

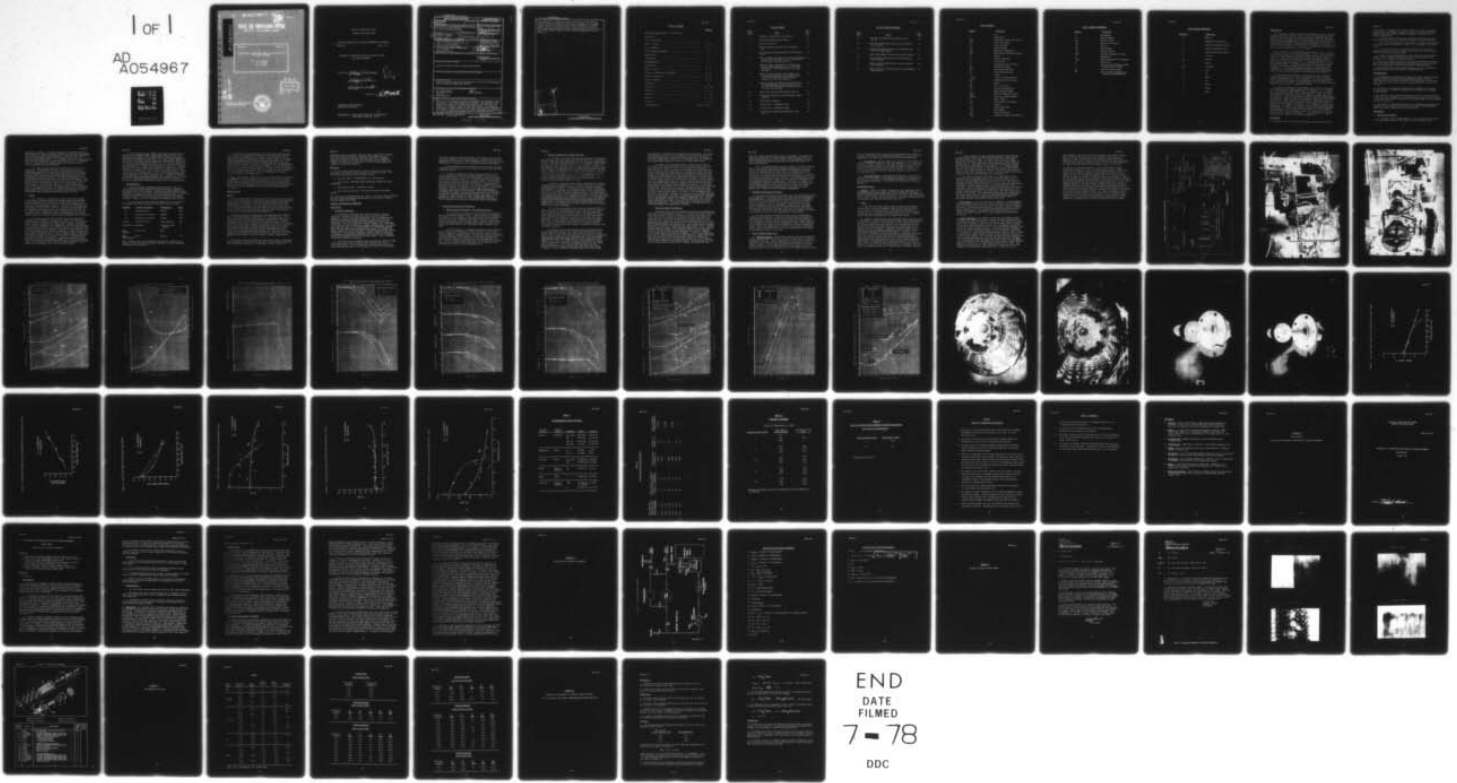
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NAVAL AIR PROPULSION CENTER

TRENTON, NEW JERSEY 08628

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MARCH 1978

EVALUATION OF WATER/FUEL EMULSION CONCEPT FOR TEST
CELL SMOKE ABATEMENT

By: A. F. Klarman
A. J. Rollo
H. C. Scott

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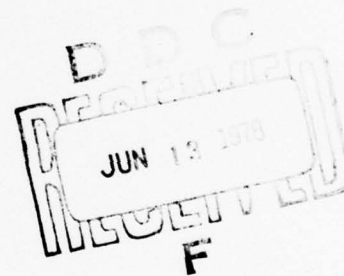
EVALUATION OF WATER/FUEL EMULSION CONCEPT FOR TEST
CELL SMOKE ABATEMENT

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exhaust emissions. A water/fuel emulsion can reduce the J79-GE-10 gas turbine engine exhaust smoke to a level that will enable test cell smoke emissions to meet a 20 percent visible opacity (Ringlemann 1) standard; however, the fuel control's inability to handle the large quantities of water required (approximately 30 percent of the engine fuel flow for the J79 GE-10 engine) appears to make the use of emulsions impractical for this engine.

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LIST OF SYMBOLS

<u>Symbol</u>	<u>Definition</u>
A	Area
C	Coefficient
CGVP	Compression Guide Vane Position
CPS	Cycles Per Second
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
EGT	Exhaust Gas Temperature
EPA	Environmental Protection Agency
F	Thrust
°F	Degrees Fahrenheit
ft	Foot or Feet
g	Acceleration Due to Gravity
gpm	Gallons Per Minute
GTC	Gas Turbine Compressor
HC	Unburned Hydrocarbons
in	Inches
in Hg A	Inches of Mercury Absolute
INT	Intermediate Power Rating
lb	Pound
MFC	Main Fuel Control
MIL	Military Specification
N	Engine Rotative Speed
NAPC	Naval Air Propulsion Center
NAVAIR	Naval Air Systems Command
NO	Nitric Oxide
NO _x	Total Oxides of Nitrogen
P	Pressure
PLA	Power Lever Angle
P/N	Part Number
ppm	Parts Per Million
PSIA	Pounds Per Square Inch Absolute

LIST OF SYMBOLS (CONTINUED)

<u>Symbol</u>	<u>Definition</u>
R	Gas Constant
°R	Degrees Rankine
RFI	Ready for Issue
RPM	Revolution Per Minute
sec	Seconds
S/N	Serial Number
SG	Specific Gravity
SWRI	Southwest Research Institute
T	Temperature
TSFC	Thrust Specific Fuel Consumption
W	Weight Flow
S	Ratio of Total Pressure to NACA Standard Total Pressure
γ	Ratio of Specific Heats
θ	Ratio of Total Temperature to Standard Total Temperature

LIST OF ENGINE SUBSCRIPTS

<u>Subscript</u>	<u>Definition</u>
o	Ambient
2	Compressor Inlet Station
3	Compressor Discharge Station
5	Turbine Discharge Station
10	Exhaust Nozzle Exit Station
a	Air Flow
avg	Average
b	Burner
corr	Corrected
f	Fuel
j	Jet
m	Meter
N	Net
s	Static
T	Total
w	Water

INTRODUCTION

The elimination of smoke from gas turbine engines has been a problem of prime concern to the Navy. The Navy, when and where possible, has developed and retrofitted gas turbine engines with smokeless combustors. This has not been possible for all engine models in the Navy inventory because of design problems and cost. New aircraft engines being designed and purchased by the Navy contain smokeless combustors. As the old "smoky" aircraft engines are retired, they are replaced with engines that contain smokeless combustors. Eventually, the fleet will have engines with smokeless combustors in all its aircraft.

With the advent of the Environmental Era starting in the mid 1960's, local authorities have been placing pressure on certain Naval activities to control jet engine test cell exhaust smoke caused by the operation of these old "smoky" engines during post overhaul performance checkruns. Since it is necessary to assure the integrity and performance of an engine after repair and/or overhaul, it is not possible for the Navy to cease testing these old engines nor is it possible for the Navy to prematurely retire them. The State of California is attempting to force the Navy to control the smoke emitted from its jet engine test cells (reference 1). The Navy is evaluating a number of smoke abatement techniques as interim methods for controlling test cell exhaust smoke until the fleet has been converted to smokeless combustor engines.

One technique being evaluated is the water/fuel emulsion concept. This concept depends on the flash vaporization of micron size water droplets suspended in fuel. During combustion, the flash vaporization of the water droplets causes a micro-explosion of the fuel drop into many smaller fuel droplets. This enhancement of fuel atomization improves combustion and results in a reduction in smoke.

The Southwest Research Institute (SWRI) under contract to the Naval Air Engineering Center (NAEC) evaluated this concept in a T63 combustor rig. In reference 2, SWRI reported that the combustor rig was capable of operating satisfactorily with a large quantity of water in the fuel, and significant reductions in smoke and oxides of nitrogen emissions were observed. Based on these results the Naval Material Command (NAVMAT) in reference 3 tasked the Naval Air Propulsion Center (NAPC) to further evaluate this concept using full scale systems. Additional support for the program was provided by the Air Force Civil Engineering Center at Tyndall Air Force Base via reference 4. The evaluation was divided into three parts: (a) effects of an emulsion on fuel control components and performance; (b) effects of an emulsion on full scale engine components and performance; and (c) effects of an emulsion on test cell exhaust smoke and engine exhaust emission levels. The results of part (a) have been previously reported in reference 5. For completeness, a copy of the fuel control report can be found as Appendix A.

CONCLUSIONS

1. Water/fuel emulsions can reduce gas turbine engine exhaust smoke to

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a level that will enable test cell smoke emissions to meet a 20 percent visual opacity (Ringlemann 1) standard; however, the following problems observed during the J79-GE-10 engine test appear to make the use of emulsions impractical:

a. The fuel control does not have sufficient fluid flow capacity to meter the required quantity of water and fuel for high power conditions.

b. The engine acceleration time requirement is exceeded when operating at the water fuel ratio required to reduce test cell smoke to 20 percent opacity.

c. A correction factor is required for engine thrust because the presence of water in the fuel increases thrust above the value obtained with fuel that does not contain water.

d. Slight corrosion occurred in the fuel control during a two-month storage period. Fuel control corrosion may be a problem because the emulsion is not completely removed by flushing.

2. Particulates, oxides of nitrogen, and smoke (Environmental Protection Agency (EPA) Engine Smoke Number) emissions measured at the engine tail-pipe were reduced when the engine was operated on emulsified fuel.

3. Carbon monoxide and carbon dioxide emissions were not significantly affected when the engine was operated on emulsified fuel.

RECOMMENDATIONS

1. The acceptability of adjusting the main fuel control specific gravity setting during post overhaul engine performance testing to obtain additional fluid flow capacity necessary to handle both the fuel plus the water added for smoke control should be established before testing other engines.

2. The effect of the emulsion and the control adjustment on transient operation should be evaluated to supplement the limited tests performed in this program.

3. The effect of long term engine storage on corrosion in the engine fuel control should be established, or a positive method of preventing corrosion in the fuel control should be determined (possibly by means of a fuel soluble corrosion inhibitor).

4. The effects of water/fuel emulsions on the components, performance and emissions of other engine models, for which no other satisfactory smoke reduction method is available, should be evaluated.

DESCRIPTION

1. Emulsification System.

a. A schematic of the system employed in the manufacture and delivery of the water/fuel emulsion to the engine is shown in Figure 1 and

pictorially in Figure 2. The main components in the system consist of a Waugh Model 110 Digital Controller, Masoneilan Model 8012 proportioning valve and a Gaulin Model MC-18 Homogenizer. Tap water from a 250-gallon tank was crudely mixed upstream of the homogenizer with JP-5 fuel containing emulsifying agents. The controller, operating the proportioning valve, was used to maintain a constant water/fuel ratio. The water/fuel ratio of the emulsion was changed by adjusting the setting on the controller between zero and 100 percent.

b. The crudely blended mixture of water and fuel was fed to the homogenizer. The homogenizer contains a high-pressure, positive-displacement pump which discharges the crudely mixed medium through a special homogenizing valve. The pressure forces open the pre-loaded adjustable valve and the medium passes through an aperture where an instantaneous pressure drop occurs. The downstream pressure is less than atmospheric, causing shearing action and cavitation bubbles. The mixture then strikes an impact ring at velocities up to 950 feet/second (ft/sec) further shattering the mixture into a dispersion of very small droplets. The dispersion size can be varied by adjusting the orifice size and pressure drop. The bypass system recycled excess flow because the homogenizer operates at a constant flow rate of 46 gallons/minute (gpm) whereas the engine only requires approximately 24 gpm at intermediate power (maximum non-afterburning fuel flow rate).

2. Engine.

a. The J79-GE-10 is a single rotor, axial flow turbojet engine incorporating a 17-stage compressor, cannular combustor, three-stage turbine, afterburner and variable area ejector-type exhaust nozzle. The inlet guide vanes and the first six stages of the compressor stator vanes have a variable angular position. The position of the vanes is established by the main fuel control as a function of compressor inlet air temperature and engine speed. The combustor section consists of the inner and outer combustion casing, ten combustion liners and the transition liner. Combustion liners are interconnected with cross-ignition tubes which provide for rapid flame propagation during starting.

b. The control system, which includes a main fuel control, an afterburner fuel control and a nozzle area control, provides engine power regulation throughout the engine operating range. The main fuel control senses the parameters of engine speed, compressor discharge static pressure, compressor inlet temperature, and power lever position. It establishes main engine fuel flows which prevent the compressor from entering the surge region, prevents rich blowout or lean die-out of the main engine combustor, and maintains compressor discharge pressure less than a prescribed maximum value. When the exhaust nozzle is operating on mechanical schedule, the control system schedules exhaust nozzle area as a function of power lever position. However, at intermediate and afterburning ratings, the mechanical nozzle area schedule is overridden by an exhaust gas temperature (EGT) signal and the exhaust nozzle area is varied to maintain the turbine discharge temperature within the limits of the EGT versus engine rotor speed (N) schedule.

c. The test engine, serial number (S/N) 433001, has been used in previous test programs at NAPC. Total engine operating time on the engine before initiation of the emulsified fuel tests was 224 hours. The engine was equipped with P-7 fuel nozzles, new Standard Combustion Liners, and a new (RFI) Main Fuel Pump (part number (P/N) 612D892 - P6, S/N 3871A) and Main Fuel Control (P/N 407767, S/N 813172). The engine was installed in the NAPC sea level test cell 2W. The installation is shown schematically in Figure 1 and pictorially in Figure 3. A standard bellmouth and screen assembly were mounted on the engine front frame. The engine was mounted on a flexure pivot thrust stand which acts on a stationary strain gage load cell to provide thrust measurement. Engine exhaust gases were discharged into a cell ejector system and exhausted to the atmosphere via a vertical exhaust stack. A support fixture for the exhaust emissions measuring equipment was anchored to the cell floor aft of the engine exhaust nozzle and forward of the cell ejector. A gas turbine compressor, model GTC-100, was used for all engine starts.

3. Instrumentation.

a. Engine performance parameters and emulsion water flow rate were acquired by the NAPC Datum Data Acquisition System, recorded and processed by an XDS 9300 computer. Selected calculated parameters were displayed in the test cell control room via cathode ray tube, for analysis. In addition, parameters from engine monitoring instrumentation were recorded manually on log sheets by test cell personnel during engine operation. Table I lists the instrumentation employed during the test.

b. The instruments listed below were employed in the analysis of the exhaust plume emitted from the engine and/or test cell stack.

<u>Pollutant</u>	<u>Analysis Principle</u>	<u>Manufacturer</u>	<u>Model</u>
HC	flame ionization	Beckman	402
CO	nondispersive infrared	Beckman	315A
CO ₂	nondispersive infrared	Beckman	315A
NO/NO _x	chemiluminescence	Thermo-Electron	10A
Particulates	gravimetric	Scientific Glass Blowing	-
Smoke (Engine)	filter stain	NAPC	-
Smoke (Engine/Stack)	opacity	Wager Co.	P5

These instruments meet the requirements specified by the EPA for the analysis of aircraft exhaust emissions (reference 6) and/or stationary source emissions (reference 7).

c. The exhaust gas sampling probes were fabricated from stainless steel tubing in accordance with reference 6 and mounted approximately eight inches (in) downstream of the engine exhaust tailpipe exit. A single point probe was employed for the particulate tests. A cruciform probe was employed during the gaseous emission and smoke tests. The cruciform probe had three 0.060 inch diameter holes at the centers of equal areas on each arm. The exhaust gas sampling line was approximately 25 feet (ft) in length and 0.375 inch in diameter. The line consisted of two ten-foot and one five-foot sections of Technical Heater Incorporated Model LP-212 Heated Gas Analysis Hose. The sample line was maintained at a temperature of $300^{\circ}\text{F} \pm 9^{\circ}\text{F}$ to prevent condensation of exhaust products or water in the sample line.

4. Fuel. JP-5 type fuel conforming to Military Specification MIL-T-5624K was employed in the test program. To this fuel were added 0.2 volume percent Tween 80 and 1.8 volume percent Span 80. These two surfactants, manufactured by ICI America, Incorporated, Wilmington, Delaware, were added to the fuel to stabilize the emulsion and prevent the coalescence of the micron size water droplets before the flash vaporization process took place.

METHOD OF TEST

Engine.

1. The engine was trimmed in accordance with the instructions and curves contained in reference 8. A seven-point baseline engine power calibration between idle and intermediate power ratings was performed with JP-5/surfactant fuel (no water). The engine was not operated in the after-burner mode during the tests. At the completion of the calibration, baseline smoke, particulate and gaseous emissions measurements were taken. All of the above was accomplished with the fuel supply line connected directly to the engine, bypassing the homogenizer.

2. Following the baseline calibrations, the homogenizer was connected into the fuel system and the emulsified fuel test phase begun. This phase consisted of operating the engine on the water/fuel emulsion for two-hours on each of five consecutive days. Specifically, the test procedure was to start the engine on JP-5/surfactant fuel, set the required power lever angle (engine power rating), then select the water/fuel ratio to be tested with the digital controller, and begin the two-hour emulsified fuel performance and/or emission measurements test cycle. At the end of two hours, the water flow was terminated and a ten-minute burn on JP-5/surfactant fuel made prior to securing the engine. Samples of emulsified fuel at varying water/fuel ratios were sent to the laboratory for analyses (viscosity, specific gravity, heating value, etc.).

3. Following the emulsified fuel test phase, another seven point engine power calibration with JP-5/surfactant fuel was performed for comparison with the pre-test calibration. In addition, the No. 1 and No. 10

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combustion liners were removed from the engine, inspected and compared with their pre-test condition. The main fuel control was also removed and preserved with MIL-L-6081 grade 1010 oil in accordance with the procedures in the Fuel Control Overhaul Manual, NAVAIR 03-110AEA-7. At the end of two months the control was disassembled and inspected for wear and corrosion.

Emissions.

