EVALUATION OF POL MATERIALS AS FOG-PRODUCING AGENTS

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The lack of adequate smoke with JP-8 in the Vehicle Engine Exhaust Smoke System (VEESS) is detrimental to the effective use of JP-8 as the single battlefield fuel. The VEESS is considered a force multiplier and is very critical in armor strategies. Adaptation of an auxiliary tank containing a POL product that provides adequate smoke is a possible solution. Efforts of this study centered on quantifying the obscuration and persistency of smoke produced by POL products. By quantifying the smoke, POL products could be identified that provided DF-2 smoke levels in VEESS simulators. Several candidates that provided adequate smoke included lightweight and multiviscosity engine lubricating oils. All POL products were examined in a diesel VEESS screener that was developed to emulate actual VEESS parameters.

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EXECUTIVE SUMMARY

Problems and Objectives: The switch to JP-8 as the fuel for the one-fuel-forward concept has rendered the vehicle engine exhaust smoke systems (VEESS) ineffective as a force multiplier. As a solution, an auxiliary tank containing a suitable Petroleum, Oil, Lubricant (POL) product for producing 10 minutes of smoke is being considered. The objective of this program was to determine which POL products could produce smoke comparative to DF-2 in both obscuration and persistency.

Importance of Project: The lack of adequate VEESS performance with JP-8 is the major detriment of using JP-8 as the single battlefield fuel. In order to restore the VEESS as a force multiplier with JP-8, it is imperative that POL products be screened for use in a VEESS environment.

Technical Approach: Two VEESS simulators were developed to screen the POL products. A single-cylinder simulator was operated in controlled conditions, with a photocell array to measure relative obscuration and persistency values of candidate fogging fluids. A multicylinder simulator was used to confirm the earlier readings of POL products in a diesel VEESS environment.

Accomplishments: Several POL candidates were identified that exceeded DF-2 performance in the VEESS simulators. These products included the light lubricating and multiviscosity oils. The heavier lubricating oils appeared to require a higher temperature for vaporization than is available in a typical VEESS. Another result showed that blending POL products with JP-8 would reduce the obscuration values as a direct function of the amount of JP-8 present.

Military Impact: With the vehicle operating on JP-8, the installation of an auxiliary tank containing a POL product currently available in armor motor pools will effectively restore the VEESS as a force multiplier.

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TABLE OF CONTENTS

Section		Page
I.	INTRODUCTION	1
II.	BACKGROUND	1
III.	APPROACH	2
	A. VEESS Field Observations	2
	1. M1/M1A1	3
	2. M2/M3	4
	3. M88/M60	5
	B. VEESS System Inspections	6
	1. M2/M3 Bradley VEESS	6
	2. M1/M1A1 Turbine VEESS Configurations	6
	3. M60/M88	7
	4. M113	8
	C. Laboratory VEESS Screeners	8
	D. Data Acquisition	8
	1. Single-Cylinder VEESS	10
	2. Multicylinder VEESS	16
IV.	DISCUSSION OF RESULTS	18
	A. Single-Cylinder VEESS Simulator	18
	1. Obscuration	18
	2. Persistency	21
	B. Multicylinder VEESS Screener Device	26
	C. Simulator Comparisons	26
V.	CONCLUSIONS AND RECOMMENDATIONS	29
VI.	LIST OF REFERENCES	30

LIST OF ILLUSTRATIONS

Figure		Page
1	Schematic of Smoke Evaluation Device	9
2	Typical Temperature Profile of Reactor During Fluid Injection	12
3	Typical Photocell Response to Smoke Formed in Reactor	13
4	Typical Plot of Decay Rate of a POL Material Illustrating Persistency	14
5	Comparative Decay Rates of Two POL Materials Illustrating Persistency	15
6	Multicylinder VEESS Fuel/POL On-Line Blending System	17
7	Sample Data Sheet for Multicylinder VEESS Screener Device Operation	28

LIST OF TABLES

Table		Page
1	M1/M1A1 Exhaust Temperature Measurements at VEESS Nozzle Location	3
2	M2/M3 Exhaust Temperature Measurements at Exhaust Outlet	4
3	M88/M60 Exhaust Temperature Measurements at Exhaust Outlet	5
4	Annual Packaged Lube Requirements for Mechanized Infantry Division (197th Inf Div as Source)	19
5	Identification of Screened POL Products	20
6	Obscuration of Smoke Produced by Various POL Materials Using Single-Cylinder Screening Device	21
7	Ranking of POL Products as a Function of Center of Area of the Persistency Curves	24
8	Comparing Ranking of POL Products Persistency With Obscuration Values	25
9	Multicylinder VEESS Screener Test Results	27
10	Test Points of Engine Test Conditions	28

I. INTRODUCTION

Recent decisions within the Department of Defense that all land-based air and ground equipment will be operated on F-34 (JP-8) instead of F-54 (DF-2) have caused a severe problem to surface. The U.S. Navy will continue use of JP-5 fuel for carrier-based aircraft. This problem is related to the smoke (fog)-producing requirement as it currently is prescribed under both offensive and defensive battlefield scenarios. Essentially all armored ground equipment is equipped with a vehicle engine exhaust smoke system (VEESS) that is used to produce smoke by injection of fuel from the main fuel system into a section of the heated exhaust. Basically, the principle of operation of the VEESS is evaporation of the liquid fuel, and then condensation of the fuel droplets outside of the exhaust system into a visible light-obscuring fog. Requirements of an effective fog in this program are that it obscures in the visible light range and persists for some period of time without evaporating or settling out due to condensation into large droplets. Several factors affect the ability of JP-8 to produce a satisfactory smoke, perhaps the most important is to maximize the time for which the fuel droplets will evaporate after the obscuring fog is produced, thus providing a smoke with adequate persistency.

II. BACKGROUND

The results of early work (1-4) done at Chemical Research, Development and Engineering Center (CRDEC) and Belvoir Research, Development and Engineering Center (Belvoir) have indicated that JP-8 would not produce effective smoke in the VEESS.

Decisions were made that prescribed the installation of an auxiliary tank that would contain smoke-producing agents. This tank would have a volume of approximately 10 gallons/10 minutes of smoke production and may be filled with liquids typically found in combat equipment motor pools. Screening of these Petroleum, Oil, Lubricants (POL) materials would need to be conducted in order to determine the most effective smoke-producing agents. Plans included the evaluation of blends of these fluids with JP-8 in order to allow longer smoke-producing time than 10 minutes. Therefore, the scope of this program was to determine POL products already available in the field that could be

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

placed in the auxiliary tank and would produce acceptable smoke for approximately 10 minutes.

III. APPROACH

A number of factors are involved with fog production, and evaluation and optimization of those factors were addressed. POL materials commonly found in motor pools were evaluated as substitute fog-generating material. This program was accomplished in the following phases. The first phase includes development of laboratory screening devices to evaluate candidate replacement materials for JP-8 in the VEESS of the various Army systems. These candidates will be POL products, additives, or materials mixed with fuel. Current VEESS system parameters, including atomization pressures, delivery rates, evaporation temperatures, and dilution ratios from the M1, M2/M3, M60 will provide guidance for development of these laboratory screening devices and the basic studies discussed below. Much of this information was provided by the Ordnance School, and additional information was obtained from preliminary field screening tests at Ft. Bliss, TX. Successful candidate POL products or system modifications will be validated in actual field vehicle systems found in armored combat equipment.

A. VEESS Field Observations

Two field trips (5,6) were made in conjunction with the JP-8 fuel consumption and performance testing to obtain first-hand knowledge of VEESS operational differences between DF-2 and JP-8. A matrix of test conditions was initially compiled to obtain a vehicle record of VEESS operation. The conditions included static fogging at tactical idle and maximum engine speed, steady-state fogging at road load speeds, and fogging during full-throttle acceleration. Unfortunately, the conditions existing on the tank trails eliminated any visual data from being recorded during the steady-state and acceleration runs due to the copious quantities of dirt and dust thrown into the air by the vehicle tracks. The dirt and dust appeared indistinguishable from fog on the video record.

1. M1/M1A1

In addition to the VEESS observations, a thermocouple was inserted in the exhaust duct such that it was coaxial with one of the VEESS nozzles. The exhaust temperatures for the M1A1 at road speeds of 20 and 30 mph (37 and 56 km/hr) are shown in TABLE 1.

TABLE 1. M1/M1A1 Exhaust Temperature Measurements at VEESS Nozzle Location

Speed, mph (km/hr)	Fuel	Exhaust Temperature, °F (°C)
20 (37)	DF-2	877 (469)
20 (37)	JP-8	876 (469)
30 (56)	DF-2	925 (496)
30 (56)	JP-8	929 (498)

At tactical idle, approximately 1250 rpm, static positioning with DF-2, fluffy, billowy clouds of fog appeared to condense upon exiting the exhaust grates. The cloud persisted for several hundred yards until it was dissipated by the prevailing winds. Under the same condition with JP-8, the observer was unsure the VEESS system was operational until the JP-8 could actually be smelled in the air. There was no evidence of any condensation of the vaporized JP-8.

