demonstrated in this report for comparing atomization data for different fuels. Traditionally, sprays have been characterized by a single measurement with a laser-diffraction instrument through the centerline of the spray. For the results presented here, laser-diffraction measurements were performed at various chords through the spray from the centerline to the edge. These line-of-sight average measurements were mathematically converted to spatially resolved drop-size distributions at different radial locations. These spatially resolved drop-size distributions were then summed up with appropriate weighting factors for drop number density and equivalent spray area to arrive at an overall cross section average. It was shown that the line-of-sight centerline measurements were not representative of the overall cross section averages.

RECOMMENDATIONS

The results presented here should be of use in correlating combustion tests of fire-resistant fuel and diesel fuel. If combustion tests are conducted at different fuel flow rates, the atomization quality may be estimated by interpolation of these results. Alternatively, atomization tests can be repeated at SwRI at the exact flow rates used for the combustion tests.

Also the atomization tests with aircraft fuel system calibration fluid may be used for comparison with tests by other laboratories of the same atomizer.

The procedures used here and described in Ref. 4 are recommended for obtaining representative cross section average drop sizes for sprays.

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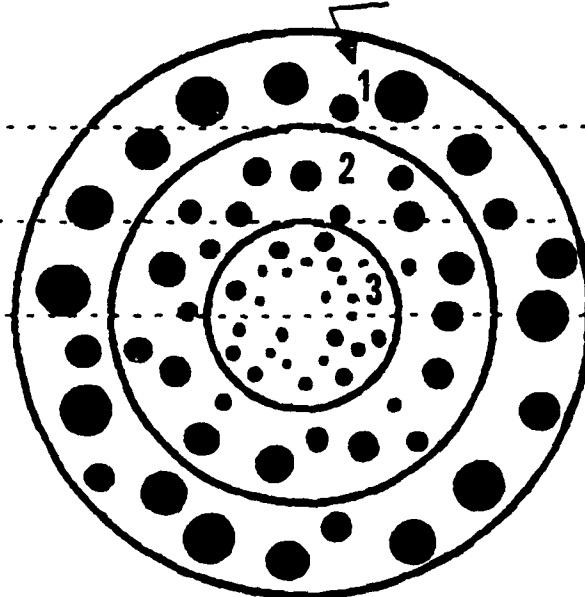
Figure A-1. Cross section of typical spray from pressure-swirl atomizer showing radial variation of drop-size distributions. Also laser-diffraction instrument measurement locations necesssary for deconvolution (Abel inversion) procedure to convert line-of-sight averages to spatially resolved distribution within each ring.
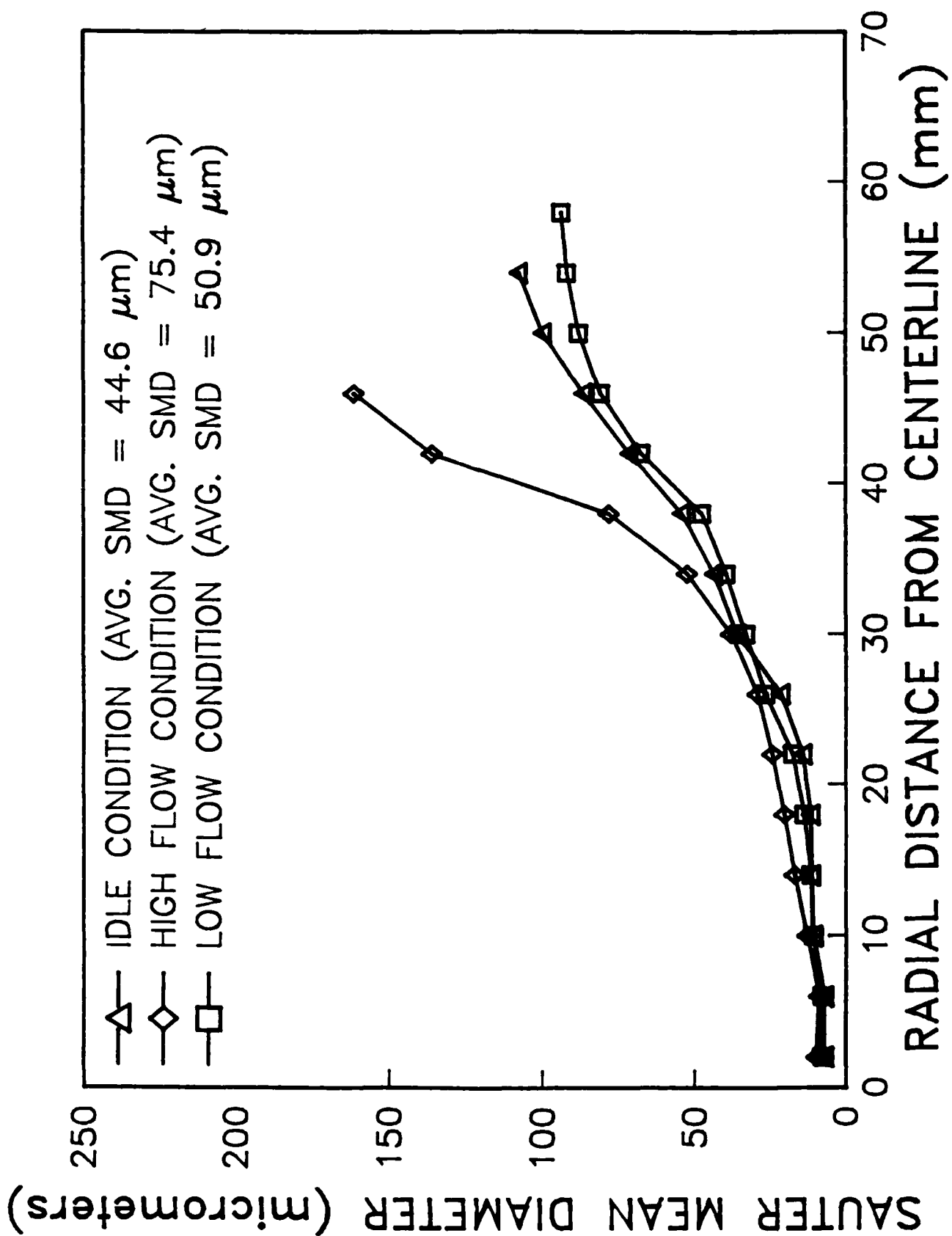
Figure A-2. Radial distributions of SMD's for AGT-1500 atomizer spraying calibration fluid at 27°C (80°F) for low flow (40 lbm/hr) and high flow (70 lbm/hr) ignition conditions, and idle condition.