4. After the engine power condition and water/fuel ratio stabilized, measurements were made of engine and test cell emission levels. The tests were broken down into the following groups.

- a. Test cell smoke - transmissometer and visual opacity.
- b. Engine smoke - EPA Smoke Number Measurement Method and transmissometer.
- c. Engine particulates - Gravimetric Method.
- d. Engine gaseous emissions - EPA Gaseous Emission Measurement Methods.

The visual opacity determinations were made by a certified reader provided by the Aircraft Environmental Support Office at the Naval Air Rework Facility (NARF) North Island.

ANALYSIS OF RESULTS AND DISCUSSION

Engine Test.

1. Introductory Comments.

a. Steady-state performance data taken during this test were corrected to standard day conditions using the equations shown in Appendix B. This was necessary because the inlet air temperature and barometric pressure can not be controlled in a sea level test cell and varied daily from standard sea level atmospheric pressure and temperature. Due to the significant effect of ambient air temperature on the sea level static thrust of a variable geometry engine, all thrust data curves are shown for an average ambient air temperature measured during the five days in which the data was acquired. No attempt was made to compare the engine test data to the model specification ratings (reference 9) since the main interest in engine output was primarily to determine any performance deviations from using various percentage water-in-fuel emulsions rather than absolute values. Also, no humidity corrections were made on the data.

b. All engine power calibrations were performed by acquiring steady-state data points at seven different power settings from idle to intermediate power. Data was taken with increasing power lever movements, and decreasing power lever movements, in order to help eliminate

any control system or engine hysteresis. The average of the two data points was employed as the engine parameter. Stabilization time was approximately five minutes. Engine transients involved jam power lever movements of one second or less for accelerations and decelerations.

c. During emulsified fuel performance testing at NAPC, the engine accumulated 30.4 test hours. Of this total, 11.4 hours were with the water/fuel emulsion.

d. In order to understand how the physical properties of the emulsion might affect engine performance, samples of the base fuel and test emulsions were sent to the laboratory for analysis and these results are presented in Table II. A good agreement exists between the theoretical and measured weight percent of water in the emulsion. This indicates that the controller was effective in regulating the quantity of water in the emulsion. As the water concentration in the emulsion was increased the specific gravity and viscosity of the sample increased. The heat of combustion of the sample decreased with increasing water content of the emulsion. As the heat release of the emulsion decreases, additional fluid (water plus fuel) flow will be required to maintain the same heat release (fuel input) in the combustor in order to maintain a given engine power condition. A problem was observed because of this increased fluid flow and it will be discussed in the section on Main Fuel Control Performance.

2. Steady-State Performance Evaluation.

a. Engine Baseline Performance - JP-5/Surfactant Fuel.

(1) A comparison of engine pre-test and post-test calibration data is presented in Figures 4 and 5. Figure 4 gives gas generator data plots of engine pressure ratio, corrected exhaust gas temperature, corrected fuel flow, compressor temperature ratio, and compressor pressure ratio versus corrected rotor speed. Figure 5 shows engine baseline performance plots of percent specification intermediate net thrust and thrust specific fuel consumption versus corrected rotor speed.

(2) The difference in the engine performance level between the pre- and post-test calibrations evident in Figure 5 is due to the effect of ambient air temperature on the sea level static thrust of a variable compressor geometry engine. The pre-test calibration was done at an average ambient air temperature of 59°F while the post-test calibration was done during a day when the average temperature was 48°F. Figure 4 shows no measurable shift in the engine pre- and post-test neat fuel operating lines indicating that the engine did not deteriorate as a result of using emulsified fuel.

b. Engine Performance with Emulsified Fuel.

(1) In Figure 6 corrected TSFC and F_N are plotted versus measured water/fuel ratio at a part power condition (57° PLA) with an average T_2 of 75°F. These data were obtained at the normal specific gravity setting of 0.82. The thrust increases slightly with increasingly higher concentrations of water in the fuel until the threshold value is reached at approximately 0.38 water/fuel ratio. The TSFC remains relatively constant since the engine is operating at cruise speed conditions where the TSFC curve is almost flat and the exhaust nozzle area is constant. The data scatter in TSFC at this part power condition was caused by pulsations in fuel supply line pressure at the inlet to the homogenizer producing erratic flowmeter readings at lower engine fuel flow rates. The threshold water fuel/ratio beyond which thrust deterioration occurs is 0.38 at a specific gravity setting of 0.82.

(2) Figure 7 shows the effect of water concentration on engine intermediate power performance at $T_2 = 48^\circ\text{F}$ for three main fuel control specific gravity settings. Corrected net thrust increases slightly (approximately 0.1 percent) as the concentration of water is increased from 0.00 to 0.10 water/fuel ratio, apparently due to the additional mass flow of the water vapor through the exhaust nozzle. A threshold value is reached, beyond which the thrust rapidly deteriorates, until the engine has lost almost 50 percent of its intermediate thrust at 0.30 water/fuel ratio. The threshold water/fuel ratio varied from 0.10 to 0.15 as the specific gravity setting of the main fuel control was changed from 0.85 to 0.79, respectively. The lowest specific gravity setting available on this engine is 0.72. The reasons for this effect are detailed in the section on Main Fuel Control Performance.

(3) A similar phenomenon can be seen in the corrected TSFC curves except that above a 0.25 water/fuel ratio the TSFC starts to increase. This is caused by the undertemperature signal from the temperature amplifier overriding the T_5 versus N control signal below 87 percent engine speed and forcing the exhaust nozzle to go full closed (301 in² versus 338 in²) in an attempt to raise T_5 . As a result, the thrust decreases at a much faster rate than the fuel flow causing a higher TSFC. This is very evident in the thrust curves at 0.25 water/fuel ratio since the nozzle was slightly open at the specific gravity setting of 0.79 and 0.82 and full closed at 0.85 where the engine speed was below 87 percent.

(4) Figures 8 and 9 show the effect of water concentration on various engine gas generator and control system parameters at intermediate power for three main fuel control specific gravity settings. Figure 8 shows actual uncorrected engine gas generator data of compressor discharge static pressure (P_{S3}), temperature (T_5), turbine discharge total pressure (P_{T5}), and temperature (T_5) versus water/fuel ratio. Figure 9 is a plot of the engine control system parameters of engine fuel flow (W_f), rotor speed (N), and exhaust nozzle area (A_j) versus water concentration. It is evident from these curves that the thrust deterioration beyond the threshold water/fuel ratios shown in Figure 7 is due to steadily decreasing engine fuel flow as water

concentration is increased with constant power lever angle. The steady-state operating point of the gas generator at the lower fuel flows is governed by engine rotor speed and exhaust nozzle area. The bowing of the 0.85 specific gravity curves at 0.25 water/fuel ratio is caused by the exhaust nozzle going full closed at the lower engine speed.

(5) Figure 10 is the same as Figure 4 except that it depicts the effect on the engine operating lines of using emulsified fuel with water/fuel ratios from 0.10 to 0.45 at part power and intermediate power condition. With the exception of increased fuel flow, the engine at part power conditions operates along its normal JP-5/surfactant fuel curves. Increasing the water content of the emulsion causes the burner efficiency to decrease and the engine automatically calls for more fuel to maintain engine turbine inlet temperature and speed. The TSFC curve in Figure 6 does not show this effect since net thrust is also increasing with the increased water addition. Above 87 percent engine speed (6700 rpm), the engine exhaust nozzle is automatically adjusted as necessary to maintain the T_5 versus N schedule shown in Figure 11. At the intermediate power setting (PLA = 76°), engine speed and exhaust gas temperature decrease with increasing water content of the emulsion as can be seen in Figure 10 with the data points labeled " T_5 versus N Exhaust Nozzle" and "Full Closed Exhaust Nozzle". In Figure 11, the performance data is plotted on the T_5 versus N schedule and falls within the normal operating limits for this engine. The water in the emulsion quenched the combustion of fuel and therefore reduced the combustion temperature (T_5). The fuel control acceleration schedule limit (discussed below) had been reached and no additional fuel could be injected into the engine to raise the combustion temperature. The engine responded to this decrease in T_5 , as it was designed by the manufacturer to perform.

c. Main Fuel Control Performance.

(1) The main fuel control performed satisfactorily throughout the emulsified fuel test program. Figure 12 is a plot of corrected emulsified fuel flow to burner pressure ratio versus corrected rotor speed. The curve (solid line) in Figure 12 represents the normal required-to-run operating line plotted from the post-test calibration data with JP-5/surfactant fuel. During one of the two-hour emulsified fuel cycles, an eight point calibration was performed with 0.20 water/fuel ratio and with the MFC specific gravity setting at 0.82. A plot (open squares) of these data shows the engine to be operating along what appears to be a different schedule about ten ratios higher than the required-to-run line. However, plotting the same parameter (solid squares) minus the water component indicates that up to 7100 rpm corrected speed the engine is actually on its normal steady-state operating schedule. At the lower speed points fuel flow is slightly higher due to a small decrease in burner efficiency. Above 7100 rpm, the total flow through the control has reached the acceleration schedule limit and the engine operates on its T_5 versus N exhaust nozzle schedule at intermediate power. Further addition of water, once the acceleration schedule limit is reached, decreases fuel flow

since $(W_f + W_w)/P_b$ and power lever angle are constant. The engine will continue to follow the T_5 versus N exhaust nozzle schedule until the engine speed decreases to a level at which the undertemperature signal from the temperature amplifier overrides and forces the nozzle to a full closed position.

(2) It is obvious from the curves in Figure 12 that the threshold water to fuel ratio beyond which performance degradation occurs is a function of the W_f/P_b ratio margin between the steady-state required-to-run fuel schedule and the acceleration fuel schedule limit. The greater the ratio margin, the higher the water concentration the engine can sustain. By enriching the acceleration fuel schedule using MFC specific gravity adjustments, the ratio margin is increased permitting greater fluid flow through the fuel control at higher water concentrations with a corresponding reduction in smoke levels. The goal is to obtain the required smoke reduction before reaching the threshold water/fuel ratio at intermediate power. At part power conditions, more than enough margin is available both to reduce smoke to, or below, 20 percent opacity and to obtain accurate performance measurements.

3. Transient Performance Evaluation.

a. Only limited transient performance tests were conducted during this test program due to time constraints. The engine transient performance was determined by running snap accelerations from idle to intermediate power with three MFC specific gravity settings and water/fuel ratios of 0.0, 0.5, 0.10, 0.15 and 0.20. The test procedure was to set the required water/fuel ratio at intermediate, decel to idle, then snap accel to intermediate as soon as the engine stabilized at idle power. This was done as quickly as possible to assure that the fuel remaining in the engine fuel control and inlet lines, which was adequate to perform the transient, was still at the required water concentration.

b. All accelerations were free of surge, stall, overtemperature, instability and overspeed. Acceleration elapsed times were measured on visicorder plots from the point at which the power lever manipulation was initiated to the point at which engine thrust had reached 95 percent of the difference between idle and intermediate levels. These plots are not included in this report but are available for further analysis upon request. Table III summarizes the results of the transient performance tests. Above a water/fuel ratio of 0.10 the acceleration time exceeded the maximum time limit of 5.3 seconds.

4. Engine Hardware Conditions.

a. Combustion Liners. As previously reported, the engine combustion liners, P/N 106C3320G24 (nine each) and one P/N 106C3320G23, were new at the beginning of test. At the completion of the test the No. 1 and No. 10 combustion liners were removed, inspected and photographed as shown in Figures 13 and 14. Close inspection revealed the liners to be in good condition exhibiting no unusual deposits or deterioration due to the emulsified fuel. The minor carbon build-up in the chamber domes is normal.

Also, no discrepancies were noted on the first-stage turbine nozzle vanes or blades. The liners had accumulated approximately 25 hours at the completion of the test, over 11 of which were with emulsified fuel.

b. Fuel Nozzles. The main engine fuel nozzles, P/N 577C796-P7, from the No. 1 and No. 10 combustion liners are depicted in their post-test condition in Figures 15 and 16. The carbon build-up on the nozzle face was the result of a previous test program on engine S/N 433001. The increase in carbon build-up evident in these figures is normal for these nozzles as they accumulate operating time and is not caused by the emulsified fuel.

c. Main Fuel Control. Disassembly and inspection of the main fuel control after two months storage revealed that traces of the emulsion were still in the control. No significant corrosion was evident on any of the internal components. A more detailed analysis can be found in Appendix C.

Environmental Test.

5. General. Figures 17 through 22 present the most significant results obtained during the test program. No unburned hydrocarbon data are presented because the data were suspect due to a break in the sample line going to that analyzer. During this phase of the test program the specific gravity setting of the fuel control was 0.82. Appendix D contains all the environmental test data obtained during the study.

6. Smoke.

a. The test cell plume visual opacity and engine smoke numbers obtained for 75 percent intermediate (INT) and INT power conditions, as a function of the water content in the emulsion, are shown in Figures 17 and 18. The smoke levels measured at the stack or engine exhaust exit for this engine operating on neat fuel at the 75 percent INT and INT power conditions did not significantly differ.

b. Figure 17 shows that the test cell plume opacity, when the engine was operated at 75 percent INT, decreases linearly with increasing water content of the emulsion. For INT power, the smoke reduction caused by the emulsion above a water/fuel ratio of 0.10 is complicated by the fact that the total flow (water plus fuel) was greater than the flow capacity of the fuel control. Increasing the water content of the emulsion caused a corresponding reduction of fuel injected into the engine after reaching the fuel control capacity limitation. This resulted in a decrease in the actual engine operating power and a lower smoke level due to both the water effect and reduced engine power. Since the 75 percent INT and INT test cell smoke opacity values are approximately equal when using neat fuel it can be assumed that the 75 percent INT curve approximates the effect of emulsions on INT power smoke values. An emulsion having a water/fuel ratio of 0.30 would be required to reduce the test cell plume opacity to 20 percent when this engine is operated in either the 75 percent INT or INT power conditions.

c. Figure 18 shows a linear relationship between visual opacities and engine smoke numbers for INT/75 percent INT power conditions with and without water in the fuel. In order to have a test cell plume opacity of 20 percent or less, this engine must have a smoke number not greater than 30. This relationship assumes that exhaust exit velocity and particle size distribution has not changed due to different engine power ratings or water content in the emulsion. It is not recommended that this correlation be used on other test cells/engine combinations because visible plume opacity is a function of test cell/engine operating characteristics such as augmentation ratio, test cell exhaust stack area, plume exit velocity, and particulate size distribution.

d. The effect of emulsion water content on engine smoke number obtained by the stained filter technique is shown in Figure 19. For 75 percent INT, an emulsion having a water/fuel ratio of 0.25 would be required to reduce engine smoke from 65 to 30 SN. It is impossible to determine the water content required to reduce INT smoke to 30 SN because of changes in engine operating power due to high water/fuel ratio emulsions. Using two different smoke measuring methods gave two different fuel/water ratios for satisfactory reduction of plume opacity to a 20 percent visual determination. The actual water fuel ratio required lies between 0.25 and 0.30. The differences between these two values reflect the errors associated with the two different smoke measuring methods. The visual opacity value is obtained by the most direct method and represents the smoke requirement the Navy has to meet.

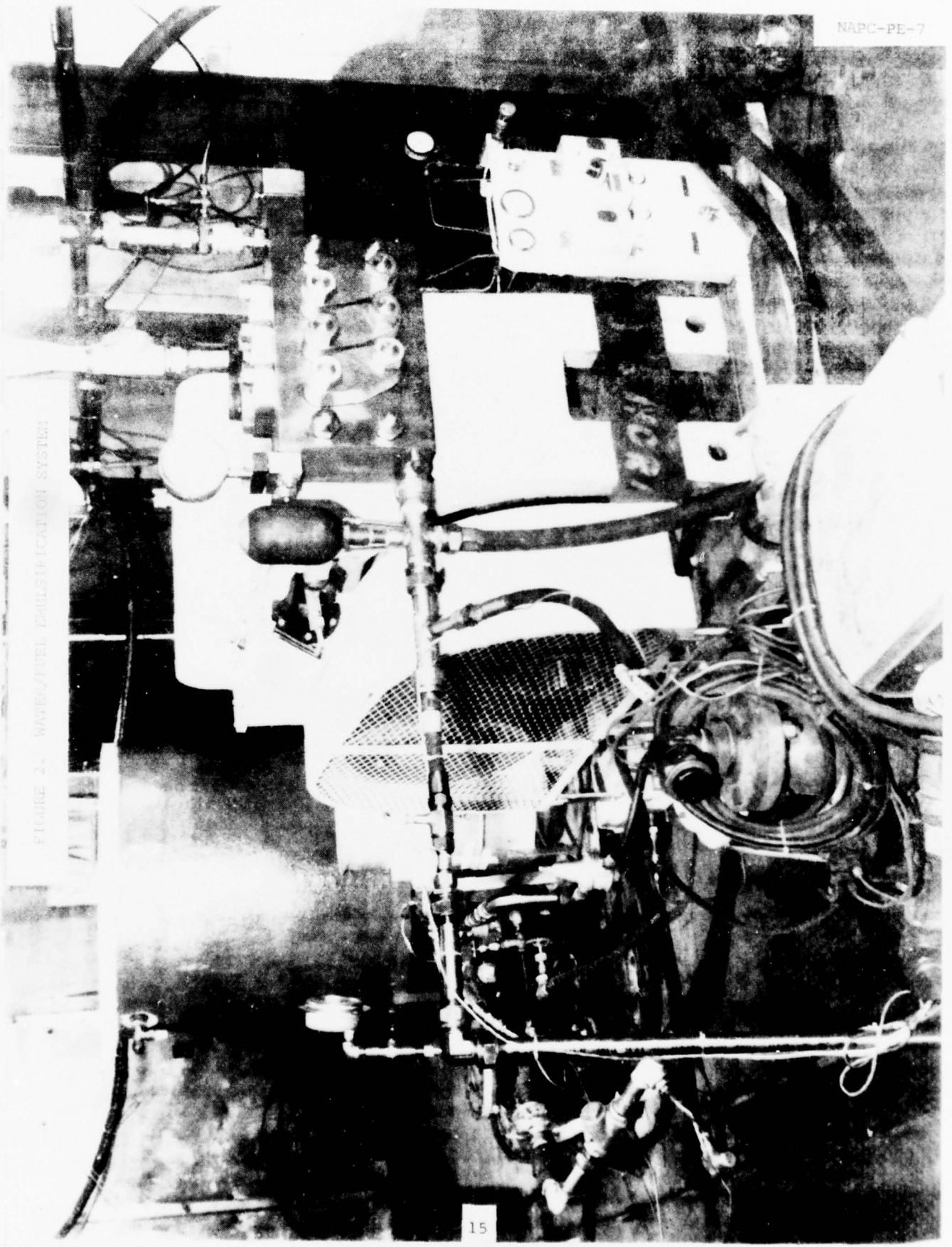
7. Particulates. Due to the difficulty in sampling a jet engine exhaust plume for particulates and the long tedious laboratory analysis method, particulate analysis was limited to INT power ratings with and without an emulsion at one water/fuel concentration. The data in Table IV indicate that a reduction in the mass of particulates emitted occurred when the emulsion was employed. An emulsion with a water/fuel ratio of 0.22 caused a 41 percent reduction in the mass of particulates emitted by the engine.