At maximum engine speed, actually a condition with the governor surging between 2400 and 3100 rpm, static positioning with DF-2, voluminous clouds of fog condensed at a position approximately 2 to 4 feet (0.6 to 1.2 meters) upon exiting the exhaust grates. The cloud persisted for a significantly greater distance than at tactical idle, and actually rose 30 to 40 feet (9 to 12 meters) above the ground before being dissipated by the winds. At the same operational condition with JP-8, the observers noted only a slight mist, which had no obscurant value, emanating from the exhaust ducts. It was felt that mist resulted at the higher engine speed and not at tactical idle because of reduced residence time of the JP-8 in the exhaust duct. The quantity of VEESS effluent is fixed for all engine speeds, and the exhaust temperature is relatively constant for the "no load" conditions. However, the mass flow of air, and thus its velocity through the exhaust duct, changes as a function of engine speed. Therefore, the JP-8 vapor has less residence time in the exhaust duct, and the degree of superheat is decreased, creating a light visible mist.

2. M2/M3

For the M3 Bradley fighting vehicle, the exhaust temperatures were taken at the outlet of the exhaust stack, a significant distance downstream from the point of VEESS introduction. The exhaust temperatures for the Bradley vehicle at road speeds of 20 and 30 mph are shown in TABLE 2. Dynamometer data for a VTA-903T show that the temperature at the point of VEESS introduction would be 200° to 400°F higher.

TABLE 2. M2/M3 Exhaust Temperature Measurements at Exhaust Outlet

Speed, mph (km/hr)	Fuel	Exhaust Temperature, °F (°C)
20 (37)	DF-2	594 (312)
20 (37)	JP-8	605 (318)
30 (56)	DF-2	624 (329)
30 (56)	JP-8	657 (347)

At fast idle, transmission in park, static positioning with DF-2, clouds of white fog rose into the sky, and persisted for several hundred yards. With JP-8, there was no sign of vapor condensation, and a strong smell of JP-8 was evident.

At maximum governed speed, transmission in park, and static positioning with DF-2, billowy clouds of fog condensed upon exiting the exhaust stack. The fog persisted for a significantly longer distance than at fast idle, and appeared to be projected into the air rather than lying along the ground. It should be noted that with both DF-2 runs when the smoke generator was turned off, fog continued to be produced for several minutes. With the use of JP-8 and the vehicle at maximum engine speed, no fog condensed from the JP-8 vapors.

3. M88/M60

The M88 and M60 have identical VEESS arrangements. Unfortunately the smoke generator in the M60 tested was inoperable. The exhaust temperatures at the exhaust pipe flapper were acquired for both vehicles, and are shown in TABLE 3. The differences in the exhaust temperatures between the M88 and M60 can be attributed to the M88 being underpowered. Thus, to achieve the same vehicle speed, more energy must be consumed, which results in an increase in exhaust temperatures.

TABLE 3. M88/M60 Exhaust Temperature Measurements at Exhaust Outlet

Vehicle	Speed, mph (km/hr)	Fuel	Exhaust Temperature, °F (°C)
M88A1	15 (28)	DF-2	920 (493)
M88A1	15 (28)	JP-8	1067 (575)
M88A1	25 (46)	DF-2	1046 (563)
M88A1	25 (46)	JP-8	1001 (538)
M60	15 (28)	DF-2	513 (267)
M60	15 (28)	JP-8	574 (301)
M60	20 (37)	DF-2	620 (327)
M60	20 (37)	JP-8	632 (333)

The initial fogging with DF-2 in the M88 vehicle was run at an engine speed of 1250 rpm. The fog condensed upon exiting the exhaust grates, and persisted for several hundred yards before dissipating. At the same condition with JP-8, no visible fog resulted.

The VEESS was also actuated at the maximum engine speed of 2350 rpm with DF-2 and JP-8. The DF-2 formed a large cloud of fog, which condensed 2 to 4 feet (0.6 to 1.2 meters) beyond the exhaust grates. The fog persisted for an extensive distance before dissipating in the prevailing winds. Once again, no fog formation was evident with JP-8 during the VEESS operation with the M88. It is expected the results would have been the same for the M60 had the VEESS been operational.

B. VEESS System Inspections

In order to evaluate the POL materials, it was necessary to develop screening devices since no aerosol formation devices were available for screening purposes. The initial plans outlined an approach that would develop devices to simulate the VEESS as close as possible.(7) Visits were made to the U.S. Army Ordnance School at Aberdeen Proving Ground, MD to obtain engineering data on the VEESS systems of the M1, M60, M88, M2/M3 and the M113 personnel carrier. The results of these investigations are summarized below.

1. M2/M3 Bradley VEESS

The M2/M3 Bradley vehicle is powered by the Cummins VTA-903T engine. The VEESS gets fuel from the unregulated high-pressure (300 psig at 2600 rpm) side of the P-T fuel system gear pump. The fuel flows through a 0.25-inch (6.35-mm) flexible line to a solenoid valve. The solenoid valve is controlled by a switch on the driver's instrument panel. The operations manual states the smoke generator should not be used unless the engine is warm [173° to 186°F (78° to 86°C)] water temperature and the engine speed is above idle (775 to 825 rpm). The fuel line from the solenoid routes to an adaptor that sprays fuel through a 0.125-inch (3.175-mm) orifice into the exhaust system, 8.5 inches (21.6 cm) downstream from the exhaust turbine. The exhaust system is a 5-inch (12.7-cm) diameter tubing, and is routed horizontally for 27 inches (68.6 cm) to a muffler; then turns 90 degrees and is routed 21 inches (53.3 cm) vertically before it is exhausted to the atmosphere. The VEESS uses 0.333 gallons/minute (1.26 liters/minute) of fuel, and the operation manual denotes that smoke continues 2 to 3 minutes after the smoke generator has been turned off.

2. M1/M1A1 Turbine VEESS Configurations

The M1/M1A1 Abrams main battle tank uses the Avco-Lycoming AGT-1500 gas turbine engine. The VEESS has an automotive-type electric fuel pump that draws fuel from a tank in the left rear portion of the hull. The fuel pump is configured so it cannot be turned on when the engine is not running or during the starting sequence. The operations manual states the minimum engine speed for smoke is 1250 rpm. The fuel flows from the pump through a 0.5-inch (12.7-mm) hose to a check valve, then is routed through 0.5-inch stainless steel tubing. The 0.5-inch tubing tees off into two 0.375-inch (9.5-mm) tubes, which routes to two nozzles 13 inches (33 cm) apart in the exhaust duct. The nozzles are swirl-type spray nozzles located 9 inches (22.9 cm) from the exit of the exhaust duct, and are angled to point upstream against the exhaust flow. The exhaust duct is attached to the engine at the recuperator, and is routed over the transmission for a total length of approximately 6 feet (1.8 meters). The VEESS fuel pump supplies the nozzles with 60 psig fuel at a flow rate of 1.3 gallons/minute (4.9 liters/minute).

3. M60/M88

The M60 main battle tank and M88 armored recovery vehicle are powered by the Teledyne Continental AVDS-1790-2C. The VEESS gets fuel from the fuel/water separator, which is supplied by the engine-driven fuel transfer pump. The fuel pressure at the fuel/water separator is between 55 and 60 psi. From the separator, the fuel flows through 0.375-inch (9.52-mm) OD tubing along the left bank (from front) of the engine. At the end of the bank of cylinders, the tubing makes a 90-degree bend towards the center of the vee, at which point, it attaches to dual in-series solenoids. Apparently both solenoids must be functional for the VEESS to operate. The solenoids are controlled by a switch on the driver's instrument panel. The operations manual states that the smoke generator should not be used unless the engine is warm and the engine speed is at least 1600 rpm. The fuel line from the solenoids tees into two 0.25-inch (6.35-mm) OD lines, which route to the turbocharger on each bank. The turbochargers have dual scroll turbines, each of which is attached by 2-inch (5.08-cm) exhaust pipe to a three-cylinder manifold. The fuel enters the exhaust in front of the exhaust diffuser associated with one of the turbine scrolls. The exhaust temperature at that point is approximately 1250°F (677°C). Since there is no nozzle on the VEESS line, the 0.25-inch (6.35-mm) OD tube dumps directly into the exhaust stream. The outlet of the exhaust turbine is a 4.5-inch (11.4-cm) exhaust pipe, which routes for approximately 40 inches (101.6 cm) before exhausting to the atmosphere behind the exhaust grates. Although there are no published values for VEESS flow, it is expected to fall within the ranges defined by the M2/M3 and the M1/M1A1.

4. M113

The M113 armored personnel carrier does not have a VEESS. Instead, it relies on the use of smoke grenades for protective cover.

C. Laboratory VEESS Screeners

A single-cylinder and a multicylinder engine were used for initial screening of POL materials for obscurance and persistency.