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Figure A-3. Comparison of spray characteristics for fire-resistant fuel and diesel fuel at 32°C (90°F) for low-flow (40 lbm/hr) ignition condition.

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Figure A-4. Comparison of spray characteristics for fire-resistant fuel and diesel fuel at 32°C (90°F) for high-flow (70 lbm/hr) ignition condition.

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Figure A-5. Comparison of spray characteristics of fire-resistant fuel and diesel fuel at 32°C (90°F) for idle condition.
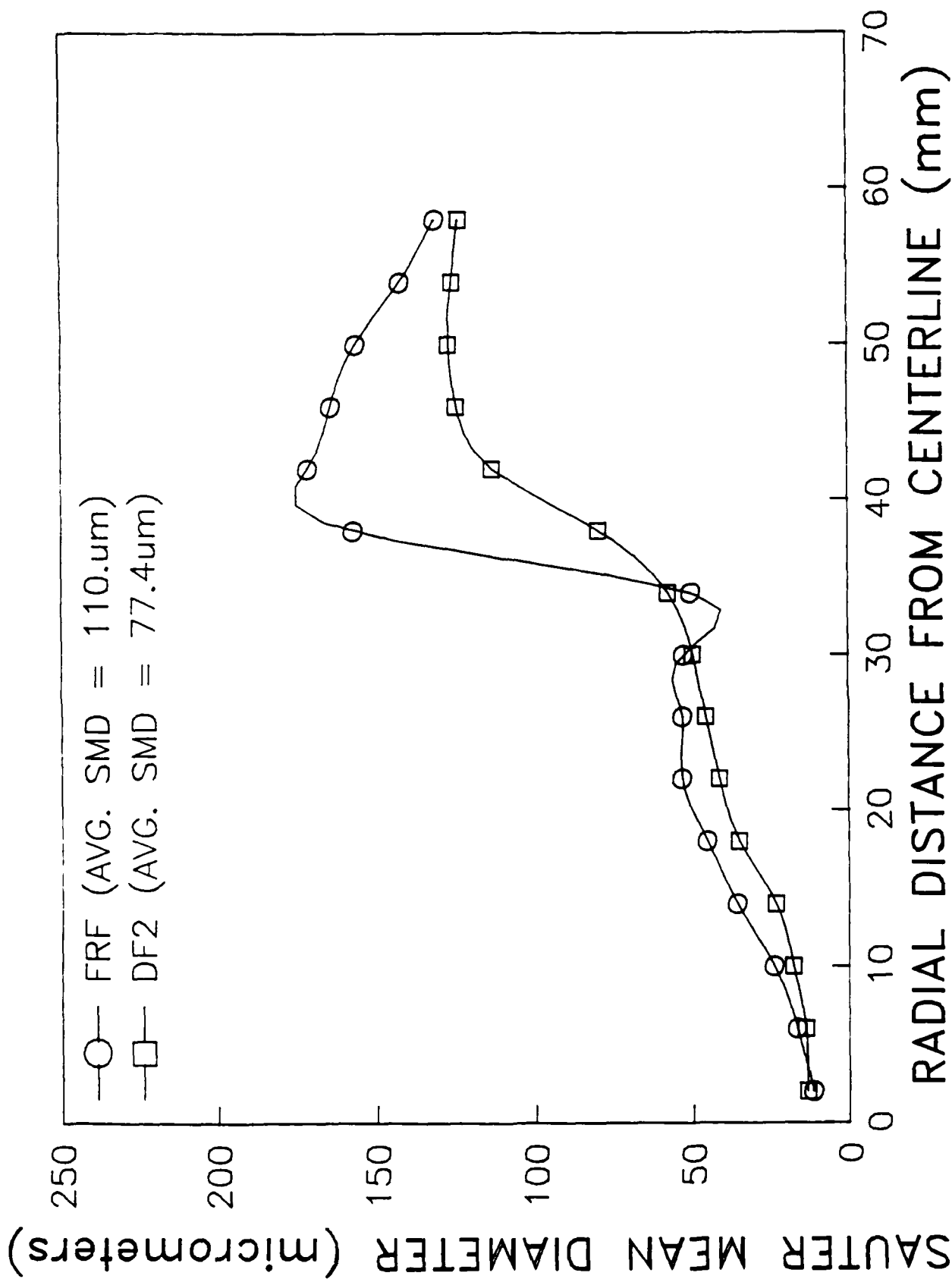
49

Figure A-6. Comparison of spray characteristics of fire-resistant fuel and diesel fuel at 4°C (40°KF) for low-flow (40 lbm/hr) ignition condition.

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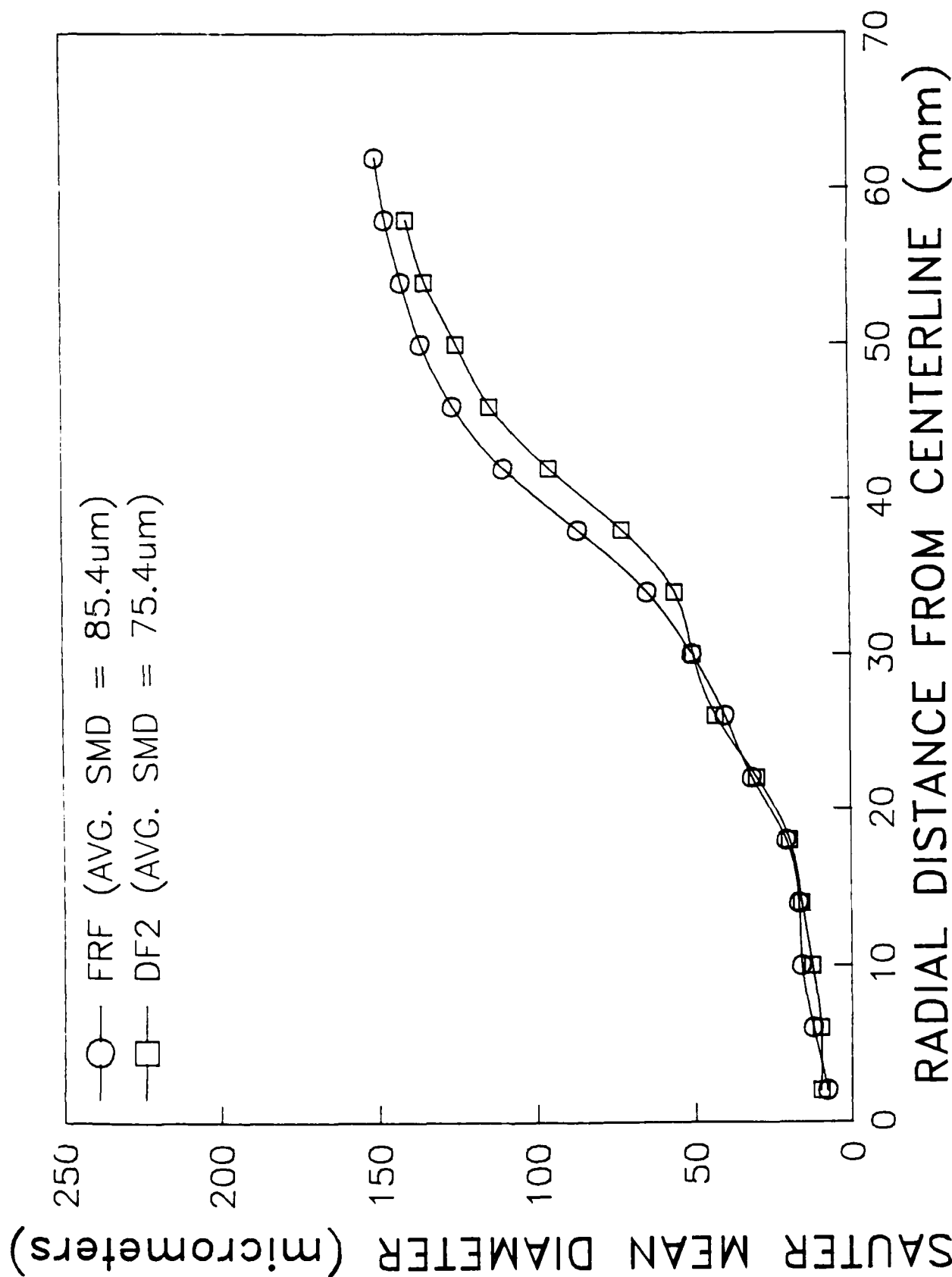Figure A-7. Comparison of spray characteristics of fire-resistant fuel and diesel fuel at 4°C (40°F) for high-flow (70 lbm/hr) ignition condition.