8. Gaseous Emissions. The effects of emulsions with different water contents on the emissions of carbon dioxide, carbon monoxide and oxides of nitrogen are shown in Figures 20, 21, and 22. What appears as a large drop in carbon dioxide in Figure 20 for the INT power rating is actually a drop-off in engine operating condition due to volumetric limitations of the fuel control (see Section 2.c.). The carbon dioxide emission levels for the 75 percent INT power condition did not exhibit any significant change until after a water/fuel ratio of 0.43 was reached. The effects of an emulsion on engine carbon dioxide emission levels are small. Figure 21 shows how the carbon monoxide emission levels varied with the water content of the emulsion. The 75 percent INT carbon monoxide emission level did not change significantly until after the water/fuel ratio exceeded 0.43. The change in INT carbon monoxide emission levels did not appear until the water/fuel ratio exceeded 0.30. The increase in carbon monoxide emissions is related to the flame quenching effect of the water. The oxides of nitrogen emission levels presented in Figure 22 show a rapid decrease for the INT power rating above the 0.15 water/fuel ratio

test condition. This rapid decrease is related to the change in actual engine operating condition due to the volumetric limit on the fuel control. At the 75 percent INT power condition, an emulsion with a water/fuel ratio of 0.57 causes a five-fold decrease in the NO_x emissions of this engine. Above a water/fuel ratio of 0.25, the effectiveness of the water to further reduce the NO_x emission starts to level off.

9. The use of water/fuel emulsions in the J79-GE-10 engine caused significant reductions in test cell exhaust plume opacity. However, at the MFC specific gravity setting of 0.82 (normal setting for JP-5), the engine was not capable of maintaining the INT power rating, when the water/fuel ratio of the emulsion exceeded 0.10. Tests at MFC specific gravity settings of 0.85 and 0.79 were conducted to determine the effects of small perturbations on MFC performance. No attempt was made to examine the extreme low specific gravity setting on the fuel control (0.72). After detailed analysis of the test data, the apparent decrease in engine performance observed at the higher water concentrations during the test program was found to be due to the flow capacity limitations of the MFC. Since the engine was not available for further testing when this factor was discovered, an analysis was made to determine how the MFC would perform at a specific gravity setting of 0.72. As shown in Appendix E, even a reduction in the MFC specific gravity setting to 0.72 would not allow enough water to be injected into the engine to reduce the plume visual opacity to 20 percent without sacrificing engine performance. Table V summarizes the significant test results obtained during the program.

FIGURE 2. WATER/FUEL EMULSIONIFICATION SYSTEM



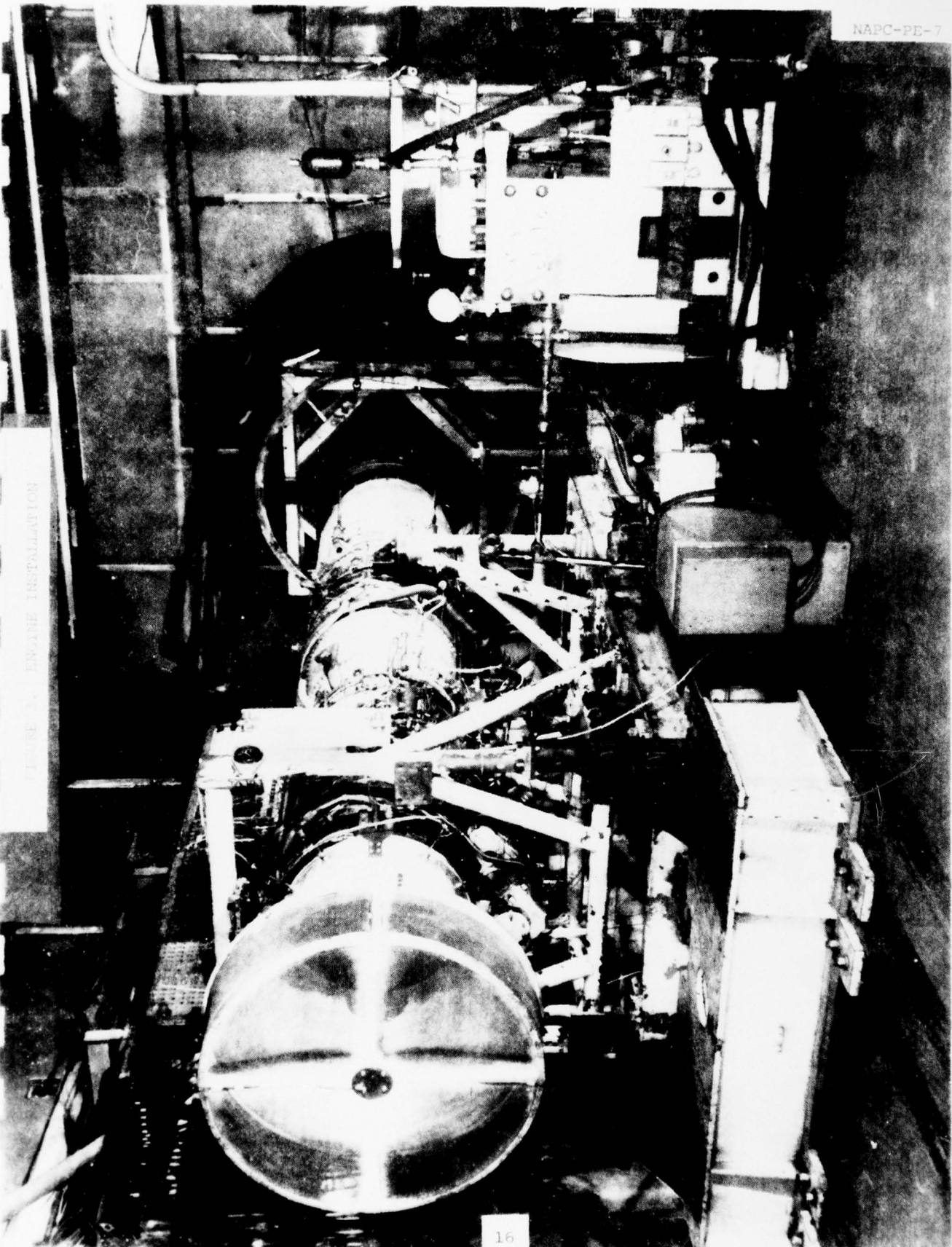


FIGURE 3. ENGINE INSTALLATION

FIGURE 4. ENGINE OPERATING LINES WITH JP-5/SURFACTANT FUEL

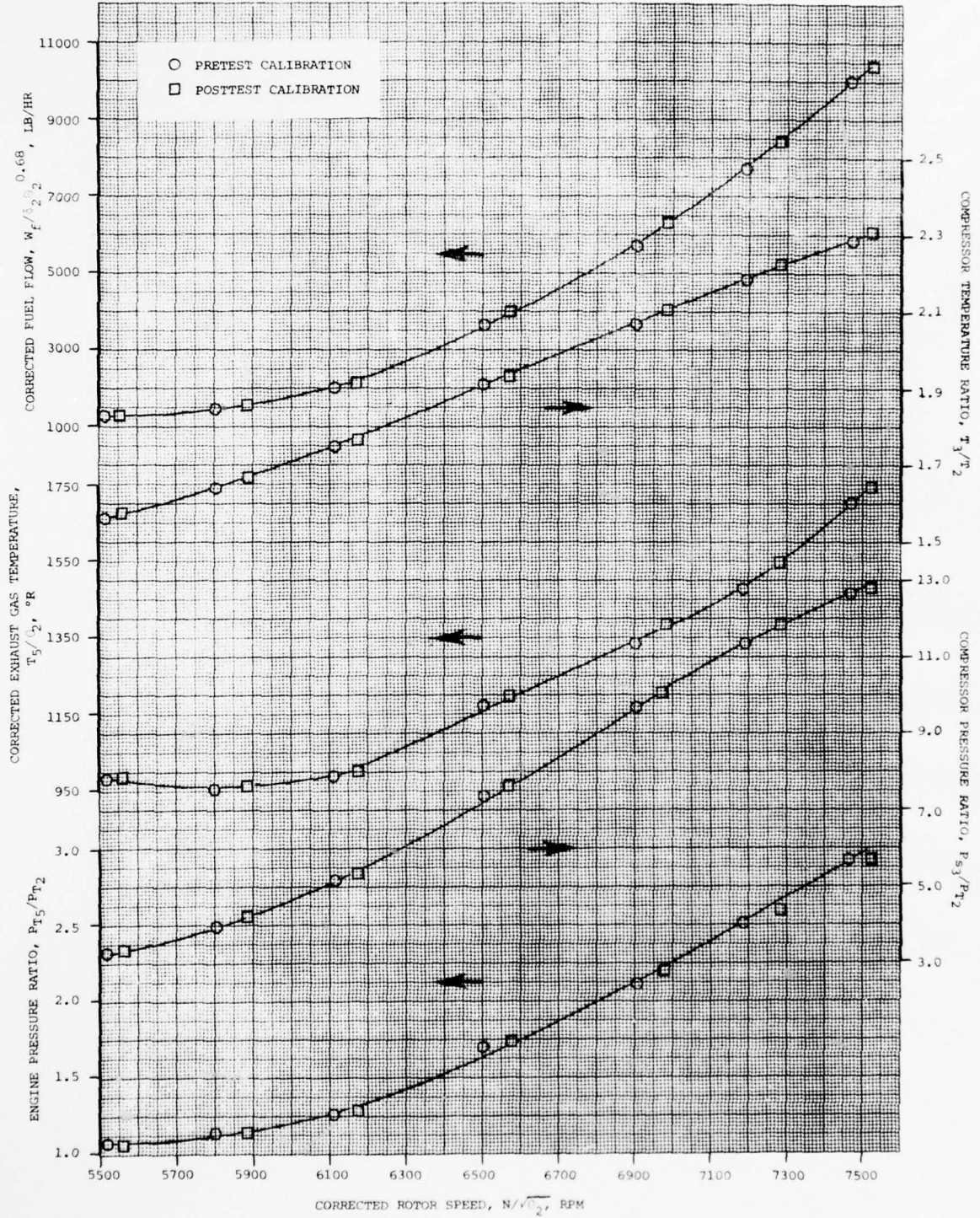


FIGURE 5. ENGINE BASELINE PERFORMANCE WITH JP-5/SURFACTANT FUEL

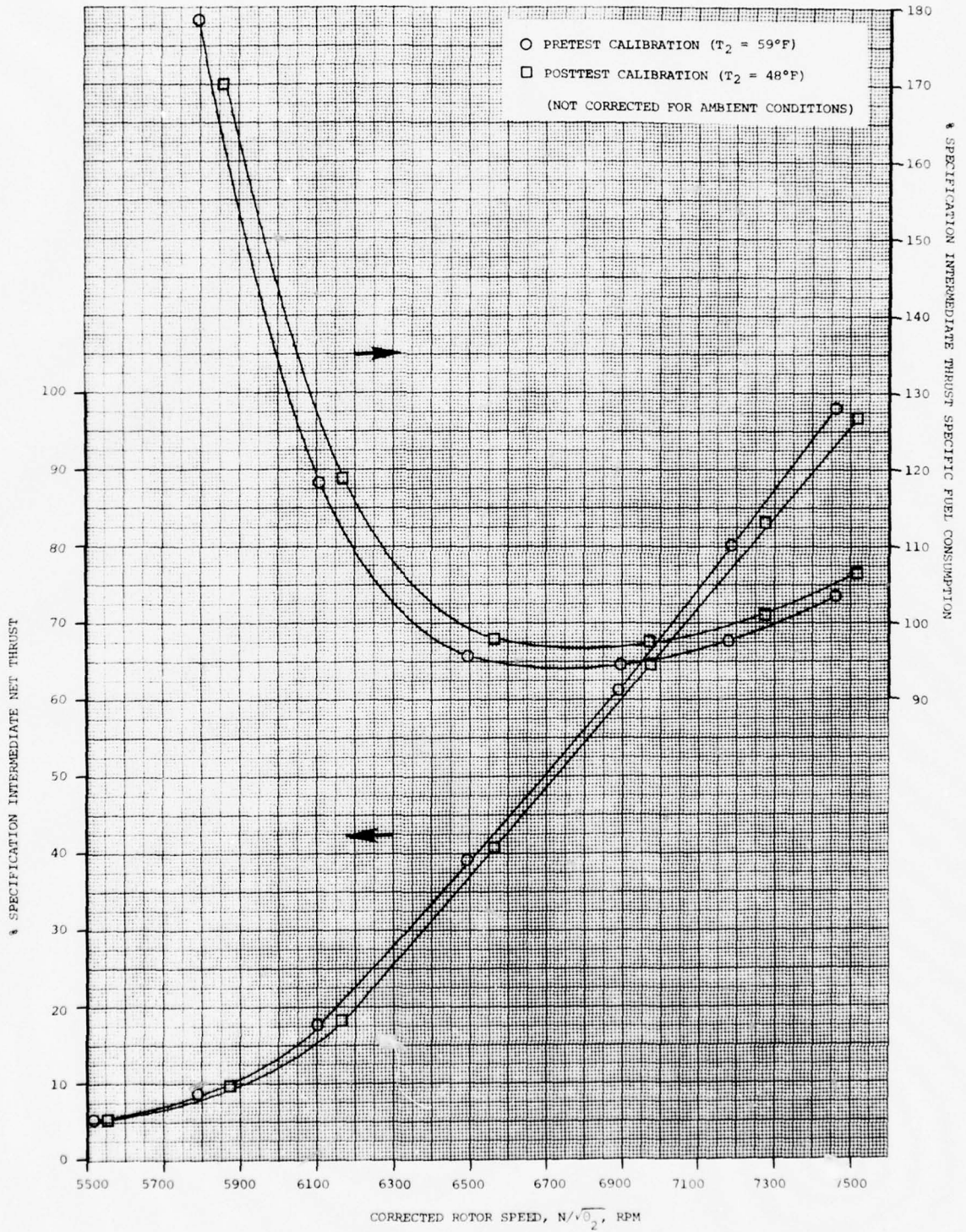


FIGURE 6. EFFECT OF WATER CONCENTRATION ON ENGINE PERFORMANCE AT PART POWER (57° PLA) AT $T_2 = 75^\circ$ WITH MPC SPECIFIC GRAVITY SETTING OF 0.82



FIGURE 7. EFFECT OF WATER CONCENTRATION ON ENGINE INTERMEDIATE POWER PERFORMANCE AT $T_2 = 48^\circ\text{F}$ WITH MFC SPECIFIC GRAVITY SETTINGS OF 0.79, 0.82 AND 0.85

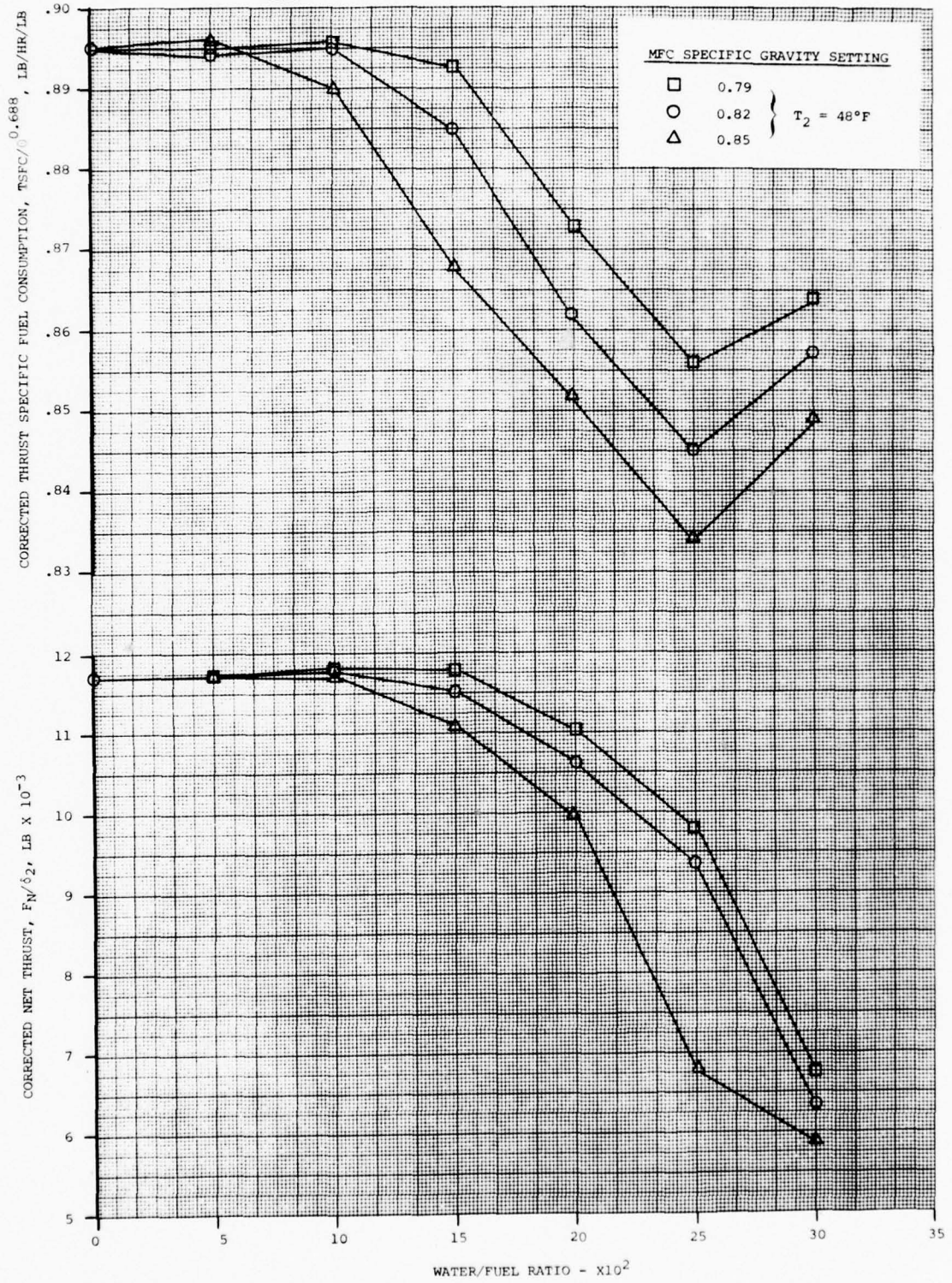


FIGURE 8. EFFECT OF WATER CONCENTRATION ON ENGINE GAS GENERATOR PERFORMANCE AT INTERMEDIATE POWER AT $T_2 = 48^\circ\text{F}$ WITH MFC SPECIFIC GRAVITY SETTINGS OF 0.79, 0.82, AND 0.85