A single-cylinder spark-ignition engine screening device was developed for the Fog Oil Replacement program.(8) Since reasonably good correlation was obtained with results from field tests using the M3A4 smoke generator, this device was used as a quick, inexpensive obscurance/persistency screening tool for POL/candidate materials. In addition to the obscurance, the persistency of the produced fog was to be evaluated using a modified smoke chamber. This chamber consists of a series of multilevel sensors designed to evaluate fog stability (Fig. 1).

A second screening device was built using a 45-kW generator set (PU-703/G) with a DDA 3-71 engine and a load bank to allow engine loading. The exhaust system was modified as required to accept test fluids to be evaluated as smoke-forming agents and thermocouples as needed. Some advantages of this system are listed below:

1. Provides diesel exhaust that may be important as nucleation sites.
2. Allows system variations that may more closely simulate the actual VEESS system.
3. Should be easily adaptable to simulate most (or all) diesel-powered VEESS systems.

D. Data Acquisition

The two primary characteristics of smoke that were evaluated can be described as the obscuration and stability or persistency of the produced cloud of fog. Since each of these characteristics is different, and yet each is important, different test procedures were developed to allow separate evaluations.

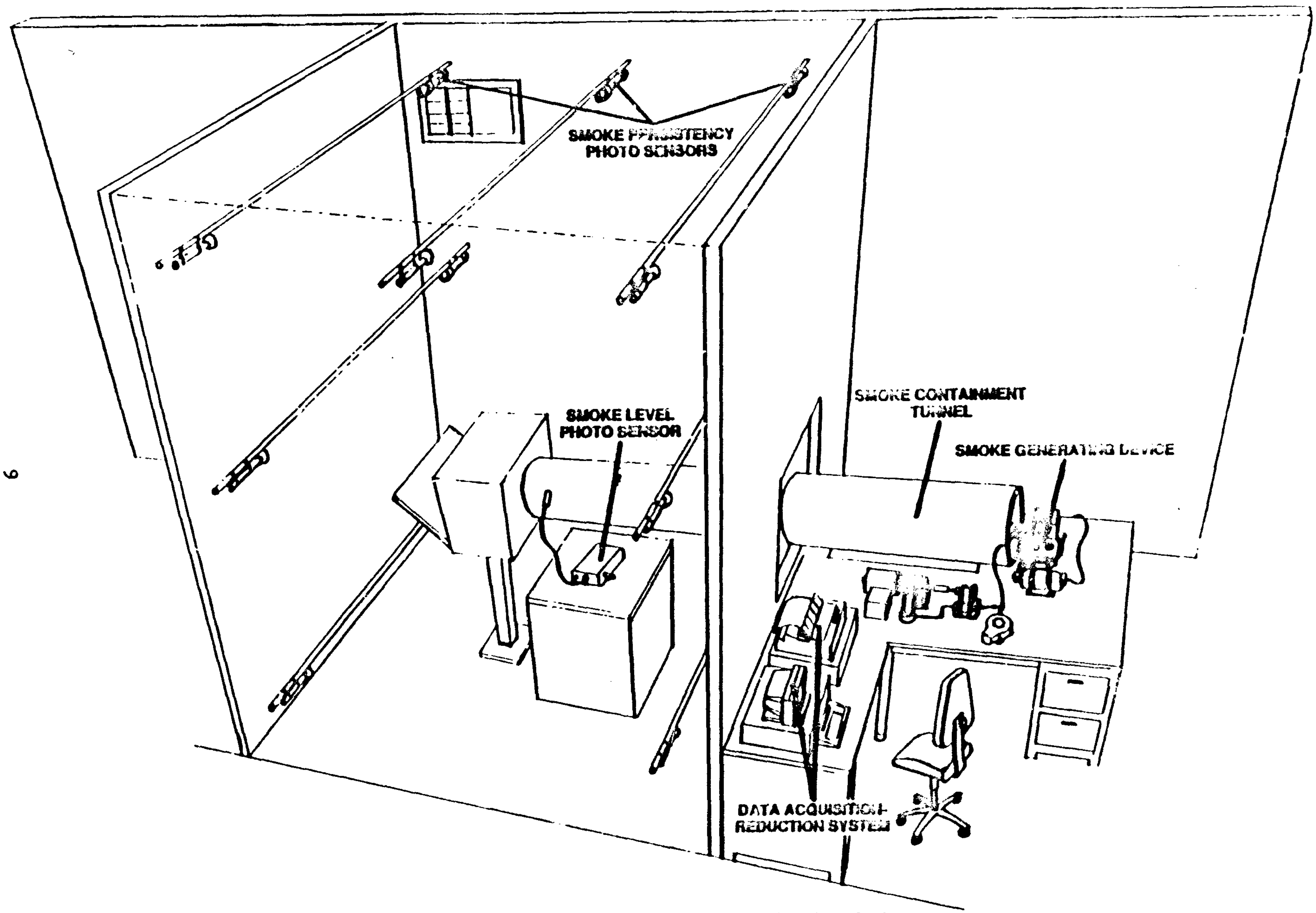

Figure 1. Schematic of smoke evaluation device

1. Single-Cylinder VEESS

A single-cylinder engine was used as a smoke generator for screening fogging agents. The engine was operated at a fixed speed and load to obtain an exhaust temperature of 1050°F (566°C). When the required exhaust temperature was reached, the candidate fogging agent was introduced into the exhaust manifold at a constant feed rate of 6 mL/min. The exhaust pipe was centrally located in a 10-feet (3.04-m) long by 14-inch (35.6-cm) diameter dilution tunnel, where the flow was regulated to provide streamlines at a velocity of 450 feet/minute (137 m/minute). At the end of the dilution tunnel, a photocell was placed to measure the obscurance of the smoke generated. The smoke exits the dilution tunnel into an 8 ft X 9 ft X 6 ft (2.4 m X 2.7 m X 1.8 m) room, lined with an array of seven photocells for measuring persistency.

A data acquisition system was used to monitor the operating parameters of the single-cylinder VEESS, and to monitor the photocells for obscuration and persistency measurements. A series of temperature and voltage measurements were acquired using a commercial data acquisition/control system. The control system has an A/D converter, multiplexer, voltmeter, and IEEE 488 interface in a single unit. The system was controlled and logged by a PC-AT personal computer with 1 Mbyte of random access memory, a 40-Mbyte hard disk, a 1.2-Mbyte floppy disk, a 360-Kbyte floppy disk, an MS-DOS operating system, and an IEEE 488 interface and interface driver. The interface driver is controlled by a program that outputs the acquired data directly into a spreadsheet format. Through the spreadsheet, the raw data can be converted to engineering data and manipulated for plotting, printing, and storage.

An array of eight photocells was used for measuring persistency and obscuration with the VEESS simulator, as shown in Fig. 1. This particular photronic cell was selected for use in the fog oil test chamber because of its special optical properties. A yellow-green glass filter allows the photocell to respond to the same light spectrum as the human eye. A gray plastic mesh acts as a filter to attenuate light so as not to overload the photocell.

Since the photocell is a current device, it should be connected to a low impedance load. An operational amplifier is used as a current to voltage converter that supplies an output voltage proportional to the light falling upon the photocell. Additional features of the amplifier allow for gain and zero adjustments as required to match the input of the data acquisition system. Photocells 1 through 7 were used for measuring persistency and were arranged around the 432-cubic feet room. Photocell 8 was used to measure obscuration and was placed approximately 1 foot (0.3 m) from the exit of the dilution tube.

For both the obscuration and persistency, the opacity measurements were based on Lambert's Law. Lambert's Law is as follows:

$$I = I_o \exp^{-kX}$$

I = intensity of light transmitted

I_o = original intensity of light source

k = extinction coefficient

X = optical path

For the experiments with the fogging agents, the I_o was fixed at 65 foot-candles, and the length X of the optical path was kept constant. The percent opacity measurements were based on the formula:

$$\text{Opacity, \%} = (1 - I/I_o) \times 100$$

a. Obscuration

For the obscuration measurements, the VEESS simulator was operated at the conditions previously described, until the opacity reached a maximum value on Photocell 8. Because the operating conditions were held constant for each test, and the light source intensity and optical path length were held constant, the difference in obscuration performance between the candidate fogging compounds is due to the extinction coefficient of the smoke produced.

Obscuration can be described as the screening of the visible portion of the electromagnetic spectrum. In order to accomplish this screening, photocells were utilized that operated in the visible white light frequency range. Calibration of the photocells are accomplished using EPA filter numbers 000550 (10.5 percent), 000551 (23.2 percent), and

000552 (40.4 percent). This procedure was used on all the photo detectors in this program.