SAUTER MEAN DIAMETER (micrometers)

RADIAL DISTANCE FROM CENTERLINE (mm)

—O— FRF (AVG. SMD = 133.um)
—□— DF2 (AVG. SMD = 91.0um)
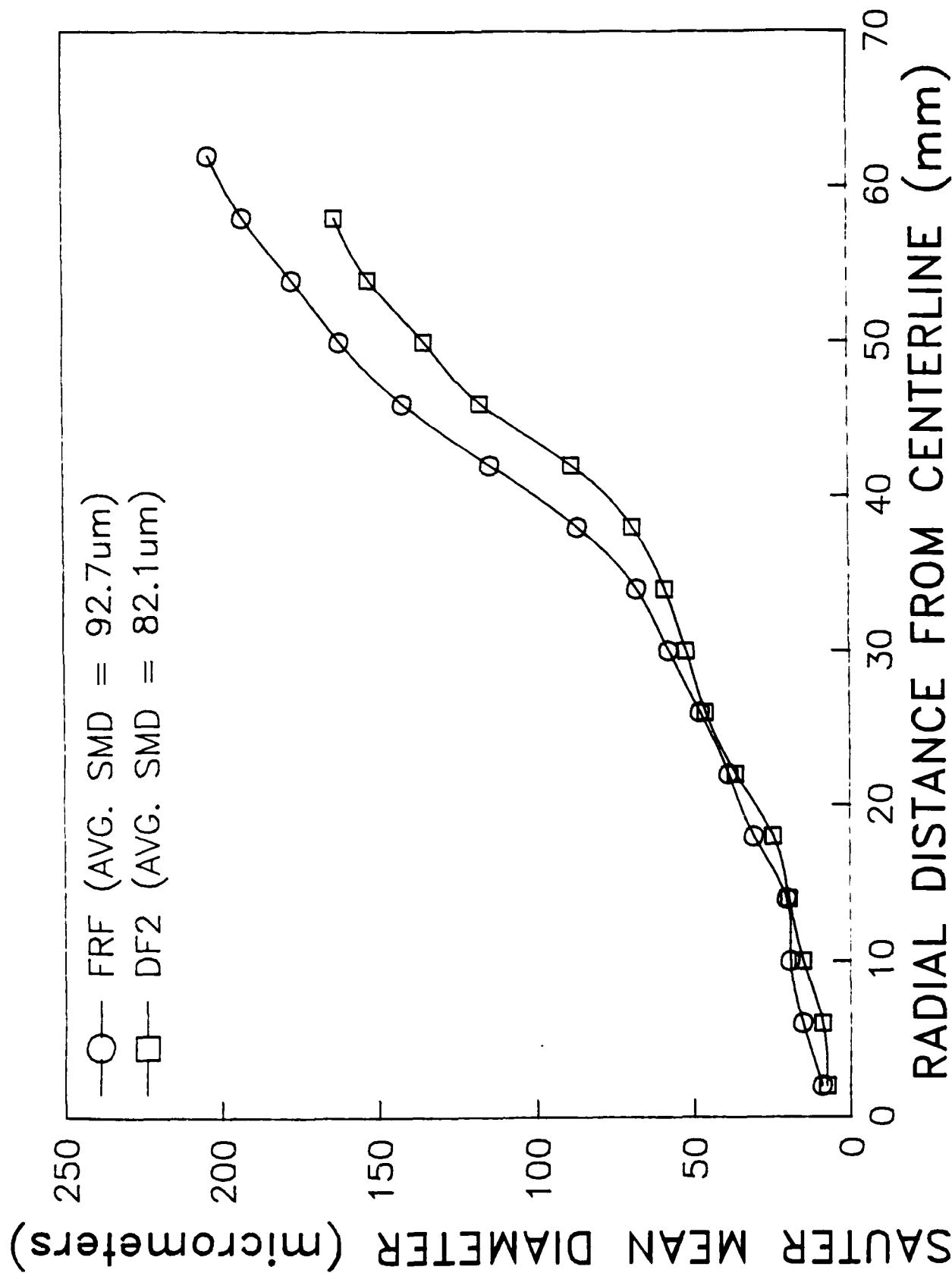
Figure A-8. Comparison of spray characteristics of fire-resistant fuel and diesel fuel at 4°C (40°F) for idle condition.