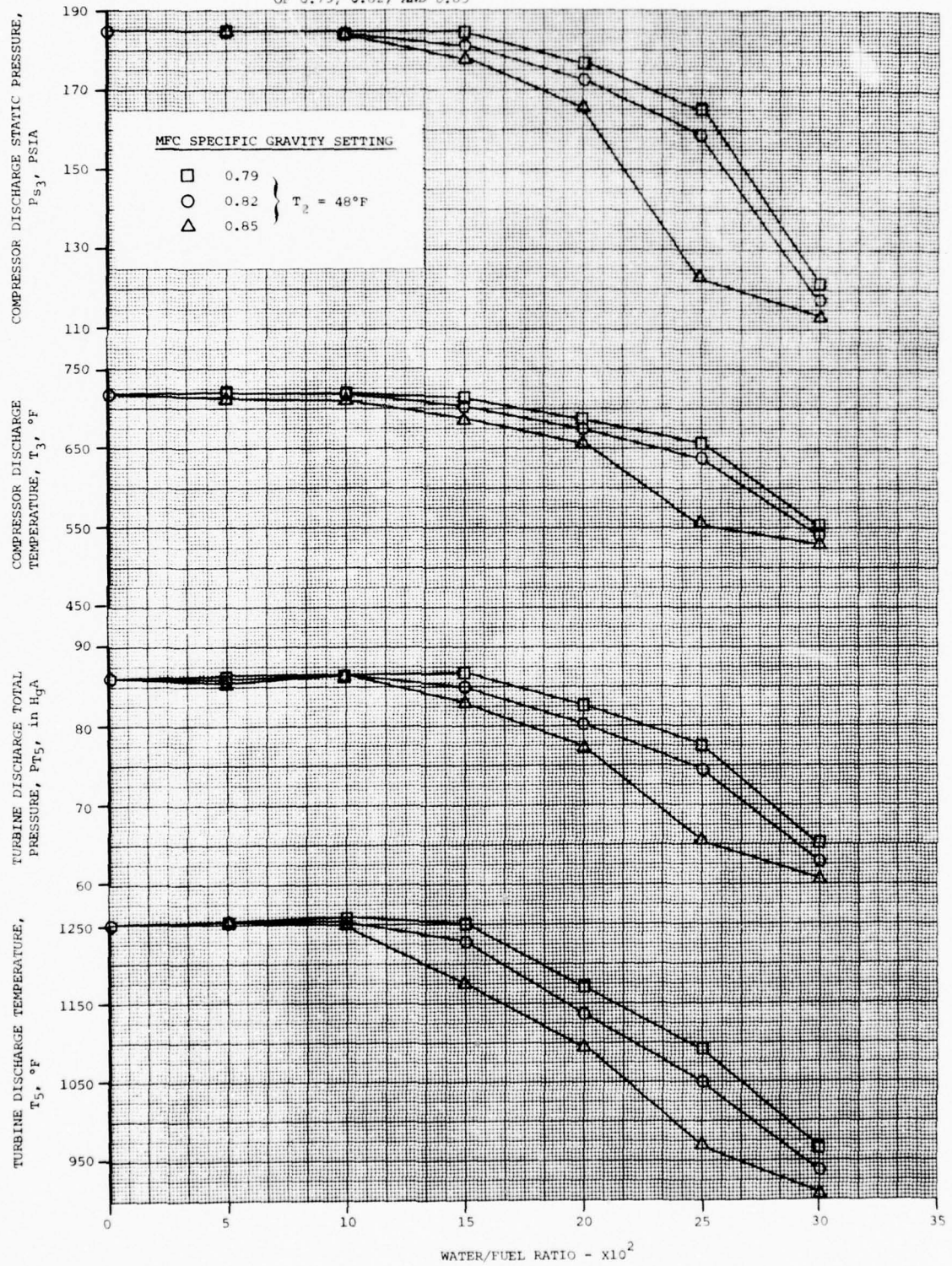


FIGURE 9. EFFECT OF WATER CONCENTRATION ON ENGINE CONTROL SYSTEM PERFORMANCE AT INTERMEDIATE POWER AT $T_2 = 48^\circ\text{F}$ WITH MFC SPECIFIC GRAVITY SETTINGS OF 0.79, 0.82, AND 0.85