The procedure, as it was ultimately used, consisted of the introduction of the test fluid in a controlled, repeatable manner by a constant volume displacement pump. Flow rates were varied, initially to determine the optimum flow rate for the heat generated with the single-cylinder exhaust gas generator. If the fluid were pumped into the exhaust system faster than it could be vaporized, the fluid simply flowed out the end of the reactor, thus providing a false reading. Fig. 2 shows a typical response to the introduction of the fluid. The reactor was heated to approximately 1050°F (566°C) and, with the onset of injection, stabilized at approximately 900°F (482°C) for the duration of the injection cycle. The result of the injection of the fluid is then monitored on the

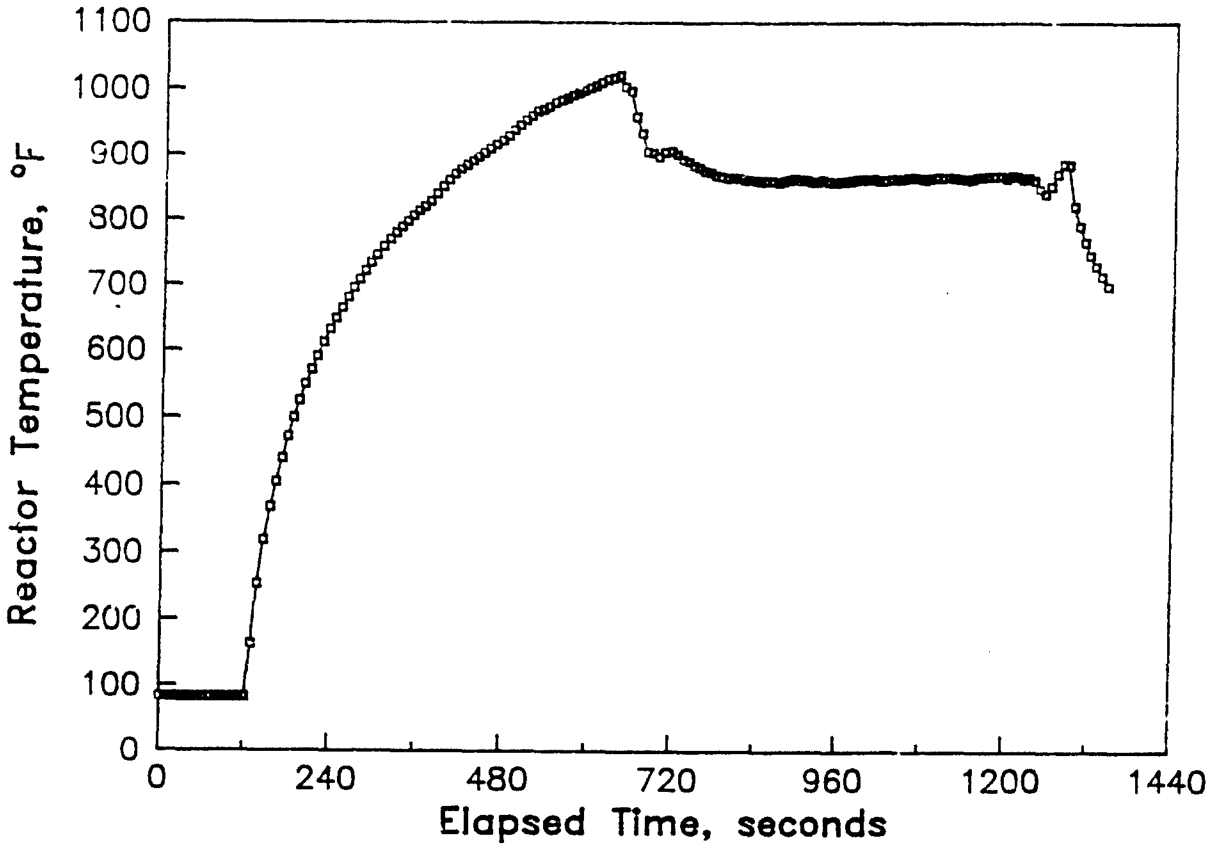

Figure 2. Typical temperature profile of reactor during fluid injection

photocell downstream from the engine. Fig. 3 shows a typical photocell response to the ongoing evaporation-condensation process. The important parameters of this process is that the reactor temperature remain constant (and in a range simulating the VEESS

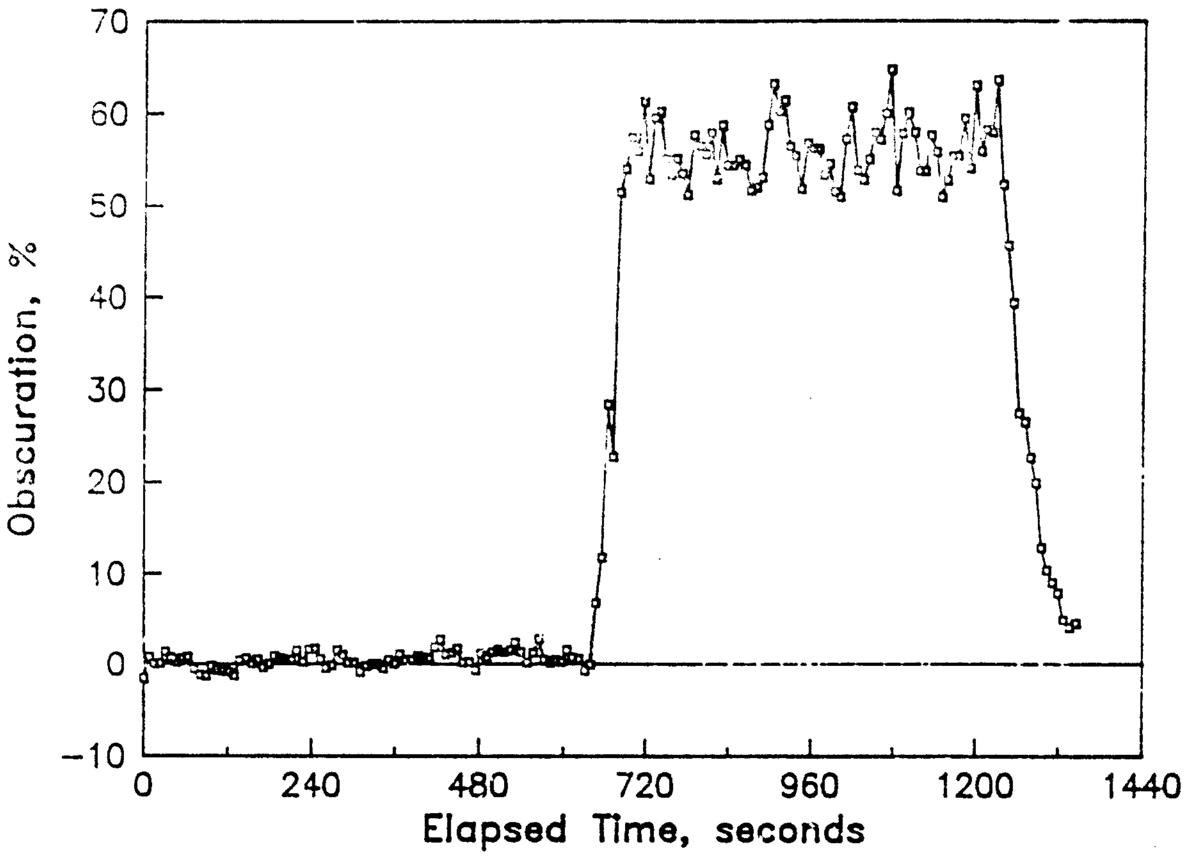

Figure 3. Typical photocell response to smoke formed in reactor

temperatures) and that the fluid flow rate remain constant. With these controlled parameters, the data obtained will be directly compared to the reference fluid (DF-2 in this case) on an equal volume basis. It is always possible that increased smoke levels could be achieved simply by increasing the fluid flow rate, using care not to exceed the amount of generated heat available within the system for evaporation purposes. As stated earlier, excess fluid will simply drip from the end of the reactor tube.

It should also be mentioned that heavier fluids such as SAE 30 or SAE 50 viscosity grade lubricating oils may not perform as well as lighter fluids such as SAE 5W or SAE 10W grade oils. The reason for this anomaly is that, due to the temperature limitations in the VEESS system, total evaporation may not occur in the heavier fluids. Therefore, on a volume per volume basis, the lighter oils may provide more obscuring smoke.

b. Persistency

The intended meaning of the term persistency as it relates to the smoke-forming process is the length of time the smoke remains together, providing the obscuring characteristics of freshly formed smoke. A number of factors are involved in this process, including volatility of the fluid, amount and composition of nucleating sites, temperature, humidity, and air velocity. Therefore, in order to compare fluids on an equal basis, factors other than fluid volatility were held constant in the facility shown in Fig. 1. Although it can be argued that this procedure is not a "real life" condition, it is felt these controls must be maintained in order to obtain a comparison between fluids that provide useful screening information. As shown in Fig. 1, the evaluation cell contains multilevel sensors that are identical to the obscuration procedure. Fig. 4 is a typical plot of the decay rate of one of the POL materials screened in this program. This figure shows that all the photocells recorded approximately the same rate of decay, and a sedimentation phenomenon does not seem to be taking place. As a result, it would seem