SAUTER MEAN DIAMETER (micrometers)
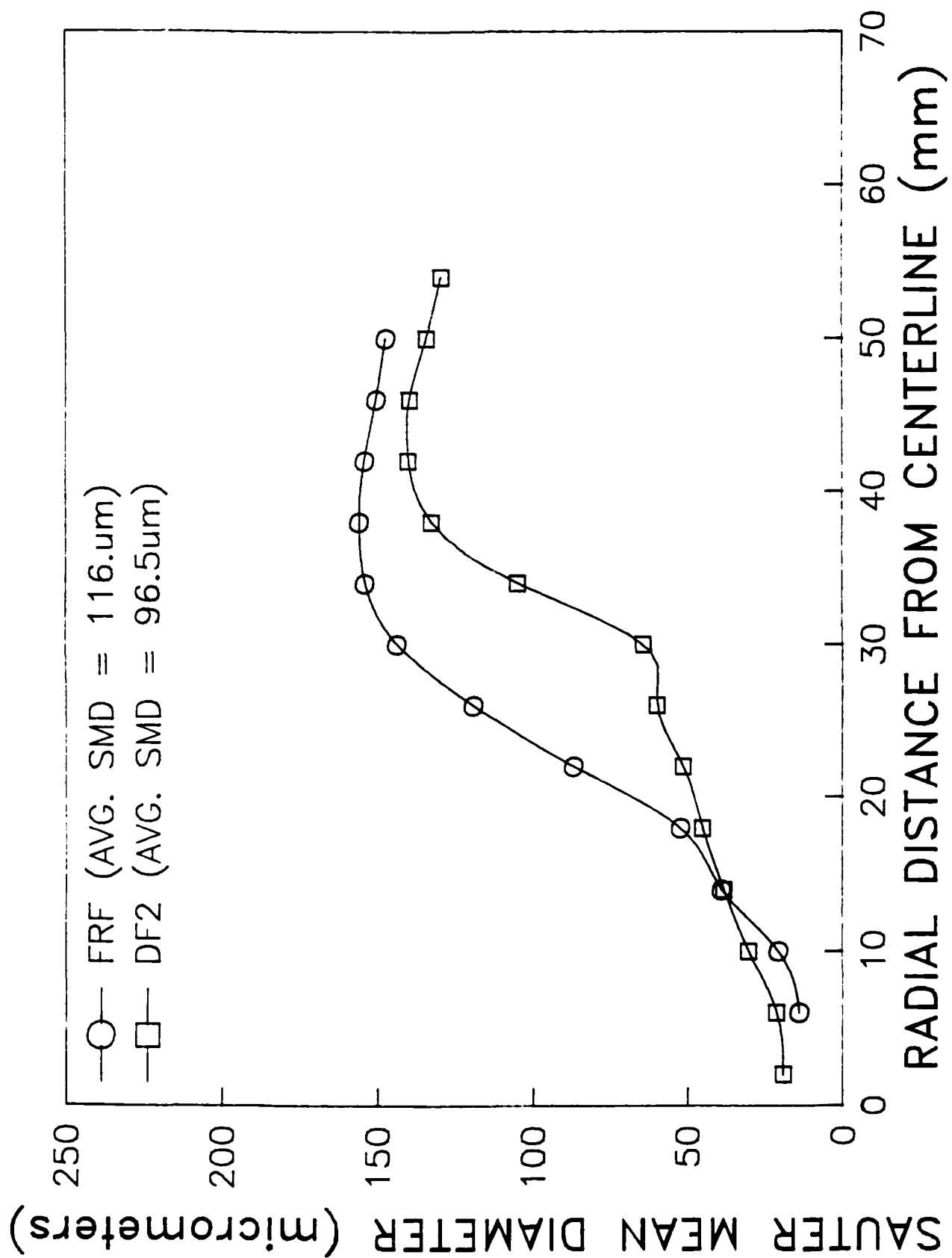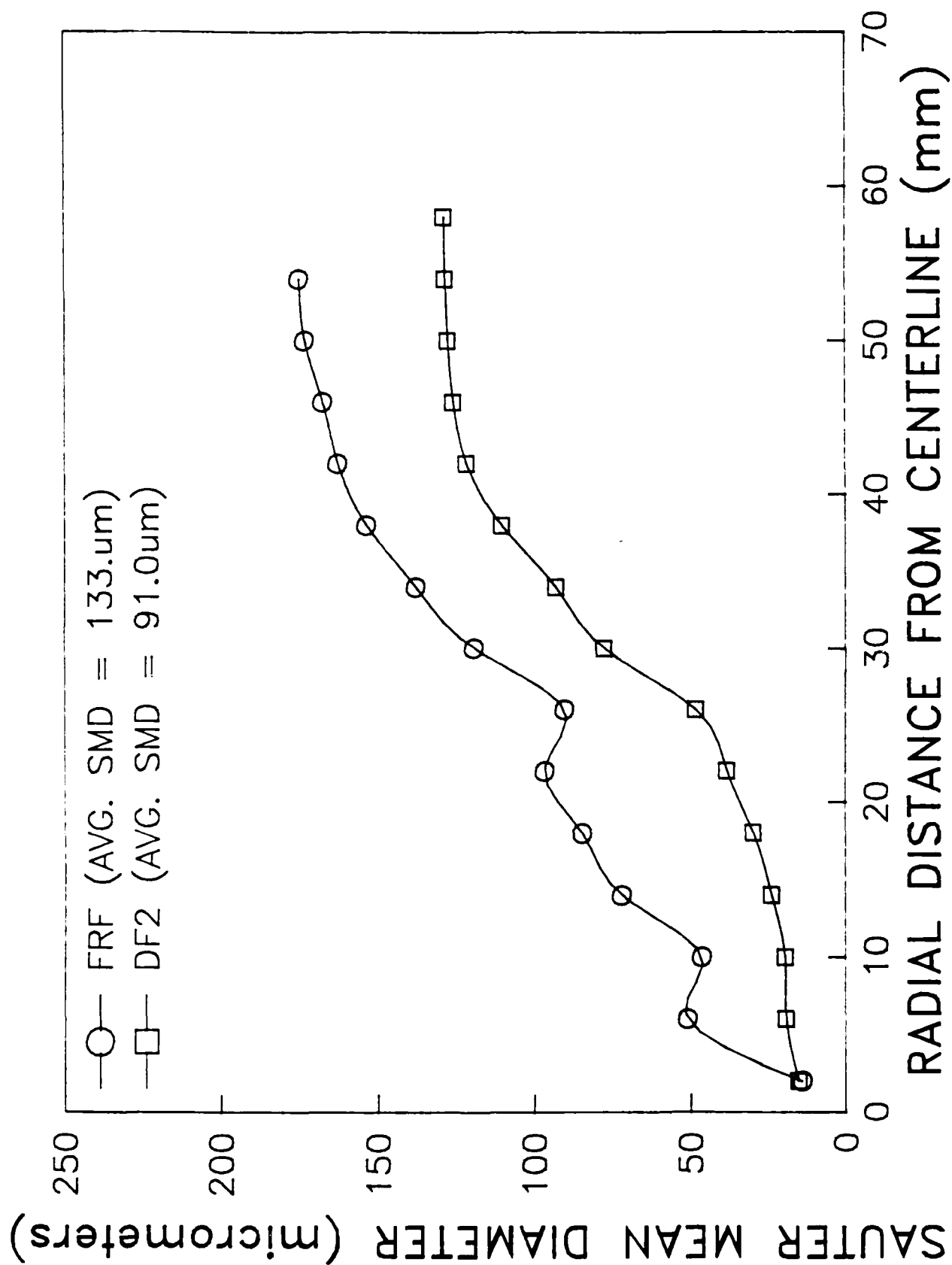