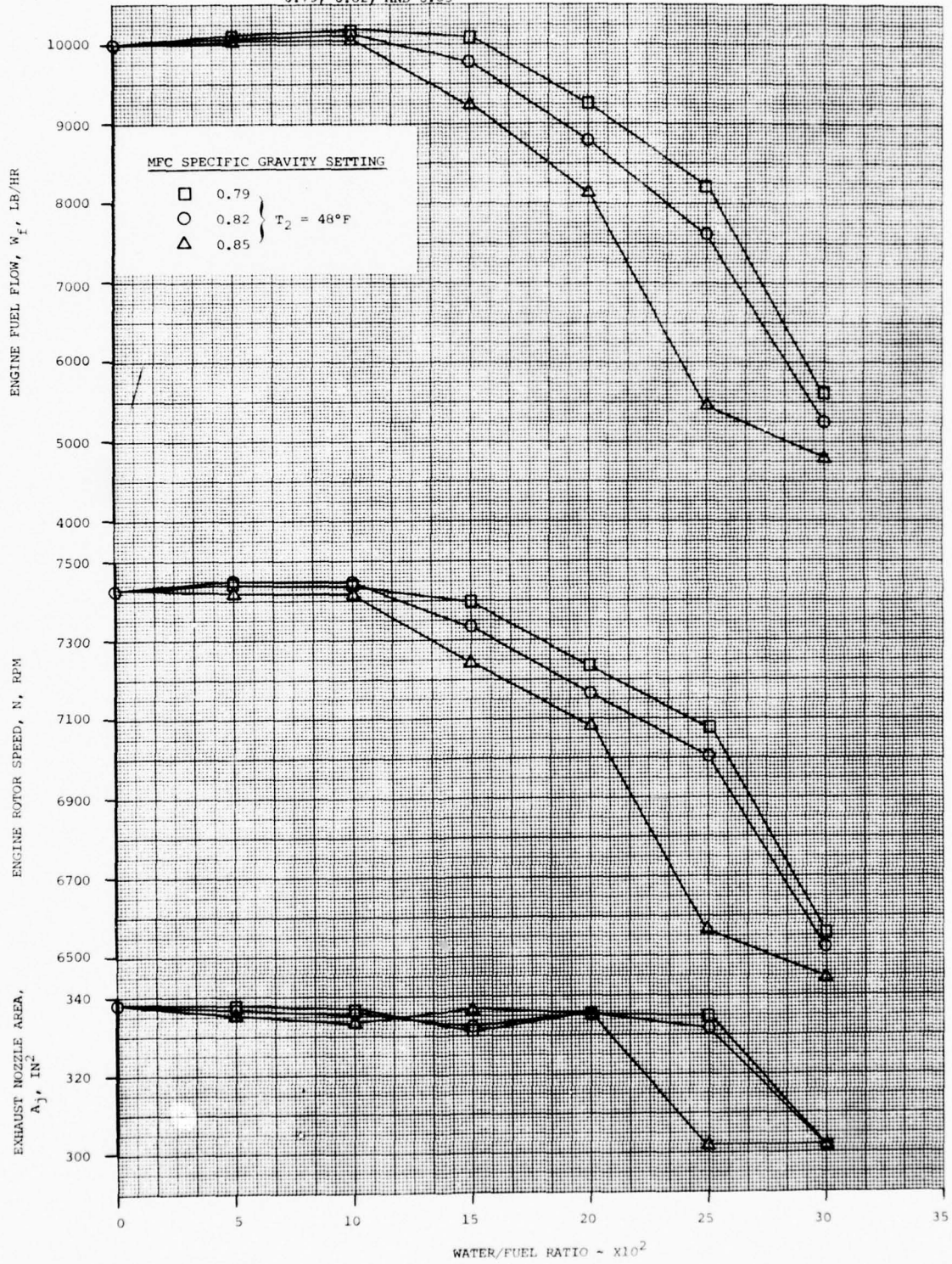


FIGURE 10. ENGINE OPERATING LINES WITH EMULSIFIED FUEL

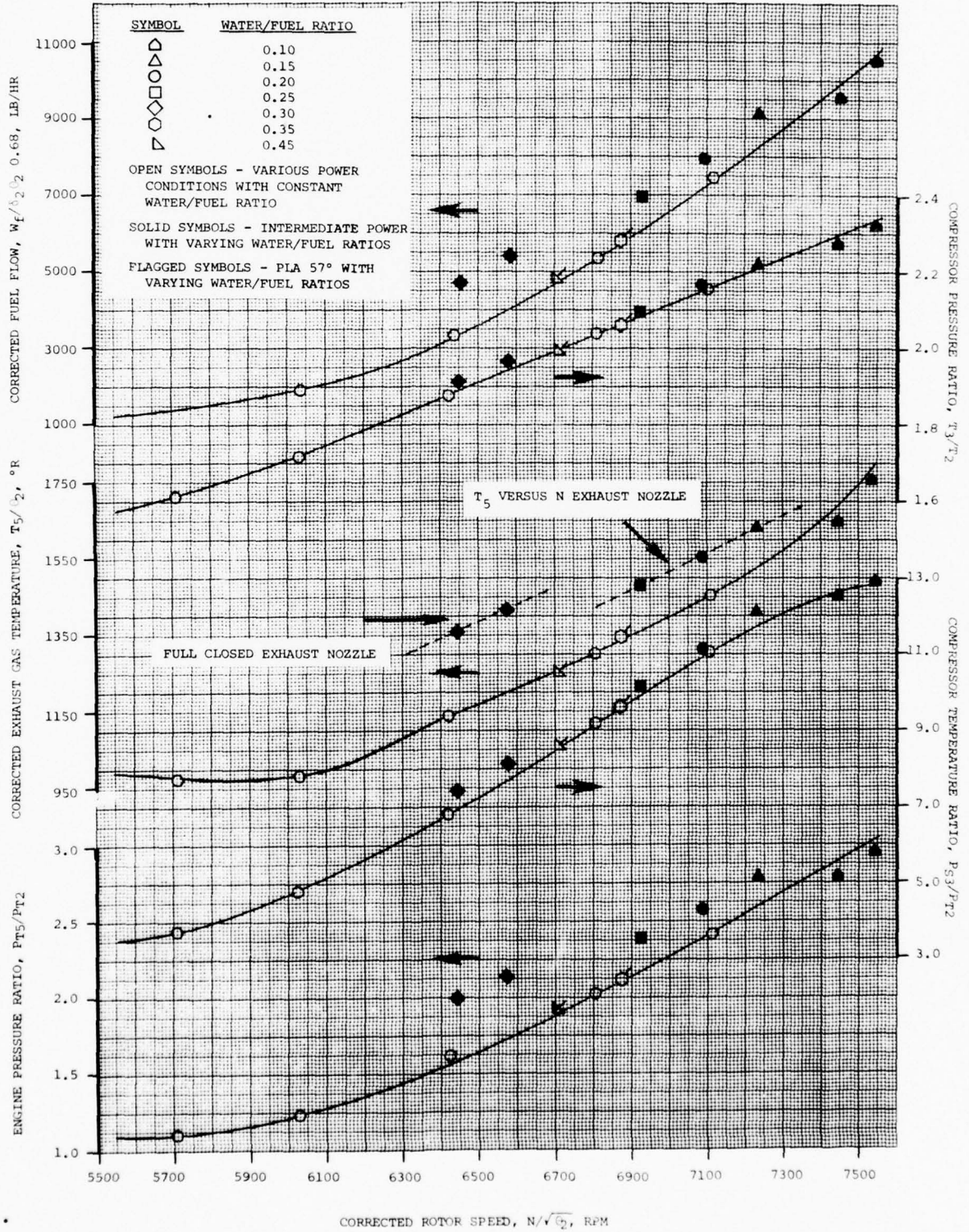


FIGURE 11. EXHAUST GAS TEMPERATURE VERSUS TOP ROTOR SPEED SCHEDULE

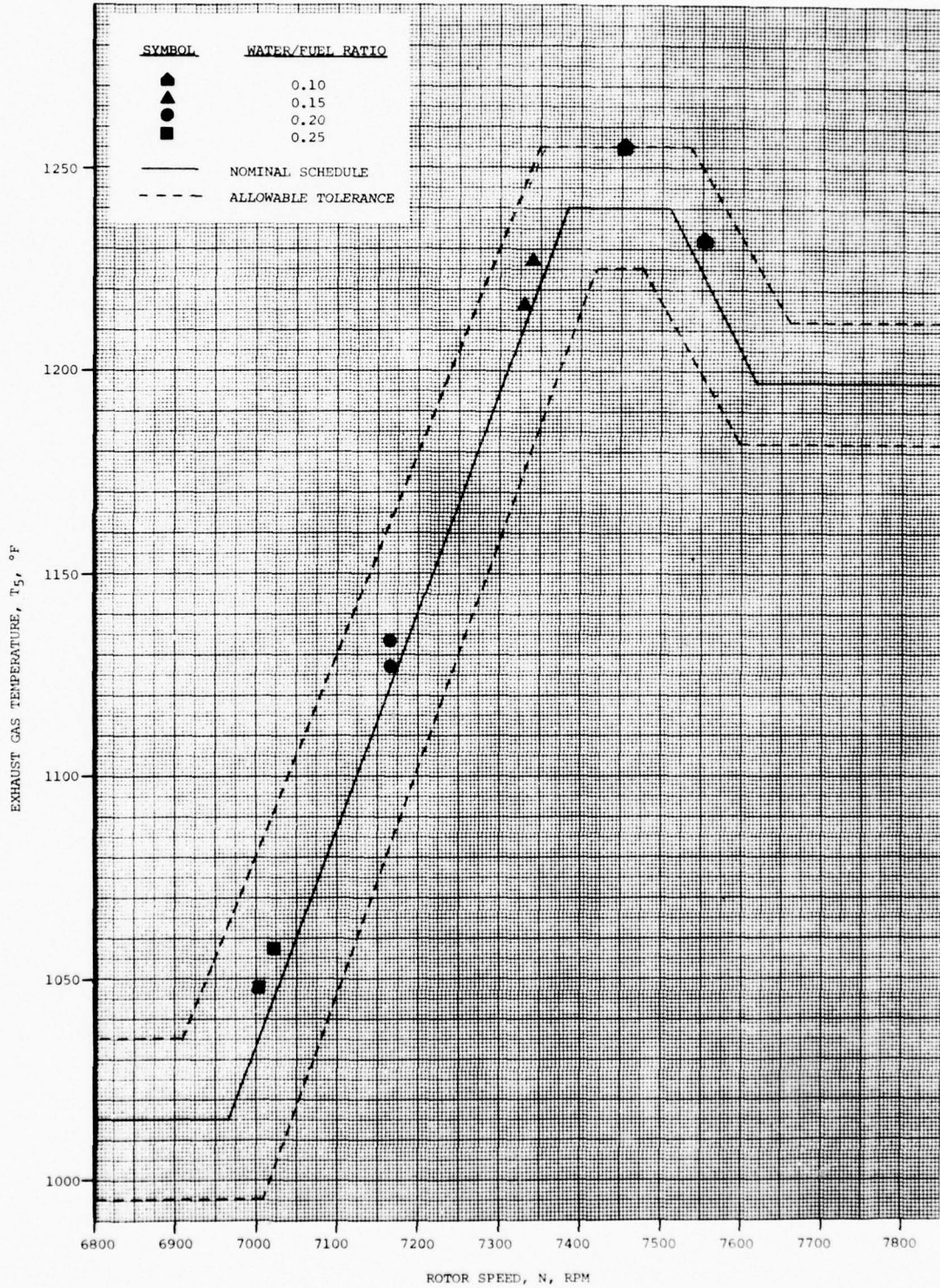


FIGURE 12. FUEL CONTROL SCHEDULES

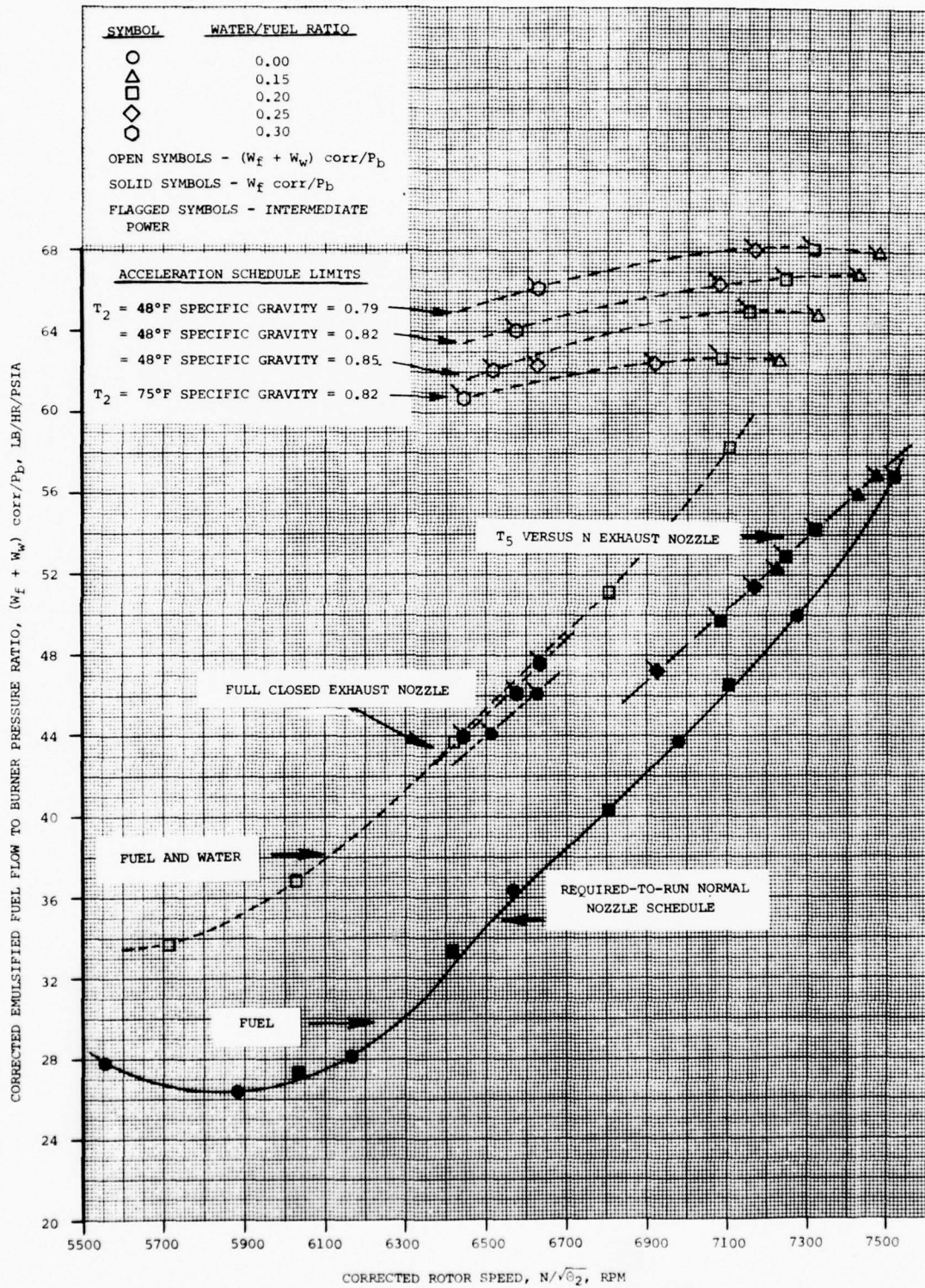


FIGURE 13. J79-GE-10 NO. 1 COMBUSTION LINER

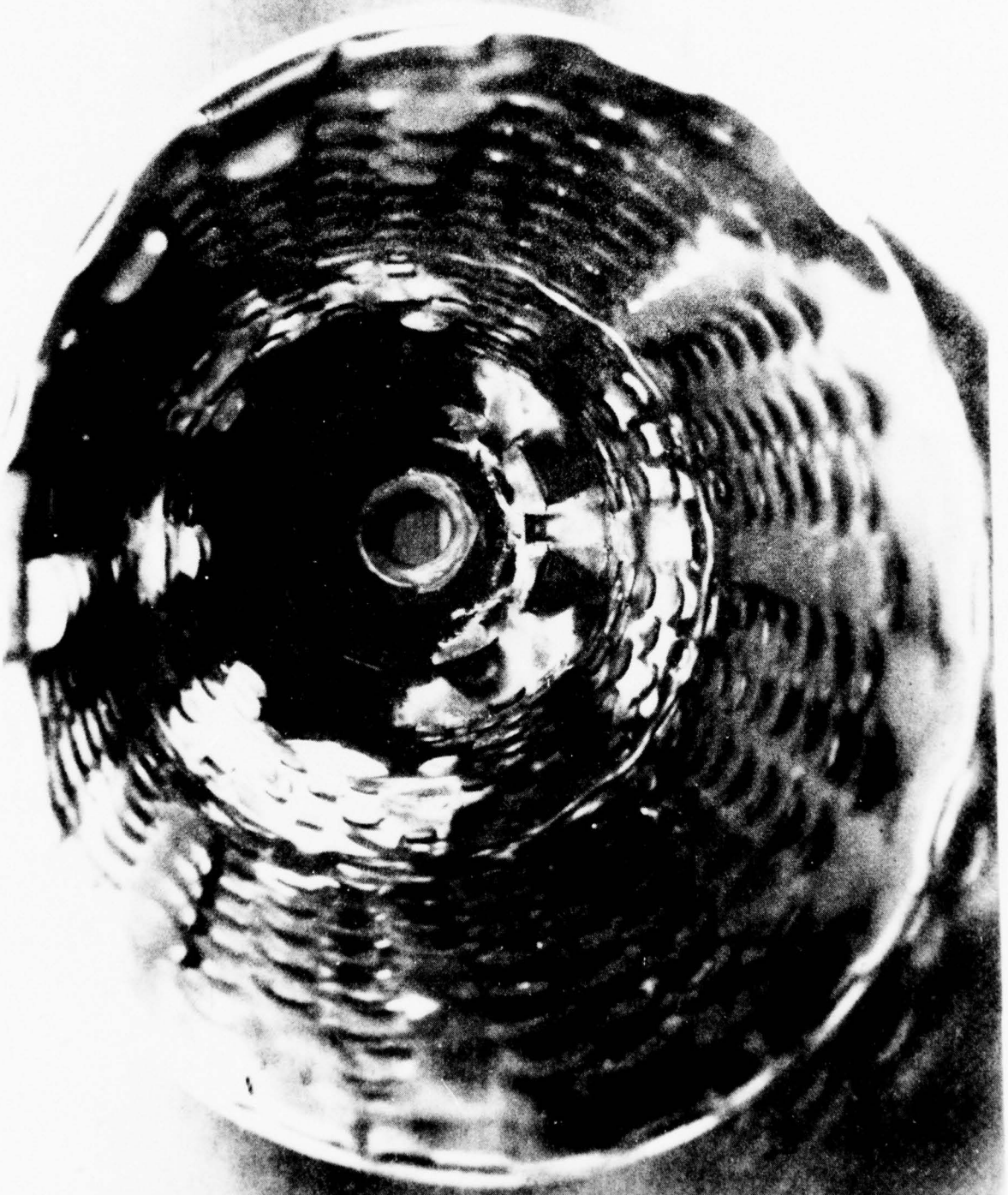


FIGURE 14. J79-GE-10 NO. 10 COMBUSTION LINER

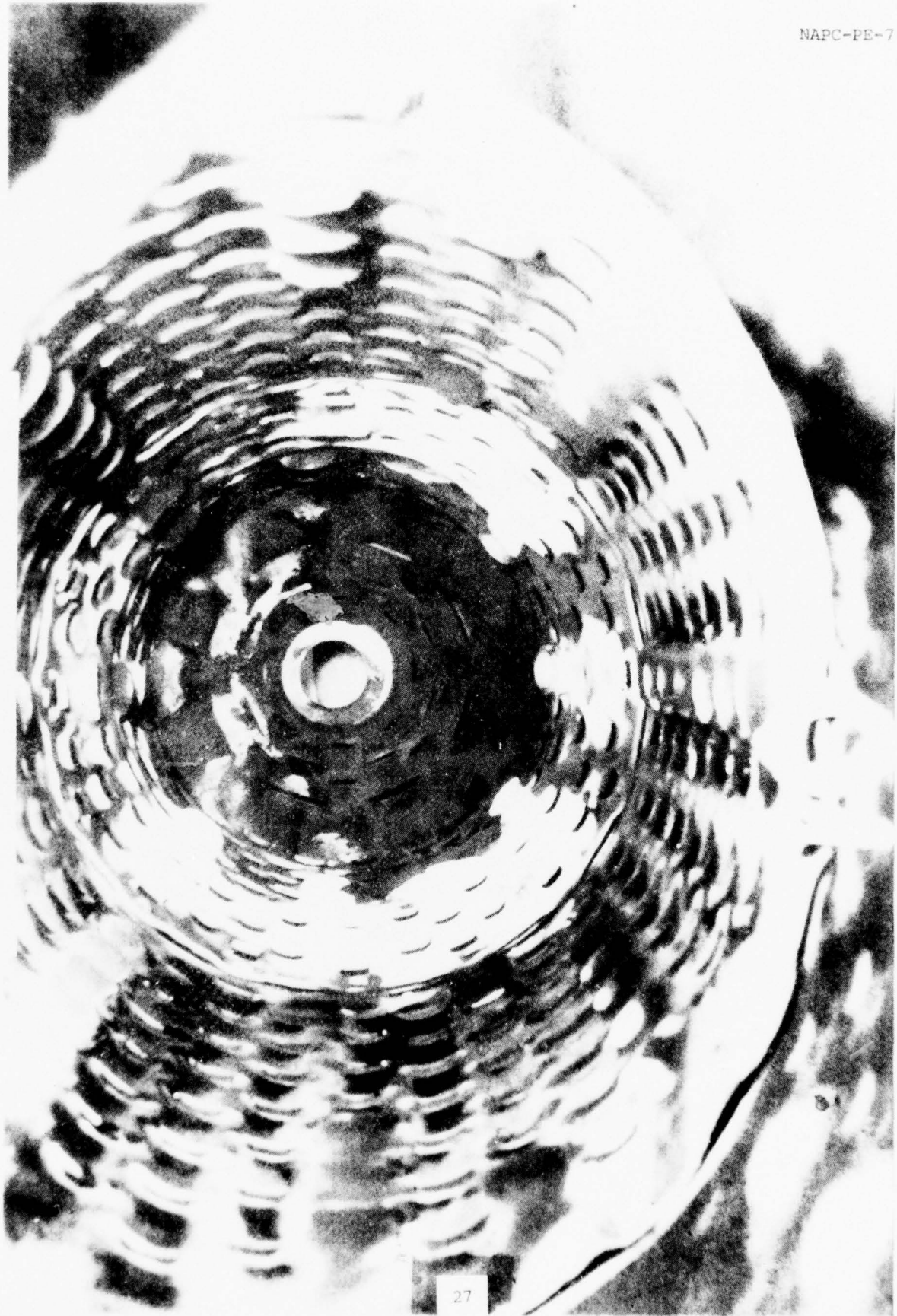


FIGURE 15. J79-GE-10 FUEL NOZZLE FROM COMBUSTION LINER NO. 1

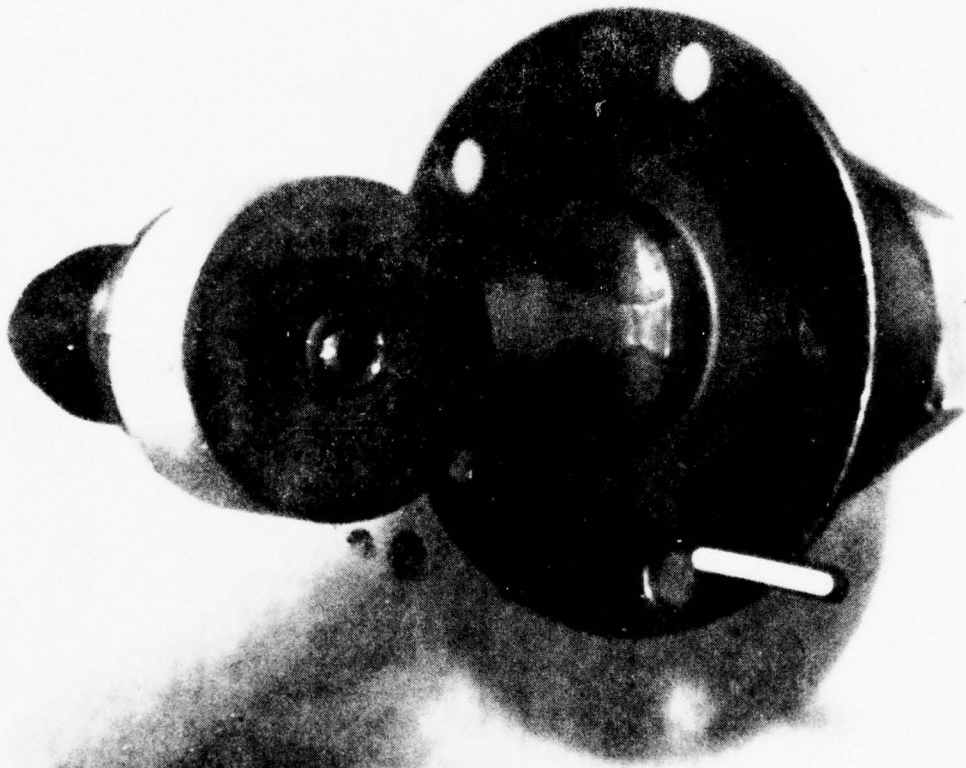
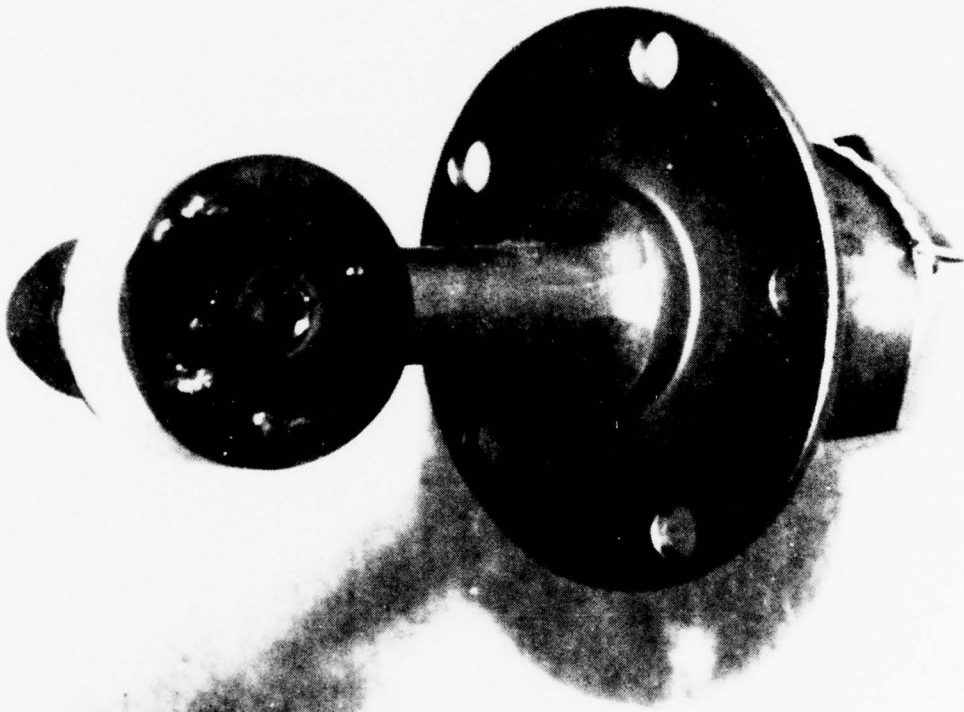