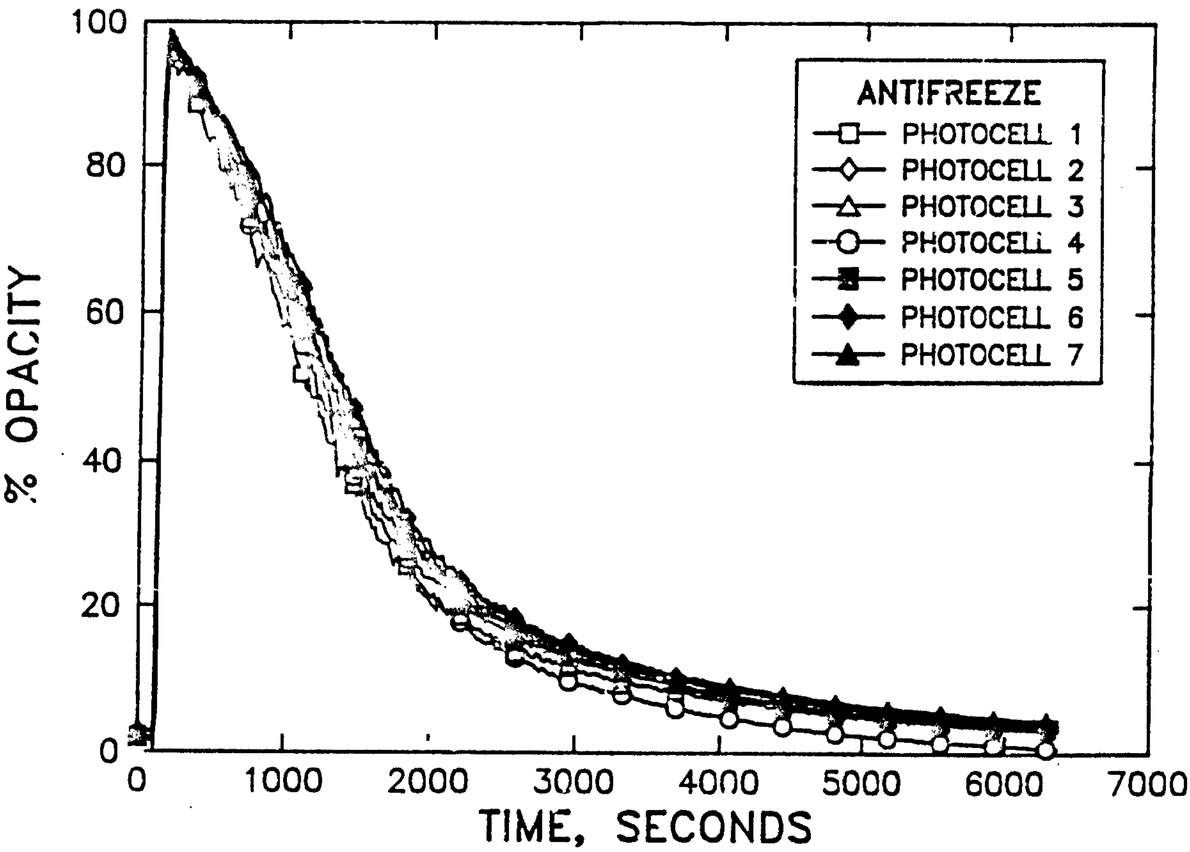

Figure 4. Typical plot of decay rate of a POL material illustrating persistency

that the dissipation is more directly related to evaporation than to sedimentation. Unfortunately, droplet-size distributions were not documented; therefore, it is not known if a monodispersed fog was produced. Fig. 5 illustrates the comparative decay rates of two of the POL materials.

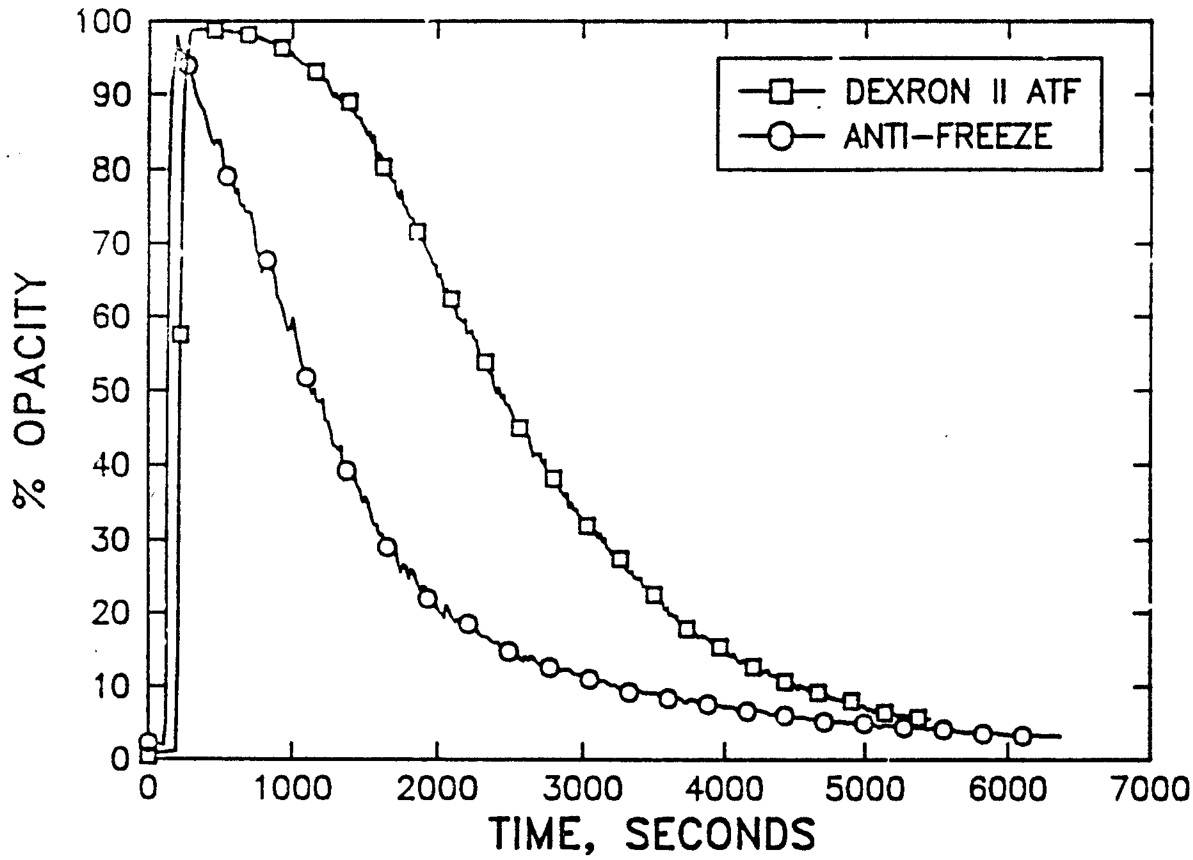

Figure 5. Comparative decay rates of two POL materials illustrating persistency

For the persistency measurements, the VEESS simulator was operated at the previously described conditions, until a maximum opacity was reached on photocells 1 through 7. At that point, the exhaust fan was turned off and shuttered, and all other vents in the room were closed. The persistency measurements taken were a function of the maximum opacity attained and the settling time of the fog produced. Basically the persistency measurement monitors the change in the extinction coefficient of the fog produced with time. A mathematical method was used to describe the persistency data in two numbers. These two numbers represent the center of area bounded by the curve of the persistency data between the maximum opacity and a predescribed lower limit. These values are calculated by numerical integration of the following formulas:

$$A = \int_{to}^{tn} O \ dt$$

$$H_t = \int_{to}^{tn} O^2/2 \ dt$$

$$H_o = \int_{to}^{tn} tO \ dt$$

$$t_c = H_o/A \qquad O_c = H_t/A$$

A = area bounded by persistency curve

O = opacity value at a given time t

dt = time step

H_t = static moment in relation to time axis

H_o = static moment in relation to opacity axis

t = discreet time t

tc = time coordinate of center of area

O_c = opacity coordinate of center of area

2. Multicylinder VEESS

The multicylinder screening device was developed to achieve the velocity, temperature, and dilution conditions as observed during the field inspections of diesel VEESS. The engine was a Detroit Diesel 3-71N mated to a generator, and packaged as a 45-kW military generator set. The generator set was loaded by a resistive load bank capable of dissipating 125 kW. The gain of the electro-hydraulic governor could be adjusted to allow the engine to be operated at speeds other than the synchronous speed of 1800 rpm.

The dilution ratio of exhaust to fogging agent for the multicylinder VEESS was calculated, based on relative engine size, from the known flows of VEESS and exhaust for the Bradley fighting vehicle. This value was calculated to be approximately 330 mL/min for the 45-kW generator set. The diesel VEESS inspected had some form of turbulence generator/heat sink after the point of fog agent introduction (i.e., turbocharger or muffler) into the exhaust stream. In order to compensate for turbulence, a swirl atomizer furnace nozzle was adapted to the 45-kW generator set. The swirl nozzle was modified to provide a maximum flow of 330 mL/min at an engine fuel transfer pump pressure of 40 psi.