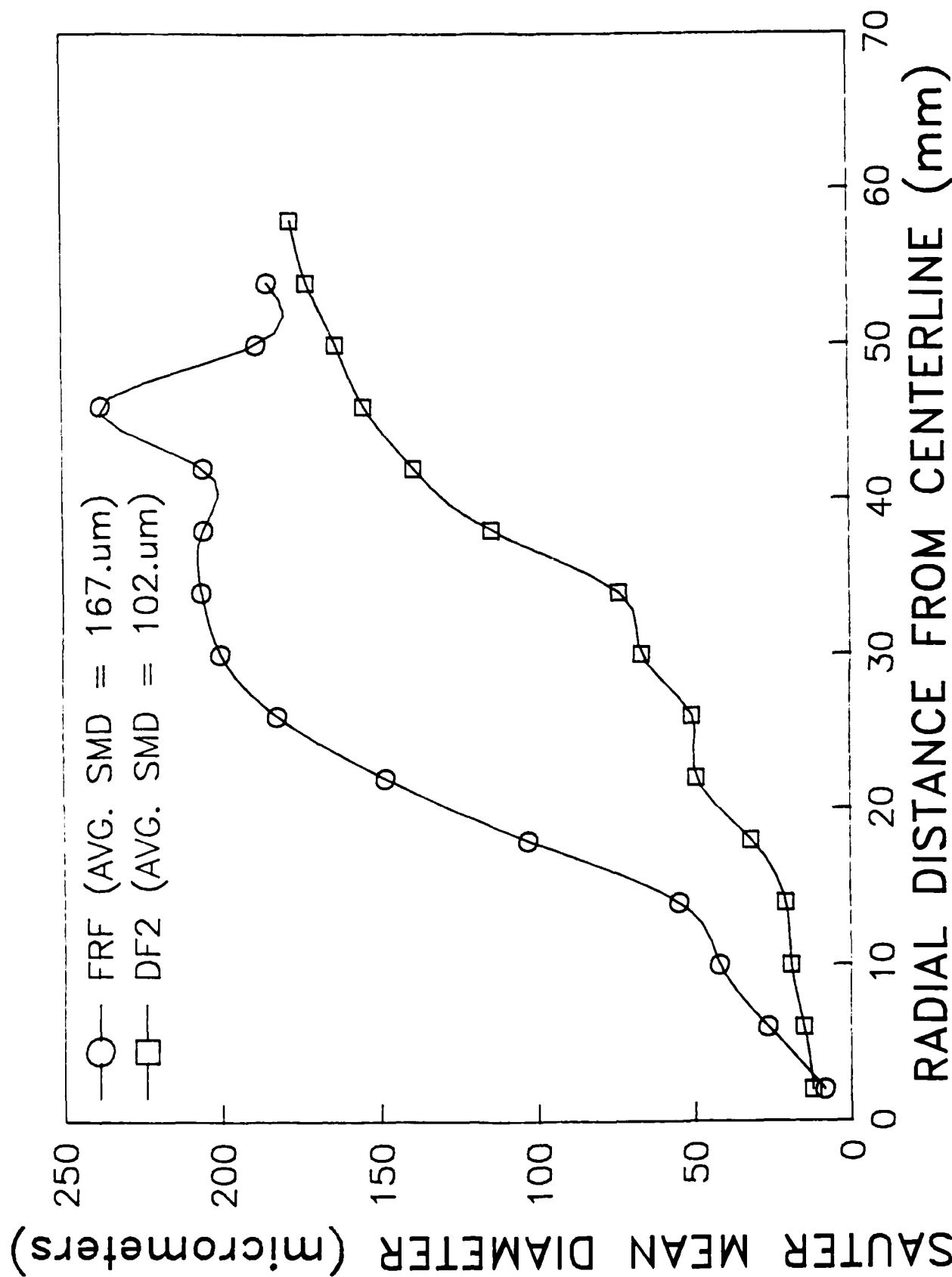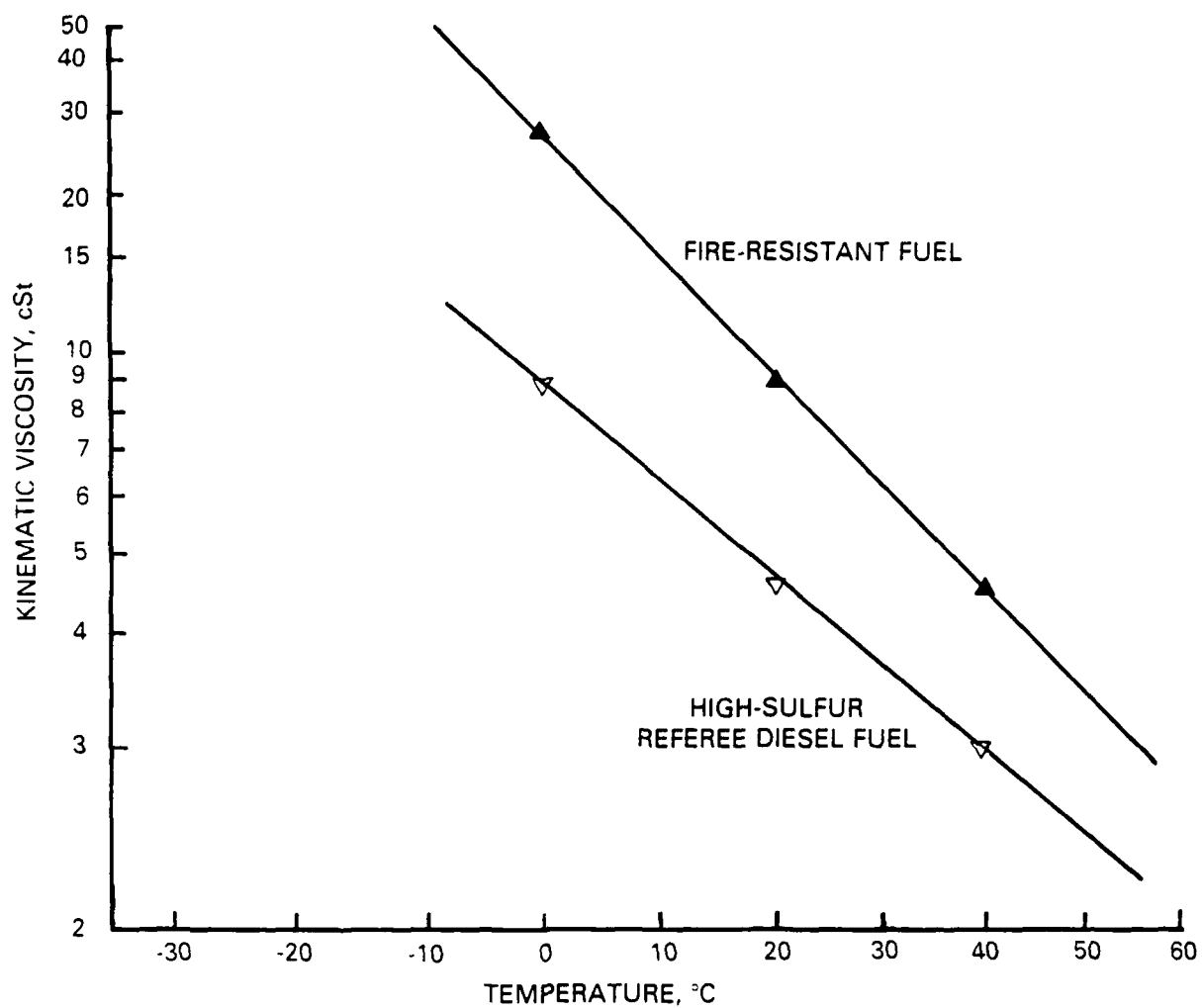
RADIAL DISTANCE FROM CENTERLINE (mm)

—O— FRF (AVG. SMD = 167.um)
—□— DF2 (AVG. SMD = 102.um)

Figure A-9. Viscosity as a function of temperature for fire-resistant fuel and diesel fuel.

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