FIGURE 15. J79-GE-10 FUEL NOZZLE FROM COMBUSTION LINER NO. 10



10

FIGURE 17. TEST CELL EXHAUST SMOKE OPACITY VERSUS EMULSION WATER CONTENT

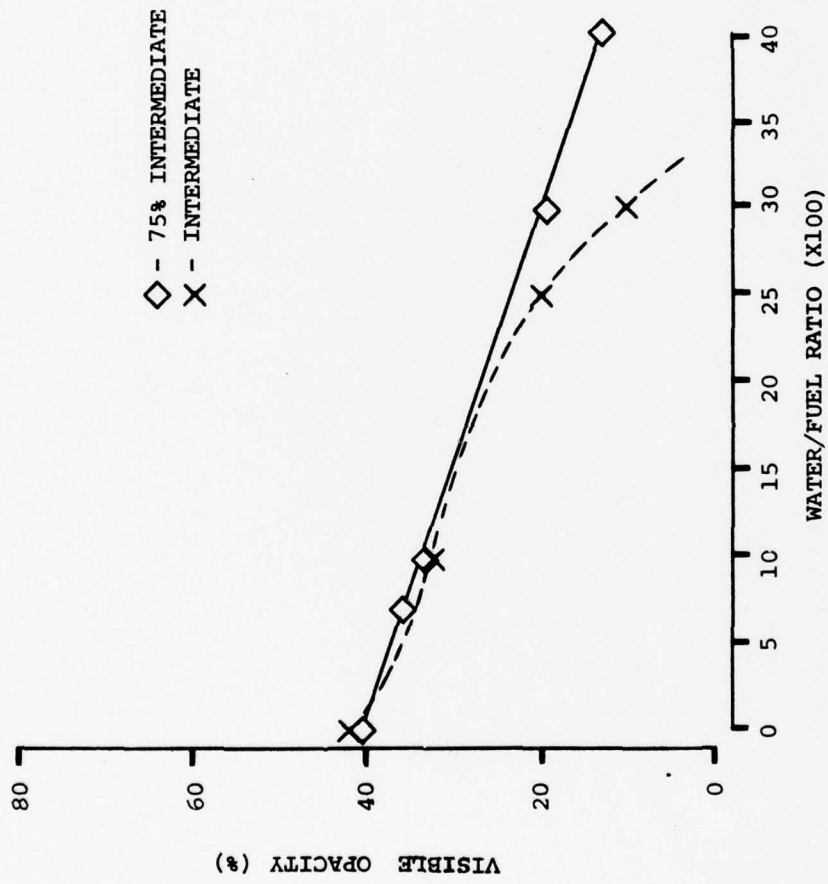


FIGURE 18. RELATIONSHIP BETWEEN ENGINE EPA SMOKE NUMBER AND TEST CELL SMOKE OPACITY

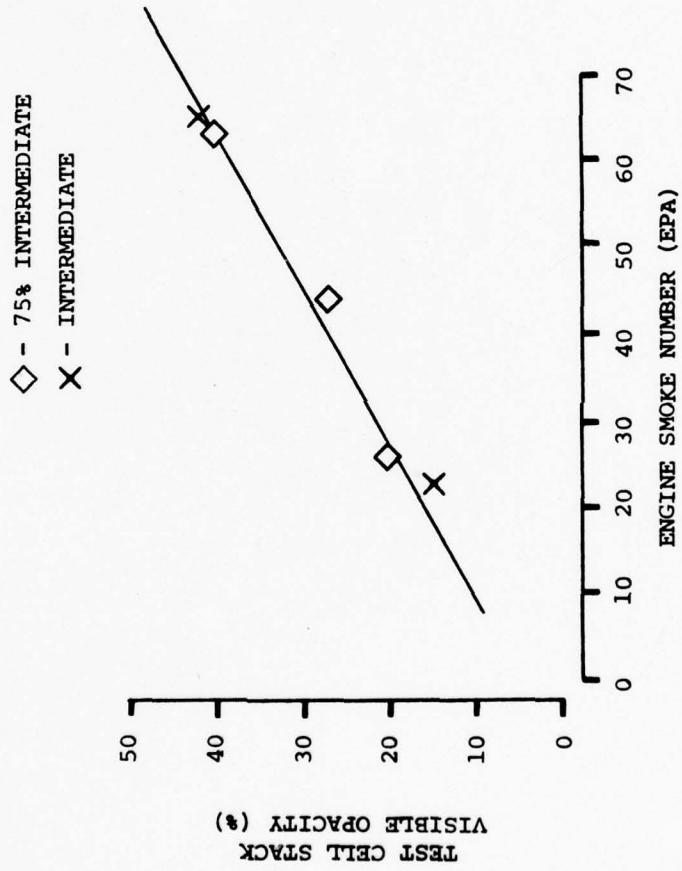


FIGURE 19. ENGINE SMOKE NUMBER VERSUS EMULSION WATER CONTENT

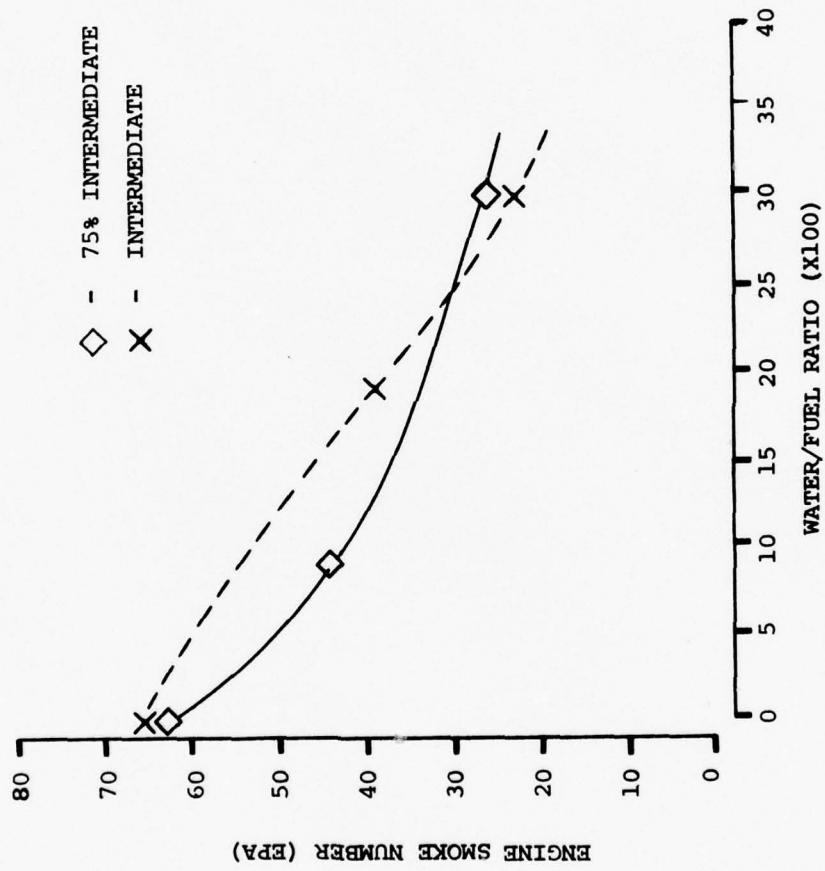


FIGURE 20. ENGINE CARBON DIOXIDE EMISSIONS VERSUS EMULSION WATER CONTENT

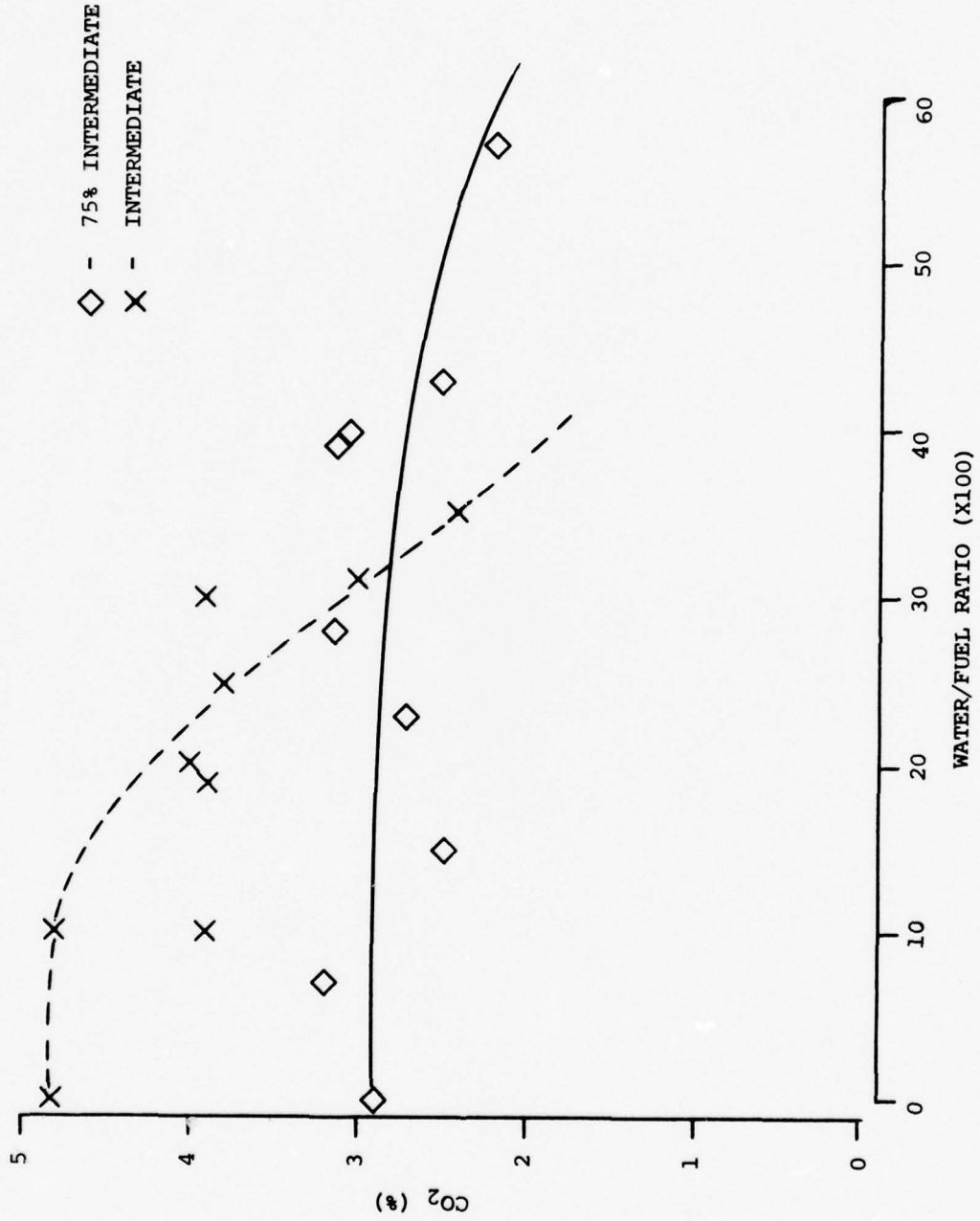


FIGURE 21. ENGINE CARBON MONOXIDE EMISSIONS VERSUS EMULSION WATER CONTENT

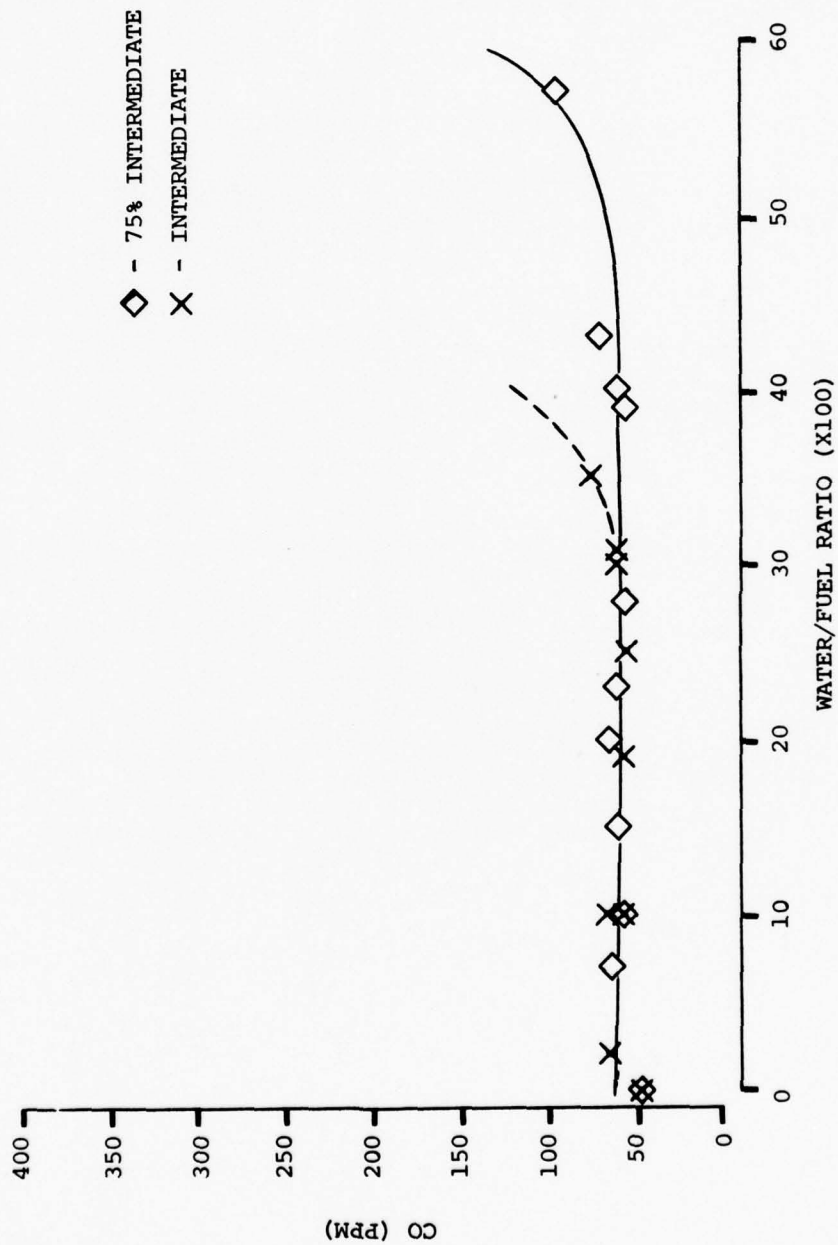


FIGURE 22. ENGINE OXIDES OF NITROGEN EMISSIONS VERSUS EMULSION WATER CONTENT

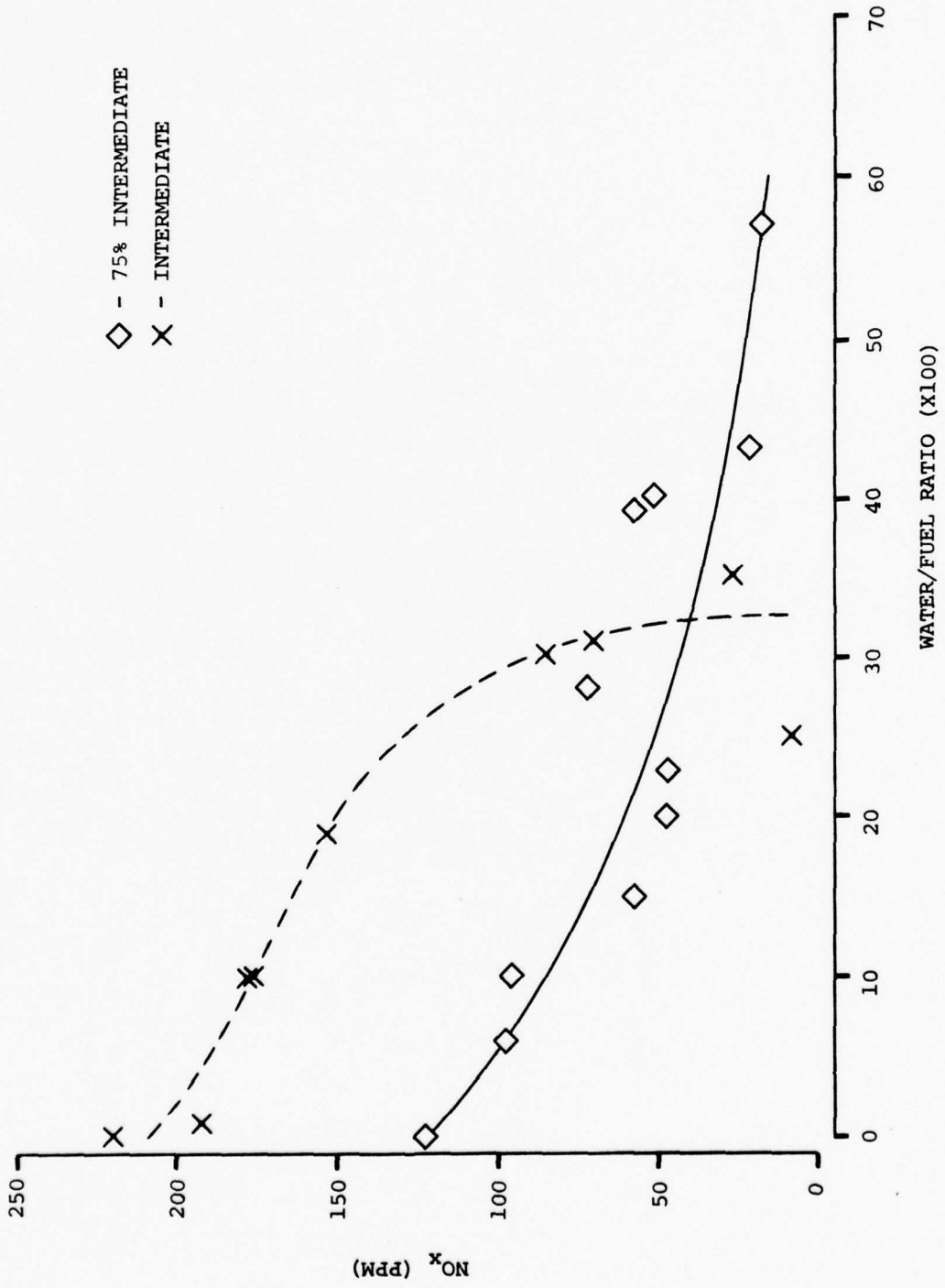


TABLE I

INSTRUMENTATION SYSTEM ACCURACIES

Variable Measured	Read-out System	Parameter	Range	Accuracy
Pressure	Scanivalve	P_{S2}, P_{S10}	0-25 psia	± 0.02 psi
		P_{T5}	0-50 psia	± 0.12 psi
		P_{S3}, P_b	0-250 psia	± 0.50 psi
		P_{S2}, P_{T2}	0-5 psia	± 0.01 psi
Temperature	Datum	T_2	to 400°	$\pm 2^\circ\text{F}$
		T_3, T_5	to 2000°F	$\pm 5^\circ\text{F}$
Flow Rate	Datum	W_{f1}, W_{f2}	0-13000 pph	± 20 pph
		W_{f3}	0-10000 pph	± 20 pph
Thrust	Baldwin Load Cell	F_N	0-15000 lb	± 50 lb
Speed	Datum	N	0-8000 rpm	$\pm 0.05\%$
Positions	Digital Voltmeter	CGVP	20° open to 17° closed	$\pm 0.5^\circ\text{F}$
		A_j	310-660 in ²	± 3.5 in ²

TABLE II
FUEL AND EMULSION SAMPLE ANALYSIS

Test Condition water/fuel ratio, lb water/lb fuel	Weight % Water in Emulsion lb water/lb total fluid		Specific Gravity @ 60°F	Viscosity, cs @ 40°F	Heat of Combustion BTU/lb (Fluid)
	Set	Measured			
0	0	0	0.817	3.2	18,489
0.10	9	13	0.838	4.1	-
0.20	17	19	-	-	15,684
0.22	18	16	0.849	5.6	-
0.30	23	25	0.860	-	14,960
0.32	24	25	0.857	4.7	-
0.35	26	27	0.864	4.5	-

TABLE III
TRANSIENT PERFORMANCE

*Inlet Air Temperature, $T_2 = 48^\circ\text{F}$

<u>Water/Fuel Ratio (X100)</u>	<u>MFC Specific Gravity Setting</u>	<u>Acceleration Time (sec)</u>
0	0.79	-
	0.82	2.00
	0.85	-
5	0.79	2.40
	0.82	2.70
	0.85	3.10
10	0.79	3.15
	0.82	4.85
	0.85	6.10
15	0.79	5.60
	0.82	5.40
	0.85	9.80
20	0.79	9.90
	0.82	10.20
	0.85	13.00

*Maximum acceleration time limit in reference 9 at this condition is 5.3 seconds.

TABLE IV

EFFECT OF EMULSION WATER CONTENT ON PARTICULATE EMISSIONS

Power Setting (Intermediate)*

<u>Water/Fuel Ratio (X10)</u>	<u>Particulates, mg/m³</u>
0	0.54
22	0.32

*Average from two runs.

TABLE VSUMMARY OF SIGNIFICANT TEST RESULTS

1. Evaluation of pre- and post-test engine calibration data revealed no measurable performance degradation as the result of using emulsified fuel.
2. The engine hot section did not exhibit any unusual deposits or deterioration due to the use of the water/fuel emulsion.
3. The net thrust of the engine increases slightly with increasing water concentration due to the additional mass flow of the water vapor through the exhaust nozzle.
4. There is a significant and increasing reduction in net thrust beyond a threshold water/fuel ratio at which the total flow (water plus fuel) through the main fuel control reaches the acceleration schedule limit. The water/fuel ratio at which this occurs at intermediate power varied from 0.10 to 0.15 as the specific gravity setting on the fuel control was changed from 0.85 to 0.79.
5. The amount of water that can be added to the fuel before the threshold water/fuel ratio is reached at nominal JP-5 specific gravity settings is not adequate for the required smoke reduction at intermediate power. The threshold ratio at lower engine power conditions is significantly higher.
6. The engine main fuel control performed satisfactorily throughout the test program with emulsified fuel.
7. The limited transient performance tests conducted revealed no engine operational problems. Engine acceleration times from idle to intermediate power increased with increasing water concentration as expected and did exceed the required time limit for this engine.
8. Engine EPA Smoke Number and test cell exhaust smoke opacity were substantially reduced. An emulsion with a water/fuel ratio of 0.30

TABLE V (CONTINUED)

reduced test cell smoke from 40 to 20 percent opacity for the 75 percent INT power condition.

9. An emulsion with a water/fuel ratio of 0.22 reduced engine particulate mass emissions by 42 percent.
10. Emulsions, containing up to 50 percent water, did not significantly alter the carbon monoxide exhaust emissions of this engine at the power rating tested.
11. The oxides of nitrogen emissions were reduced when the engine was operated on emulsified fuel. The amount of reduction was dependent on the engine power rating and water/fuel ratio of the emulsion.