The VEESS was plumbed with a three-way valve to draw from the on-board fuel tank (DF-2), or from a drum (JP-8). Also included in the plumbing was a rotameter and valve to monitor the flow of fuel to the nozzle. An on-line POL blending system was also included, which consisted of an electric pump, rotameter, and valve. This system was connected to the fuel line by a tee at the entrance to a static mixer. The output of the static mixer was connected to the swirl nozzle in the center of the exhaust pipe. Fig. 6 is a schematic of the fuel/POL blending system for smoke production with the multicylinder VEESS.

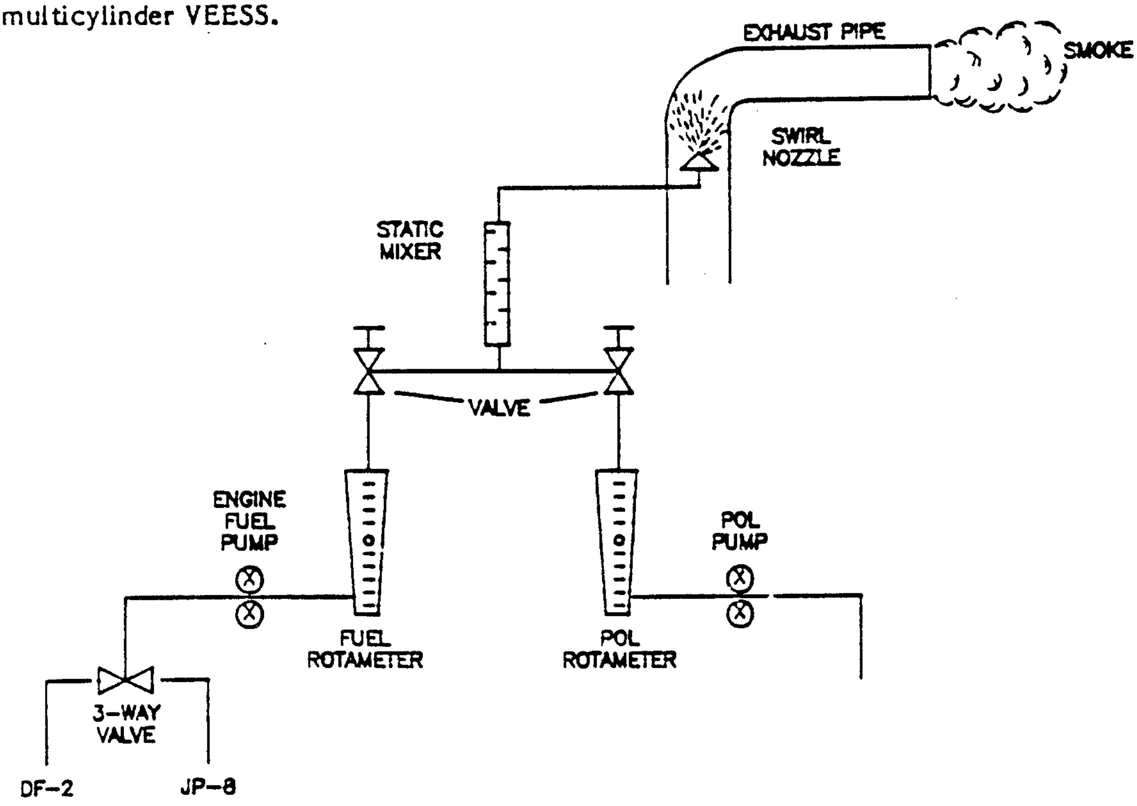

Figure 6. Multicylinder VEESS fuel/POL on-line blending system

The 45-kW generator set was operated at three separate speeds to provide a range of velocities, thus residence time, for smoke production. The speeds that provided stable operation of the generator set were 1400, 1800, and 1930 rpm. The engine was operated at four loads at each speed in order to provide different temperature profiles for evaluating temperature effects on smoke production. A video record of every speed/load/fog candidate run was maintained for subjective evaluations of smoke performance.

IV. DISCUSSION OF RESULTS

As discussed earlier, considerations were given to installing an auxiliary tank onboard each of the vehicles equipped with a VEESS in order to provide approximately 10 gallons (37 liters) of fluid, i.e., 10 minutes smoke capability. It was anticipated that fog oil would be utilized as the fluid to produce the smoke. However, it was also felt that other POL materials already used in the motor pool may be used in the event that fog oil was not available. It was also felt that other materials such as the heavier oils (SAE 30 to 50 grade) may be more effective than fog oil, and, therefore, the possibility exists that these products could be diluted with JP-8 to stretch the 10-minute time limit to perhaps 100 minutes or more. It was decided, therefore, to evaluate all the POL products that could be obtained, including blends of these POL products with JP-8. TABLE 4 is a list of POL products representing the annual requirements for a mechanized infantry division. This list was used as guidance to request the appropriate fluids, eliminating the obvious unacceptable products such as greases or special lubricants. TABLE 5 lists and identifies those POL products actually screened in this program.

A. Single-Cylinder VEESS Simulator

1. Obscuration

The single-cylinder VEESS simulator was used to obtain the data shown in TABLE 6. The intent was to compare, on an equal volume basis with fog oil, the smoke produced from the various POL materials under the same conditions of flow rate and injector pressures. The temperature of the exhaust section used to vaporize the fluid was established on results of VEESS investigations of actual hardware. Also, all the data were normalized against fog oil as 100 percent and reported as such.

TABLE 4. Annual Packaged Lube Requirements for Mechanized Infantry Division (197th Inf Div as Source)

NSN	POL Symbol	Product Name	Specification	Container Size	Quantity Used
9150-00-191-2722	OE/HDO-10	Single-Grade Lubricant	MIL-L-2104	55-gal. Drum	101
9150-00-186-6668	OE/HDO-10	Single-Grade Lubricant	MIL-L-2104	5-gal. Can	2,200
9150-00-186-6681	OE/HDO-10	Single-Grade Lubricant	MIL-L-2104	1 qt	1,604
9150-00-188-9858	OE/HDO-30	Single-Grade Lubricant	MIL-L-2104	5-gal. Can	1,844
9150-00-189-6729	OE/HDO-30	Single-Grade Lubricant	MIL-L-2104	55-gal. Drum	67
9150-00-188-9864	OE/HDO-30	Single-Grade Lubricant	MIL-L-2104	1 qt	1,663
9150-01-152-4118	OE/HDO-15/40	Multiviscosity Lubricant	MIL-L-2104D	5-gal. Can	2,000
9150-01-152-4119	OE/HDO-15/40	Multiviscosity Lubricant	MIL-L-2104D	55-gal. Drum	530
9150-01-152-4117	OE/HDO-15/40	Multiviscosity Lubricant	MIL-L-2104D	1 qt	2,310
9150-01-035-5393	GO-80/90	Gear Lubricant	MIL-L-2105	5-gal. Can	409
6850-00-181-7933	NR*	Antifreeze	MIL-A-46153	1-gal. Can	1,771
6850-00-181-7940	NR	Antifreeze	MIL-A-46153	55-gal. Drum	130
9150-00-698-2382	DXT2	Hydraulic Fluid	GM DEXRON-II	1 qt	460
9150-00-657-4959	DXT2	Hydraulic Fluid	GM DEXRON-II	5-gal. Can	300
9150-00-252-6383	OHA	Hydraulic Fluid	MIL-H-5606	1 qt	3,555
9150-01-935-9809	OHT	Hydraulic Fluid	MIL-H-6083	5-gal. Can	270
9150-00-935-9807	OHT	Hydraulic Fluid	MIL-H-6083	1 qt	880
9150-00-111-6256	FRH	Synthetic Hydraulic Fluid	MIL-H-46170	1 qt	240
9150-00-111-6254	FRH	Synthetic Hydraulic Fluid	MIL-H-46170	1 gal.	208
9150-00-843-1636	ATF	Transmission Fluid	Ford Type F	Can	600
9150-01-064-4536	CLP	Cleaning Lubricant	MIL-L-63460	1 pt	600
9150-01-053-6688	CLP	Cleaning Lubricant	MIL-L-63460	1 gal.	85
6810-00-205-6786	—	Denatured Alcohol		1 qt	820
9150-01-102-9455	BFS	Brake Fluid	MIL-B-46176	1 gal.	750
9150-00-261-7895		Fog Oil	MIL-F-12070	55-gal. Drum	80
9150-00-190-0905	GAA	Auto/Artillery Grease	MIL-G-10924	1 qt	816
9150-00-190-0907	GAA	Auto/Artillery Grease	MIL-G-10924	35-lb Pkg	337
9150-00-935-1017	GAA	Auto/Artillery Grease	MIL-G-10924	14-oz Tube	1,231
9150-00-257-5370	GG 1, 2, 3	Graphite Grease	VV-G-671	1 qt	200
9150-01-663-9795	NR	Wheel Bearing Grease	MIL-G-18709	Can	100
9150-00-985-7099	NR	Aircraft Turboshaft Lube	MIL-L-23699	1 qt	840
9150-00-782-2627	NR	Aircraft Turbine Lube	MIL-L-7808	1 qt	216
9150-00-529-7222	CRC 556	Lube		Tube	480
NSN not in AMDF	---	Unknown		1 qt	2,114
9150-01-178-4726	---	Unknown			1,834