REFERENCES

1. LAW SUIT: People of the State of California versus Department of the Navy, Civil Case No. C-76-0045 WHO, United States District Court for the Northern District of California of 9 January 1976.
2. REPORT: U.S. Army Fuels and Lubricants Research Laboratory (SWRI) Final Report AFLRL No. 84 "Reduction of Exhaust Smoke From Gas Turbine Engines By Using Fuel Emulsions", C. A. Moses and C. W. Coon, September 1976.
3. AUTHORIZATION: NAVMAT Work Request No. N0003777WR75020 dated 1 October 1976.
4. AUTHORIZATION: AFCEC Project Order No. 77-036 dated 24 February 1977.
5. REPORT: Naval Air Propulsion Test Center Letter Report No. NAPTC-LR-77-26 of 3 August 1977.
6. REGULATION: Code of Federal Regulations, Volume 40, Part 87, Regulations on Control of Air Pollution from Aircraft and Aircraft Engines.
7. REGULATION: Code of Federal Regulations, Volume 40, Part 60, Regulations on Standards of Performance for New Stationary Sources.
8. MANUAL: Intermediate Maintenance, NAVAIR 02B - 105AGD-6-1, for Turbojet Engine Models J79-GE-10 and J79-GE-10A of 1 October 1972; Change 4 of 1 June 1974.
9. MODEL SPECIFICATION: General Electric Company Turbojet Aircraft Engine J79-GE-10 Specification No. E-2039-A of 5 October 1965, Revised 1 March 1967.

NAPC-PE-7

APPENDIX A

FINAL REPORT ON

EVALUATION OF EMULSIFIED FUEL EFFECTS ON ENGINE COMPONENTS

NAPC-PE-7

NAVAL AIR PROPULSION TEST CENTER
TRENTON, NEW JERSEY 08628

NAPTC-LR-77-26

EVALUATION OF EMULSIFIED FUEL EFFECTS ON ENGINE COMPONENTS

FINAL REPORT

3 AUGUST 1977

Prepared by

Rudy E. Harrer
R. E. HARRER

EVALUATION OF EMULSIFIED FUEL EFFECTS ON ENGINE COMPONENTS

FINAL REPORT

NAVAIR Work Unit Plan No. NAPTC-966

References

- (a) NAVMAT Work Request No. N0003777-WR-75020 dated 30 Nov 1976
- (b) NAPTC Letter Report PE63:EWM:jas 3960 Ser E757 dated 15 May 1975
- (c) NAPTC Formal Report NAPTC-PE-60 of June 1975
- (d) NAVWEPS 02B-105AGC-502, Handbook Service Instructions Turbojet Engine Model J79-GE-8 and 8A dated 15 April 1965
- (e) NAPTC Contract No. N00140-77-M-1979 issued 17 March 1977
- (f) NAVAIR 03-110AEA-7, Technical Manual Overhaul Instructions, Fuel Control P/N 407767 dated 15 March 1971

Enclosures

- (1) Figure 1

1. Introduction.

a. The Navy has a program to retrofit older aircraft engines with "smokeless" combustors; however, all engines will not achieve "smokeless" operation for some period of time. Since these engines are tested at various Naval Air Rework Facilities (NARF's) following overhaul, those engines that smoke may at times produce sufficient smoke to be considered objectionable by the local citizens.

b. A contemplated solution for the reduction of engine exhaust smoke emission is the addition of water to the fuel system in such a manner as to produce a fuel/water emulsion. Testing by Southwest Research Institute had shown the emulsification principle to effectively reduce smoke with a small scale combustor rig. This principle was proposed for test cell smoke abatement at the NARF's. Prior to incorporating this technique as a standard test cell procedure, an engine test program has to be conducted to verify that the emulsification principle works, to determine the water concentration required and any detrimental effects. Therefore the Naval Air Propulsion Test Center (NAPTC) initiated such a program, which was authorized by reference (a).

c. A previous attempt to operate an engine with fuel containing water at NAPTC showed that engine malfunction would occur when a low concentration of water, less than 2 percent, was injected into the fuel stream (reference (b)). Also, the effects of water on fuel controls are rather notorious (reference (c)). However, one significant difference in this test program is that the water is divided into very fine droplets in the fuel with the aid of a homogenizer, which may eliminate the reference (b) and (c) problems. With this background, a decision was made to perform the program in two phases. The Phase I testing would evaluate the J79-GE-10 fuel components

NAPTC-LR-77-26

with the fuel/water emulsion under simulated post overhaul test cell engine operating conditions. Phase II testing would consist of the J79-GE-10 engine test in which the necessary water to fuel ratio would be established for smoke reduction using simulated post overhaul engine operating conditions.

d. The results of the Phase I testing were transmitted verbally to cognizant personnel so that a timely completion of the engine test program could be scheduled.

2. Conclusions.

a. The J79 engine fuel pump and control do not corrode significantly when subjected to an emulsion of water in fuel for a short period of time (13.6 hours).

b. Fuel system flushing and proper preservation techniques cannot eliminate all the emulsion from within the components.

c. A homogenized emulsion of water in fuel (15 parts water to 100 parts fuel) will begin to separate after twenty-four hours of storage.

d. Operation with an emulsion causes a slight shift in metered flow characteristics beyond that compensated for by resetting the control's density adjustment.

3. Recommendations.

a. The test program should proceed with the full scale engine evaluation.

b. The engine fuel control should be stored for an extended period of time, after being preserved, so that the effects of the residual emulsion can be evaluated.

c. Consideration should be given to adding a corrosion inhibitor to the fuel water emulsion to eliminate the necessity of flushing the fuel system after each engine shutdown.

4. Description. The selection of the J79-GE-10 fuel system for evaluation with emulsified fuel containing water was of special interest because rust and/or water contamination are the most predominant problems with the J79 fuel system. Of particular interest was the fuel control because many of the subcomponents within the body had a nitride coating. These coatings, desirable for their surface hardening characteristics, are more susceptible to corrosion. The fuel control (P/N 407767) is manufactured by Woodward Governor Company of Rockford, Illinois. The control, which meters engine fuel flow, controls the inlet guide vanes (IGV) and maintains engine rpm, is designed for operation with JP-4 and JP-5. High pressure filtered fuel is supplied by a model 024090-019 fuel pump manufactured by Sundstrand Aviation Mechanical, a unit of the Sundstrand Corporation, formerly Pesco Products Division of Borg-Warner Corporation. Both the pump and control are directly driven by the engine gearbox. For purposes of the test program both articles were located on a variable speed drive with a fuel system as

shown on figure 1, enclosure (1).

5. Method of Test.

a. The simulation of the NARF post overhaul engine test procedure was based upon the engine test requirements of reference (d). The decision was made to operate two hours per day for five days with emulsified fuel. The ten hours accumulated would simulate total test cell time. Following each two hours of operation, the system was flushed for fifteen minutes with JP-5 fuel, a procedure that would be mandatory for scheduled test cell shutdowns if the emulsion principle were to be incorporated. During shutdown periods between the tests, the residual fuel in the system was not drained nor was any attempt made to keep the system filled. Tests on odd days of the five day program, simulated engine and fuel system checkout, functional evaluation, turbine wear in, and performance check runs. During the even days the tests simulated trouble shooting techniques, throttle bursts, afterburner functional tests, and a brief normal operating period.

b. Emulsification of the fuel was accomplished by homogenizing a water and JP-5 mixture. Two percent by volume of emulsifier was added to the JP-5 before mixing with the water. The emulsifier consisted of sorbitan monooleate (Span 80) and polyoxyethylene sorbitan monooleate (Tween 80) in a nine to one ratio respectively. This solution was fed to the homogenizer and mixed with water at the inlet. A volume of water equivalent to fifteen percent of the JP-5 volume was injected. The analysis of the emulsion generated was 13 percent water, 85.3 percent fuel, and 1.7 percent emulsifier. This emulsion was then rehomogenized each morning prior to initiation of a test sequence.

c. Newly overhauled fuel components were requested. However, due to priority restrictions, only a new fuel control was available for the test program. The fuel pump was removed from an in-house engine. Because pump time and condition were unknown, it was disassembled and inspected prior to installation for test. The fuel control was assumed to be satisfactory. The components were mounted on a 112 KW (150 horsepower) variable speed drive and evaluated. Upon the conclusion of the test the pump was disassembled and inspected at NAPTC. The control was shipped under contract (reference (e)) to the manufacturer, Woodward Governor Company, for disassembly and inspection. Preservation prior to shipment was in accordance with reference (f).

6. Discussion and Analysis of Results.

a. Emulsification of the fluid was accomplished without any difficulty. Seven 0.19 m^3 (50 gallon) drums of JP-5 were initially doped with $0.38 \times 10^{-1} \text{ m}^3$ (1 gallon) of emulsifier and stirred for twenty minutes to assure total dispersion. By visual observation, the emulsifier was dispersed almost immediately. The fuel was then transferred into a 1.9 m^3 (500 gallon) holding tank and pumped through the homogenizer. After stabilizing homogenizer pressure at 17.24 MPa (2,500 psi), water was injected into the flow stream at a rate of $126 \text{ cm}^3/\text{s}$ (2 gpm) until 0.20 m^3 (53 gallons) were amassed. Recirculation of this mixture was continued for twenty minutes

and then stopped so that emulsion stability could be determined. Slight skimming occurred between 24 and 48 hours. A thin layer of JP-5 could be seen floating on top of the emulsion. This mixture, when reemulsified through the homogenizer regained its stability characteristics. A decision was therefore made to retain the same emulsion for the entire test program using a daily fifteen minute regeneration cycle immediately prior to the test. During this brief period the homogenizer, which had a fixed displacement, processed 2.36 m³ (625 gallons) of fluid.

b. Prior to installation, the J79-GE-10 main engine fuel pump, P/N 512D892P, S/N 466 was disassembled and inspected. Bluing of the high pressure pump gears, minor pitting on the front cover bearings, and over-temperature or bluing on the body bearings were the only component discrepancies noted. The pump was reassembled and installed on the variable speed drive along with the main fuel control. A partial pretest calibration was conducted with JP-5 fuel to assure system and component acceptance, followed by a check out run using odd day test conditions. Total operation with JP-5 fuel was 4.2 hours before operation with emulsion was started. Performance of the control was within acceptable limits.

c. During the first cycle of operation with emulsion, it was noted that metered fuel flow (kilograms per second) was approximately one percent lower than that obtained with JP-5. Upon completion of the earlier evaluation with JP-5, the specific gravity adjustment on the control had been increased to compensate for the higher specific gravity of the emulsion (0.837). Without the adjustment, a higher weight flow than that with JP-5 (specific gravity 0.814) would have been anticipated. The flow increase would have been approximately 1.4 percent. The resultant lower flow with the emulsion could not be explained. It was hypothesized that perhaps the pump caused emulsion breakdown and the non-homogeneous mixture resulted in lower flow. However, subsequent samples taken downstream of the control showed that the fluid was still homogeneous. The low flow characteristics gradually diminished and at the end of the fifth cycle flow was approximately 1.7 percent higher than the JP-5 data. Since final calibration with JP-5 showed no sign of increase or change from the earlier data it was judged that the variation with emulsion was due to a combination of instrumentation tolerances and the effects of the emulsified fluid. Other than the flow variation, no other noticeable performance variations were observed.

d. The fuel flush, which followed every cycle, was conducted for fifteen minutes. Total fuel flow during each flush cycle was between 0.284 and 0.378 m³ (75 and 100 gallons). While being flushed, the throttle linkage was actuated through its 1.97 rad (113°) arc as speed was varied between 524 and 1047 rad/s (500 and 1000 rpm). To help minimize emulsion entrapment, the top-most control fitting was also opened and allowed to vent and drain fuel. The time period and flow quantity were selected as appropriate values for elimination of the bulk of the residual emulsion. Samples taken of the fuel at the end of the flush period still contained milky traces of the emulsion. Upon conclusion of the flush, this residual emulsion inside the fuel system remained until the following day's test. The rest period between the third and fourth cycle included a weekend layover. In addition to these soaks,

with minimal traces of emulsion present, shutdown periods with full emulsion entrapment were also programmed. Each cycle contained three or four three-minute rest periods totalling 0.9 hours for the test. An additional total of 2.5 hours were accumulated between cycle shutdown and flush initiation for the test. These shutdowns, when compiled with emulsion operational time of 10.2 hours resulted in the components being exposed to the 13 percent water emulsion for a total of 13.6 hours. The total time that the components were exposed to the water/fuel emulsion was considered comparable to that exposure time which would be experienced during actual test cell performance checks at the NARF's.

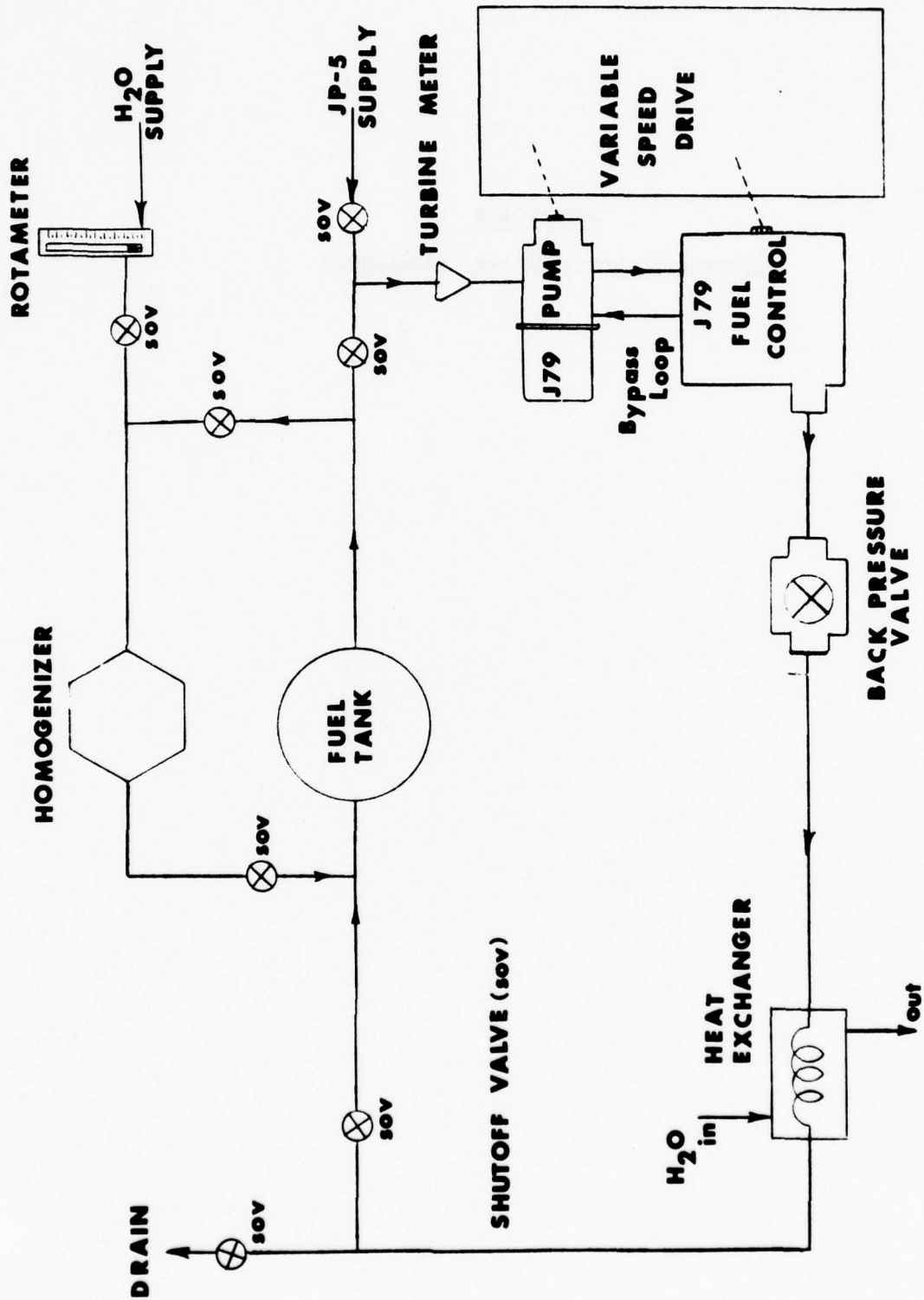
e. Upon completion of the final test the fuel pump and control were removed for internal inspection. The pump disassembly was conducted in-house as was done prior to the test program. No change in pump condition was noticeable. None of the internal components exhibited any trace of corrosion due to the emulsion. Disassembly of the fuel control was accomplished at Woodward Governor's facility in Rockford, Illinois. After testing, the control was preserved with Military Specification MIL-O-6081 Grade 1010 oil. Disassembly of the control was conducted twelve days after conclusion of the test program. Complete control teardown disclosed superficial discoloration on five nitrided components. Three were judged to be a result of the machining process which removed the nitride coating and two were deemed to be the result of exposure to water. The three nitrided components which were discolored due to machining were the pistons from the P₃ (P/N 405298), the Governor Pilot (P/N 401687) and the CIT Pilot (P/N 402668) valve assemblies. Nitrided components which displayed water induced discoloration patterns were the internal surface of the fuel relief valve piston (P/N 405286) and the on-off speed adjustment lever (P/N 402643) in the area where it is attached to the speed adjustment piston. Additionally, the springs of the fuel relief valve assembly (P/N's 192215 and 192169) which are nestled within the piston (P/N 405286) of the relief valve were slightly corroded. During disassembly of the control quantities of emulsion were found within cavities even though two hours of post test operation were performed with clean JP-5 and prior to preservation, all ports were thoroughly drained. The remaining emulsion trapped inside the control broke down allowing free water to contact metal and begin oxidation of some sub-components. Although all of the aforementioned components were in good condition and considered by Woodward to be acceptable for reuse, it was thought that the relief valve (P/N 405292) would be most susceptible to corrosion during any extensive shutdown or storage after having been exposed to the emulsion. Based on these results, it was recommended that the full scale engine test be conducted and that an extended storage period for the engine fuel control be scheduled to determine whether significant corrosion of the relief valve or any other component would occur. The results of the engine program and inspection of the fuel control will be reported separately.

f. Flushing of the fuel system components with JP-5 following each shutdown would present added complexity and expense to the normal NARF engine test. This requirement might be eliminated with the incorporation of a corrosion inhibitor in the fuel/water emulsion. Corrosion inhibitors, which also promote emulsification of water in fuel, could be incorporated as a component of the emulsifier which is initially blended into the JP-5 fuel.