*NR = None Reported

TABLE 5. Identification of Screened POL Products

POL Sample No.	BFLRF Lab No.	Sample/Blend Description	Blend Ratio, %
1	AL-15119-L	MIL-F-12070 Fog Oil	100
2	AL-17629-F	MIL-T-83133 JP-8 Fuel	100
3	NA*	JP-8/Fog Oil	50/50
4	NA	JP-8/Fog Oil	75/25
5	AL-15542-F	VV-F-800 DF-2	100
6	NA	Commercial Automatic Transmission Fluid (ATF)	100
7	NA	Commercial ATF/JP-8	50/50
8	NA	Commercial ATF/JP-8	25/75
9	NA	MIL-H-5606E Hydraulic Fluid (HF)	100
10	NA	MIL-H-5606E HF/JP-8	50/50
11	NA	MIL-H-5606E HF/JP-8	25/75
12	NA	MIL-H-46170A Hydraulic Fluid	100
13	NA	MIL-H-46170A HF/JP-8	50/50
14	NA	MIL-H-46170A HF/JP-8	25/75
15	AL-14801-L	OE/HDO-10 Single-Grade Lubricant	100
16	NA	AL-14801-L/JP-8	50/50
17	NA	AL-14801-L/JP-8	25/75
18	AL-15689-L	OE/HDO-30 Single-Grade Lubricant	100
19	NA	AL-15689-L/JP-8	50/50
20	NA	AL-15689-L/JP-8	25/75
21	AL-15478-L	OE/HDO-40 Single-Grade Lubricant	100
22	NA	AL-15478-L/JP-8	50/50
23	NA	AL-15478-L/JP-8	25/75
24	AL-14214-L	Company A OE/HDO-15/40 Multiviscosity Lubricant	100
25	NA	AL-14214-L/JP-8	50/50
26	NA	AL-14214-L/JP-8	25/75
27	AL-16215-L	Company B OE/HDO-15/40 Multiviscosity Lubricant	100
28	NA	AL-16215-L/JP-8	50/50
29	NA	AL-16215-L/JP-8	25/75
30	AL-14280-L	Company C OE/HDO-15/40 Multiviscosity Lubricant	100
31	NA	AL-14280-L/JP-8	50/50
32	NA	AL-14280-L/JP-8	25/75
33	NA	MIL-A-46153 Antifreeze	100
34	NA	MIL-B-46176A Silicone Brake Fluid (BF)	100
35	NA	Silicone BF/JP-8	50/50
36	NA	Silicone BF/JP-8	25/75
37	NA	DOT 3 Brake Fluid (BF)	100
38	NA	DOT 3 BF/JP-8	50/50
39	NA	DOT 3 BF/JP-8	25/75
40	NA	MIL-L-23699 Turbine Oil	100

* NA = None Assigned.

TABLE 6. Obscuration of Smoke Produced by Various POL Materials Using Single-Cylinder Screening Device

POL Sample No.	Obscuration, (% Obscured)
1	100
2	6.3
5	74.8
6	93.2
7	38.5
8	12.8
9	51.5
10	11.5
11	6.4
12	86
13	44.9
14	18
15	92.4
16	46.2
17	20.4
18	71.9
19	39.8
20	16.7
21	66.1
22	41.0
23	20.5
24	79.5
25	38.5
26	14.1
27	83.4
28	43.6
29	18.0
30	84.7
31	41.1
32	14.1
33	76.8
34	40.0
37	82.7
40	94.5

It soon became obvious that several factors were evolving from these studies: 1) fog oil, equivalent to a lighter viscosity grade lubricant, was optimized for the temperatures typically measured in the VEESS. This optimization was apparent when other lighter grade lubricants gave essentially the same high obscuration reading. Other fluids such as 30- and 40-grade lubricants did not perform as well as the 10-grade lubricants. It was theorized that the reason for these results was that the temperature in the VEESS was insufficient to totally vaporize the fluid. Further evidence of this possibility was that liquid dripped from the exhaust; therefore, total vaporization was not accomplished. 2) other results obtained indicated that diluted solutions of lubricant and JP-8 produced smoke approximately equivalent to the proportion of lubricant. These results were obtained early in the program, indicating that the effects of dilution did not produce enhanced results; therefore, the amount of smoke produced from the 10-gallon tank could not be greatly extended by diluting with JP-8.

2. Persistency

Upon examining the persistency results for all seven photocells for all the fogging candidates, two things became apparent. First, the large amounts of data for all photocells made it hard to discern any quantitative results, and second, there appeared to be no evidence of any stratification of the fog as the droplets agglomerated. The absence of stratification made it feasible to average all the photocells into a representative persistency curve. With the averaged curve, the numerical integrations were performed to obtain quantitative results.

The numerical integrations resulted in two numbers that represent the magnitude (percent opacity) and duration (time) of the center of area bounded by the persistency curve. The integrations were performed from the time of maximum opacity (which was assigned $t_i = 0.0$), to the time t_n when the persistency curve crossed a lower opacity threshold. The lower threshold was estimated based on meteorological visible range.(9) This method was based on the threshold of brightness contrast between an object and its background.

$$\epsilon = (B_o - B_b)/B_b \tag{1}$$

ϵ = threshold of brightness contrast = 0.02
B_o = brightness of object as seen by observer
B_b = brightness of background

$$B_o = B_o{*} \exp^{-kx} + B_f (1 - \exp^{-kx}) \tag{2}$$

$$B_b{*} = B_b{*} \exp^{-kx} + B_f (1 - \exp^{-kx}) \tag{3}$$

$B_o{*}$ = intrinsic brightness of object = 1.00
$B_b{*}$ = intrinsic brightness of background; in our case, a blackbody = 0.0
B_f = brightness due to light scattering by fog droplets
k = extinction coefficient
x = optical path length

Equations 2 and 3 are substituted into Equation 1, and reduced to obtain Equation 4.

$$\exp^{kx} = (B_o{*}/\epsilon B_f) + 1 \tag{4}$$

Then using obscuration data for fog oil, some assumptions were made. The first assumption was that opacity as measured by the photocell in the dilution tube is purely a function of transmittance. The second assumption was that the extinction coefficient calculated for the dilution tube existed in the smoke room. Using an opacity of 0.7790,

$$I = I_o \exp^{-kx} \tag{5}$$

$$O_p = 1 - I/I_o \tag{6}$$

$$O_p = 1 - \exp^{-kx} \tag{7}$$

an optical path length of 14 inches, and substituting into Equation 7; an extinction coefficient of 0.1078 is obtained. The extinction coefficient, plus the optical path length of 45 inches for the smoke room, the threshold of brightness contrast of 0.02, and the intrinsic brightness of an object equal to 1.00 are substituted into Equation 4, then solved for the brightness due to light scattering. Then the

$$\exp^{(0.1078)(45)} = 1.00/(0.02)\, B_f + 1 \tag{8}$$

$$B_f = 0.3941$$

perceived brightness of an object to the observer can be estimated by substituting the proper values into Equation 2. Therefore, the

$$B_o = 1.00 \exp^{-0.1078(45)} + 0.3941 \left[1 - \exp^{-1078(45)}\right]$$

$$B_o = 0.3988$$

visibility limit constrained to the optical path length of 45 inches (114.3 cm), and a constant extinction coefficient for fog oil, indicates the fog must dissipate to a threshold of 40 percent before the photocells can be perceived against a dark background. Thus, the lower limit for numerical integration was chosen as 40 percent.

The results of the numerical integrations between the maximum opacity attained and the 40-percent level are shown in TABLE 7. The data presented in TABLE 7 are the POL Sample No., the time coordinate of the center of area ($\bar{T}$), the opacity coordinate of the center of area ($\tilde{O}$), and a period of fog dissipation (τ). The period of fog dissipation is the ratio of $\tilde{T}/\tilde{O}$, and is considered a time averaged period, rather than a discreet period, as a result of the numerical integration. The POL products in TABLE 7 are ranked in the order of decreasing $\tilde{T}$, because the bottom line requirements denote the length of time the smoke persists. However, $\tilde{O}$ appears to represent a shape factor as to how the persistency curve dissipates before reaching the lower threshold. In some cases, the curve remained at a very high opacity, then rapidly dissipated to the lower level; other curves had almost linear dissipation, while others dissipated rapidly, becoming asymptotic to the lower threshold. Thus, it is felt τ gives the best overall ranking of how the POL products persist. One should notice that the order of rank changes when the POL products are compared on the basis of τ.

TABLE 7. Ranking of POL Products as a Function of Center of Area of the Persistency Curves

POL Sample No.	Time, $\tilde{T}$, seconds	Opacity, $\tilde{O}$, % Opacity	Period, τ, s/% Opacity
12	2001.59	62.04	32.26
1	1618.86	62.23	26.01
27	1287.35	63.03	20.42
24	1245.23	63.99	19.46
30	1115.05	63.06	17.68
21	1114.93	62.69	17.78
15	1104.64	63.18	17.48
18	1083.20	62.49	17.33
34	1058.41	62.81	16.85
5	1046.61	60.58	17.28
40	965.16	63.55	15.19
6	909.19	63.70	14.27
37	873.17	62.45	13.98
9	683.17	61.19	11.16
33	436.53	59.19	7.38
2	0.0	0.0	0.0

When examining the data in TABLE 8, which ranks the POL products in order of descending τ, along with the obscuration results, several observations are noted. The main observation is that the persistency period and the obscuration values do not rank the POL products in the same order. A possible explanation is that the obscuration results, which measure the absorption coefficient, do not take into account the fog

TABLE 8. Comparing Ranking of POL Products Persistency With Obscuration Values

POL Sample No.	Period, T, s/% Opacity	Obscuration, % Obscured
12	32.26	86
1	26.01	100
27	20.42	82
24	19.46	79
21	17.78	66
30	17.68	85
15	17.48	92
18	17.33	72
5	17.28	75
34	16.85	40
40	15.19	94
6	14.27	93
37	13.98	83
9	11.16	51
33	7.38	77
2	0.0	6

droplet diameter and the droplet-size distribution.(9) It would seem the droplet dissipation, as measured by persistency, is a strong function of the droplet diameter and droplet-size distribution.

Another observation has to do with POL products themselves. It appears that several of the perceived "heavier" POL products did not perform as well as "lighter" candidates. It is felt the persistency performance is a function of the percentage of the POL product that falls within the boiling range of fog oil. Therefore, several of the "heavier" products could have the majority of their boiling range above, and a limited percentage within the range of fog oil. An interesting persistency result was the MIL-H-46170A fluid (Sample No. 12), a synthetic oil, which displayed a greater persistency than fog oil. Because of limited chemical and physical characterization of the POL products, the effect of the synthetic properties can only be speculated. It should be noted that several POL candidates exceed the persistency values of DF-2 in simulated VEESS operation. The period for JP-8 is reported as zero, which indicates the JP-8 did not produce enough smoke to reach the lower threshold.

In summation, it appears the persistency results could be better understood if a) smoke droplet diameter and droplet-size distribution were known, and if b) chemical and physical properties of POL products could be correlated with persistency results.

B. Multicylinder VEESS Screener Device

Results obtained from the multicylinder VEESS screener are presented in TABLE 9. These subjective ratings were developed from visually reviewing the video taken of each sample evaluation. The actual rating that is reported is only one test result that was obtained for each sample. These subjective ratings were designated as A having the most obscuration capability; B, medium obscuration; and C, the least obscuration capability. The test matrix in TABLE 10 was conducted on each sample. Additional data were recorded for each test fluid sample on the "sample data sheet" shown in Fig. 7. These data were collected in order to document the many parameters known to affect smoke formation. Unfortunately, the important parameters such as ambient temperature, humidity, and wind velocity could not be controlled. The effect from these parameters are known but not measured.

These tests were conducted to determine if the POL candidates would produce smoke in a diesel exhaust environment. As accurately as the engine speed, load, and VEESS flow could be controlled, the qualitative evaluations of the smoke cloud proved to be purely subjective. The changing meteorological conditions made it difficult to evaluate POL fogging candidates qualitatively on a day-to-day basis. However, one consistent subjective evaluation was that the smoke cloud appeared to have the greatest "visual density" at the lowest speed and highest engine load. It is postulated that the maximum diesel particulate loading occurs at that condition, in which the particulates may act as nucleation sites for the vaporization/condensation process. The lack of quantitative measurements of smoke opacity, particulates, and exhaust velocities make it difficult to evaluate any speed/load effects on VEESS performance other than what can be conjectured.

C. Simulator Comparisons

The two laboratory VEESS screener devices were compared in order to determine if the single-cylinder engine could effectively be used to simulate diesel VEESS. Although the

TABLE 9. Multicylinder VEESS Screener Test Results

POL Sample No.	Visual Rating* at 1800 rpm - 75% Load
1	A
2	C
3	A
4	B
5	B
6	B
7	B
8	B
9	B
10	B
11	C
12	B
13	B
14	B
15	A
16	A
17	B
18	B
19	B
20	B
21	B
22	B
23	B
24	A
25	B
26	B
27	B
28	B
29	A
30	B
31	B
32	B
33	C
34	C
35	C
36	C
37	A
38	B
39	B

* Letters designate subjective rating with A = most obscuration, B = medium obscuration, and C = least obscuration.

TABLE 10. Test Points of Engine Test Conditions

Load, %	Speed, rpm		
100	1930	1800	
75	1930	1800	1400
50	1930	1800	1400
25	1930	1800	1400
0	1930	1800	1400

45 kW DD 3-71N Generator Set
JP-8 / POL Smoke Generation

Fuel__________ POL Product__________ Page____

Run Number					
Date					
Time					
Barometric Pressure, In-Hg					
Dry Bulb, F					
Wet Bulb, F					
ENGINE					
Engine Speed, RPM					
Coolant Temp., F					
Oil Pressure, psi					
Fuel Pressure, psi					
Exh. Temp. w/o Smoke, C					
Exh. Temp. w/ Smoke, C					
GENERATOR					
Ammeter, % Load					
Voltmeter, Volts					
LOAD BANK					
Load, kW					
Ammeter, Amps					
Frequency, Hz					
SMOKE					
Fuel Flow, ml/min					
POL Flow, ml/min					
POL Pressure, psi					

COMMENTS

Technician__________

Figure 7. Sample data sheet for multicylinder VEESS screener device operation

ratings from the multicylinder screener were subjective, it was felt that the obscuration results from the single-cylinder device were indicative in every case but one. For the exception, the POL fluid was MIL-A-46153 antifreeze (Sample No. 33). In the single-cylinder simulator, an obscuration value of 77 percent of fog oil was achieved without any operational problems. In the multicylinder VEESS, the antifreeze not only failed to produce smoke, the material polymerized, plugging the swirl nozzle. This result indicates that a multicylinder diesel VEESS needs to be used as a final test for evaluating any POL product or VEESS modification.

V. CONCLUSIONS AND RECOMMENDATIONS

The results of this testing have shown that a number of products available in the motor pool could be used in an auxiliary tank system to produce adequate smoke to replace DF-2 in the VEESS. The results of the obscuration and persistency measurements indicated that any of the crankcase lubricants, i.e., OE/HDO-10, 30, and 40 single-grade and 15/40 multigrade, and MIL-H-46170A Hydraulic Fluid would be suitable replacements for DF-2. Other fluids such as turbine oils, automatic transmission fluids, and brake fluids would also be acceptable substitutes for DF-2 in the VEESS. Results of these studies also showed that the physical properties of fog oil were probably optimized to smoke-producing systems such as the fog generators. It was thought, initially, that other POL products may produce greater quantities of smoke and could, therefore, be diluted with JP-8 to extend the smoke-producing time provided with the 10-gallon reservoir. Fluids such as 30- or 40-grade oil were expected to produce greater amounts of smoke since their volatility (evaporation rate) was lower than fog oil. Results of tests conducted on these fluids showed a lesser amount of smoke formed than fog oil, and some fluid was dripping from the end of the reactor. This condition indicated that the temperature typically found in VEESS was not high enough to vaporize the heavier end products of the 30-grade oil. BFLRF results also showed that by diluting the POL with JP-8, essentially equal proportions of smoke were produced based on the amount of POL that was blended. For example, 50/50 blend of JP-8 and 30-grade oil produced approximately 50 percent of the amount of smoke of the 30-grade oil above.

It is expected that increasing the temperature of the VEESS may increase the quality of smoke produced with heavier fluids. However, experiments to verify this possibility were not performed. It is not considered good judgment to increase the surface temperatures in the turbocharged section of the exhaust, due to resultant effects on the exhaust valves.

Results obtained on the single-cylinder screener device provided reliable, repeatable data that correlated with field data when available. It is recommended that this device be used in the future to screen candidate fluids under development. It would be useful to incorporate a droplet sizing device to study the effect of test parameters on droplet sizes as that factor affects obscuration and persistence. It would also be beneficial to determine droplet concentration (population) as well as vapor concentration. These factors would be useful in better understanding the relative effectiveness of the various fluids under evaluation.

The multicylinder diesel engine generator simulator proved to be useful for rapid screening of fluids under field conditions. Since all the factors involving exhaust component contribution to smoke droplet condensation are not well documented, it is believed this device served to generate smoke under realistic conditions. Since this is a field test device, contributing factors such as wind velocity and temperature could not easily be normalized from run to run. Therefore, only qualitative results could be obtained. This device did provide some very interesting system effects on the fluid that would not have been detected in simple evaporation-volatility tests. Specifically, the antifreeze sample was giving erratic results until it was discovered that the fluid was undergoing severe thermal degradation and gum formation. It is recommended that laboratory VEESS systems be developed using actual engine systems from armored equipment such as the Cummins VTA-903T used in the M2/M3 Bradley vehicle. This engine should be instrumented to allow an accurate system for measuring smoke concentration. The photocell light meter measuring device used with a single-cylinder screener engine would provide useful information if incorporated into a smoke-containing device such as a large tube.

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