APPENDIX B

EQUATIONS AND CALCULATED PARAMETERS

FIGURE 1. FUEL EMULSION TEST SCHEMATIC



ENCLOSURE (1)

EQUATIONS AND CALCULATED PARAMETERS

1. P_{T2avg} = Average of 4 measurements
2. T_{oavg} = Average of 5 measurements
3. P_{s10avg} = Average of 4 measurements
4. P_{s2avg} = Average of 4 measurements
5. $\delta_2 = P_{T2avg}/29.92$
6. $\theta_2 = T_{oavg} (^{\circ}R)/518.7$
7. $\sqrt{\theta_2} = \sqrt{T_{oavg} (^{\circ}R)/518.7}$
8. $\theta^{.68} = (T_{oavg} (^{\circ}R)/518.7)^{.68}$
9. $N = C \times (\text{cps of counter})$
10. $N_{corr} = N/\sqrt{\theta_2}$
11. P_{s3} = Single Measurement
12. P_b = Single Measurement
13. P_{T5avg} = Average of 6 measurements
14. P_{s3}/P_{T2avg}
15. P_{T5avg}/P_{T2avg}
16. T_{3avg} = Average of 5 measurements
17. T_{3avg}/T_{oavg}
18. $EGT = T_{5avg}$ = Average of 12 measurements from standard harness
19. $W_{f1} = Hz_1 \times C_{f1} \times SG$
20. $W_{f2} = Hz_2 \times C_{f2} \times SG$
21. $W_{ft} = W_{f1} + W_{f2}/2$
22. $W_{f3} = Hz_2 \times C_{f3} \times SG$
23. $W_{ft\ corr} = W_{ft}/\delta_2 \sqrt{\theta_2}$
24. W_{ft}/P_b

EQUATIONS AND CALCULATED PARAMETERS25. $W_{a2} =$ (For Bellmouth Installation)

$$70.727 \times A_2 \times K \times P_{s2avg} \sqrt{\frac{2g}{R T_{oavg}} \frac{\gamma}{\gamma-1} \left(\frac{P_{T2avg}}{P_{S2avg}}\right)^{\frac{\gamma-1}{\gamma}} \left[\left(\frac{P_{T2avg}}{P_{S2avg}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

26. $W_{a2corr} = W_{a2} \sqrt{\theta_2}/\delta_2$

27. F_m

28. $F_{mcorr} = F_m/\delta_2$

29. $TSFC = W_{ft}/F_m$

30. $TSFC_{corr} = TSFC/\theta^{.688}$

31. CGVP = measured by use of calibrated potentiometer

32. A_j = measured by use of calibrated potentiometer

APPENDIX C

RESULTS OF TESTS ON FUEL CONTROL

NAPC-PE-7

OPNAV 5216/144 (REV 6 70)
S N 0107 LF 778 8099

DEPARTMENT OF THE NAVY

Memorandum

PE71:RH:vyh
10350

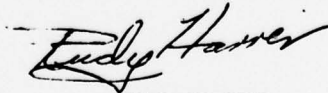
DATE: 6 September 1977

FROM R. Harrer, PE71

TO A. Klarman, PE71

SUBJ NAVAIR WUP NO. NAPTC-966 - Fuel Control Storage Test

1. The J79-GE-10 engine fuel control, which was used during a test cell program to evaluate the effects of water/fuel emulsions on pollution reduction, was partially disassembled on 30 June 1977 to inspect the effects of storage on the internal components. The control, P/N 407767, S/N 813172, had been preserved with 1010 oil on 29 April 1977 after completion of a 10 hour test program.
2. Removal of the fuel control cover and internal inspection of the 3D bracket assembly revealed no corrosion buildup. Specific inspection of the fuel relief valve assembly and the on-off speed adjustment lever also revealed no corrosion. These two components had displayed corrosion patterns during an earlier evaluation program of the J79-GE-10 fuel system.
3. One component, the IGV valve plunger assembly (P/N 401620), had land scoring and a small area of intergranular corrosion. The mating sleeve could not be removed from the control body and therefore sleeve inspection was not possible. Photographs of the plunger were taken by PE6 personnel (Jim Newhart); however the pictures have not been received from NADC.
4. Traces of emulsion were still apparent within the control. The greatest quantity was removed from the fuel relief valve cavity. It is not known how long the engine was run following the final injection of emulsion. However the continued presence of water in the control is a danger to the integrity of the control during storage. The recommendation to provide a corrosion inhibitor to the fuel during any contemplated program is warranted to minimize this danger.



RUDY HARRER

UNITED STATES GOVERNMENT

Memorandum

TO : Tony Klarman

PE71:REH:jjm
10340
DATE: 21 September 1977

FROM : Rudy Harrer

SUBJECT: Fuel/Water Emulsion Test - NAPTC WUA No. 966

REF : (a) NAPTC Memo PE71:RH:vyh 10350 dtd 6 Sep 77

ENCL : (1) Figures 1 thru 5

1. Photographs of the J79-GE-10 IGV plunger assembly which were discussed in reference (a) are forwarded as Figures 1 thru 4 of enclosure (1). A detail of the IGV valve assembly from which the plunger was removed (shown in figure 5) displays the areas where photographs were taken.
2. Flaking on the leading land edge (Figure 1) and spalling in the crotch of the second land (Figure 3) may have been due to fatigue stress, however without sectioning of the plunger no valid assessment can be made. Corrosion on the filter, shown on Figure 2, was judged to be due to residual flux used in soldering the filter to the plunger. Finally, Figure 4 shows the black radial lines which were typical on the lands, and two spots of corrosion. This corrosion was most likely due to the water in the fuel. Cause of wear was not determinable. All photographs are at 45 x magnification.


RUDY HARRER



5010-108

C-3

Buy U.S. Savings Bonds Regularly on the Payroll Savings Plan

FIGURE 1. AREA A

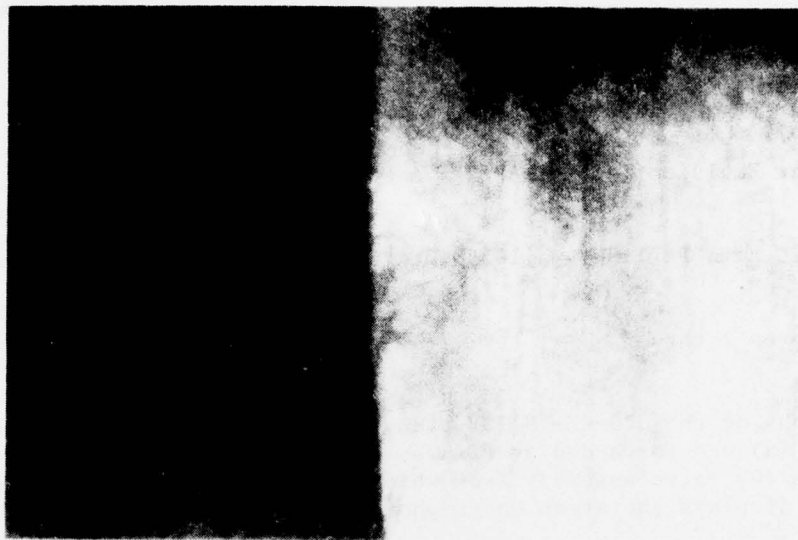


FIGURE 2. AREA B

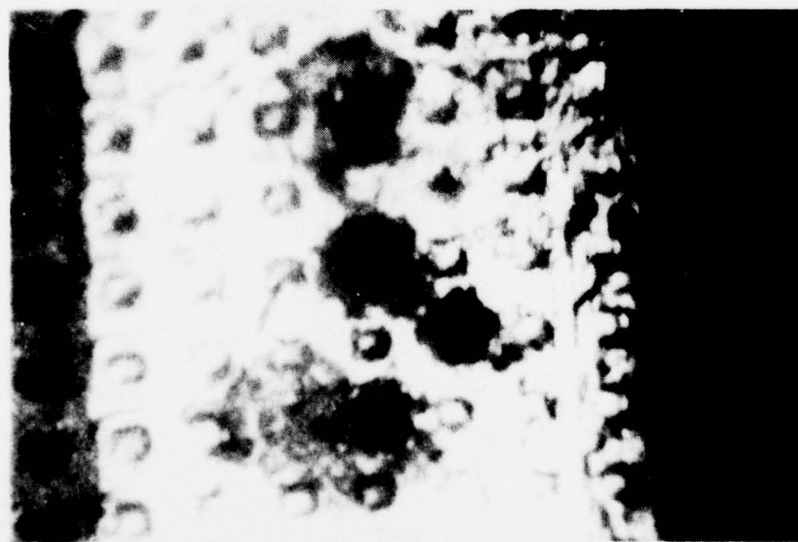


FIGURE 3. AREA C

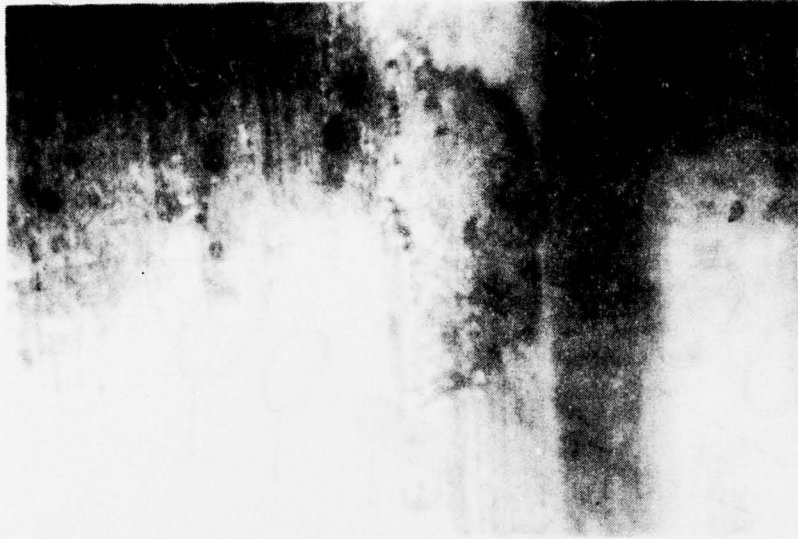
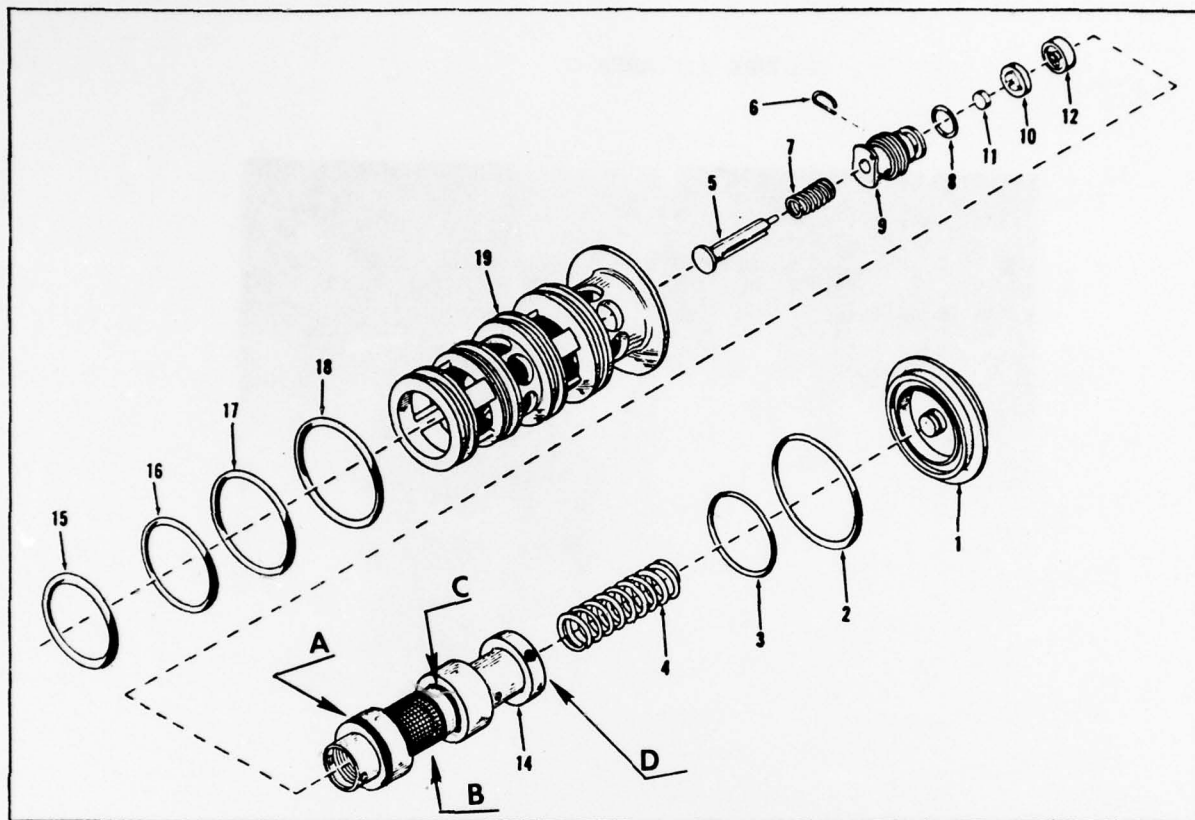


FIGURE 4. AREA D



FIGURE 5. VALVE DETAIL BREAKDOWN



A - Area of Flaking
 B - Area of Corrosion

C - Area of Spalling
 D - Area of Corrosion

FIG. & INDEX NO.	PART NO.	DESCRIPTION	1 2 3 4 5 6 7							UNITS PER ASSY.	USABLE ON CODE
			1	2	3	4	5	6	7		
	402638	VALVE ASSEMBLY, IGV (See figure 2 for NHA)								REF	
-1	401948	. CAP, IGV valve								1	
-2	2-124L308-8	. PACKING, PREFORMED (02697) (182579) (KD)								1	
-3	2-22L308-8	. PACKING, PREFORMED (02697) (182565) (KD)								1	
-4	192202	. SPRING, IGV plunger (helical) (KD)								1	
-5	401853	. PLUNGER, Power actuator								1	
		(ATTACHING PARTS)									
-6	401712	. CLIP, IGV valve stem (KD)								1	
		-----*									
-7	192201	. SPRING, IGV plunger (helical) (KD)								1	
-8	2-10L308-8	. PACKING, PREFORMED (02697) (182557) (KD)								1	
-9	401894	. SEAT, IGV clamping								1	
-10	401751	. SPACER, IGV power booster (KD)								1	
-11	401711	. DISK, IGV valve (KD)								1	
-12	401709	. SEAT, IGV valve								1	
-13	Not Used										
-14	401620	. PLUNGER ASSEMBLY, IGV								1	
-15	2-119L308-8	. PACKING, PREFORMED (02697) (182575) (KD)								1	
-16	2-120L308-8	. PACKING, PREFORMED (02697) (182576) (KD)								1	
-17	2-121L308-8	. PACKING, PREFORMED (02697) (182577) (KD)								1	
-18	2-122L308-8	. PACKING, PREFORMED (02697) (182578) (KD)								1	
-19	403527	. SLEEVE, IGV valve								1	

APPENDIX D

ENVIRONMENTAL TEST DATA

SMOKE

Engine Power	Water/Fuel Ratio	Smoke Number	Engine Opacity %	Stack Opacity %	Ringlemann Number
Idle	0.00	29.0	4.0	6.0	9.0
	0.00	60.0	9.0	22.0	36.0
	0.04	44.0	3.0	11.0	-
30% INT	0.13	-	3.0	8.0	-
	0.19	34.0	2.0	7.0	-
	0.26	-	0.4	10.0	16.0
	0.00	63.5	8.0	21.0	40.0
	0.07	-	6.0	22.0	38.0
	0.09	44.0	1.0	11.0	-
	0.10	-	3.0	15.0	27.0
75% INT	0.15	-	3.0	10.0	-
	0.22	-	3.0	8.0	-
	0.30	26.0	1.0	7.0	20.0
	0.41	-	1.0	7.0	13.0
	0.57	-	1.0	4.0	-
	0.00	65.0	8.0	21.0	40.0
	0.11	45.0	2.0	6.0	-
NR	0.25	30.0	2.0	6.0	-
	0.37	21.0	1.0	4.0	-
	0.00	65.0	6.0	21.0	42.0
	0.02	-	4.0	11.0	-
	0.10	-	3.0	13.0	32.0
INT	0.19	39.0	2.0	8.0	-
	0.25	-	3.0	9.0	20.0
	0.30	23.0	2.0	6.0	15.0
	0.35	-	1.0	5.0	-

NOTE: INT = Intermediate; NR = Normal Rated

PARTICULATESPower Setting (INT)

<u>Water/Fuel Ratio</u>	<u>Particulates mg/m³</u>
0.00	0.65
0.00	0.43
0.19	0.31
0.25	0.32

GASEOUS EMISSIONSPower Setting (IDLE)

<u>Water/Fuel Ratio</u>	<u>CO ppm</u>	<u>CO₂ %</u>	<u>HC ppm</u>	<u>NO ppm</u>	<u>NO_x ppm</u>
0.00	320	1.38	34.7	5.0	7.5
0.00	400	1.58	6.5	7.8	7.8

GASEOUS EMISSIONSPower Setting (INT)

<u>Water/Fuel Ratio</u>	<u>CO ppm</u>	<u>CO₂ %</u>	<u>HC ppm</u>	<u>NO ppm</u>	<u>NO_x ppm</u>
0.00	45.0	4.83	7.7	218.8	219.2
0.02	65.0	4.0	2.1	195.0	192.1
0.10	65.0	4.8	3.3	178.4	178.4
0.10	55.0	3.9	2.2	176.4	176.4
0.19	55.0	3.9	2.2	152.9	152.9
0.25	55.0	3.8	-	7.8	7.8
0.30	60.0	3.9	2.8	78.4	84.3
0.31	60.0	3.0	2.8	70.6	70.6
0.35	62.5	2.4	2.7	26.5	26.5

GASEOUS EMISSIONSPower Setting (30% INT)

<u>Water/Fuel Ratio</u>	<u>CO ppm</u>	<u>CO₂ %</u>	<u>HC ppm</u>	<u>NO ppm</u>	<u>NO_x ppm</u>
0.00	70.0	1.65	9.3	35.0	37.5
0.13	77.5	1.91	-	18.6	18.6
0.26	102.5	1.65	5.1	15.7	19.7
0.62	107.5	1.65	11.1	7.8	9.8

GASEOUS EMISSIONSPower Setting (75% INT)

<u>Water/Fuel Ratio</u>	<u>CO ppm</u>	<u>CO₂ %</u>	<u>HC ppm</u>	<u>NO ppm</u>	<u>NO_x ppm</u>
0.00	45.0	2.90	4.6	115.0	122.5
0.07	65.0	3.20	-	9.6	98.0
0.10	55.0	3.20	-	91.1	95.0
0.15	60.0	2.48	1.8	56.8	57.8
0.20	65.0	2.50	1.4	47.0	47.0
0.23	60.0	2.70	-	47.0	47.0
0.28	55.0	3.16	-	80.6	86.2
0.39	55.0	3.13	-	55.9	57.8
0.40	60.0	3.05	1.95	51.0	51.9
0.43	70.0	2.50	1.4	21.0	21.2
0.57	95.0	2.19	2.5	15.7	17.6

GASEOUS EMISSIONSPower Setting (NR)

<u>Water/Fuel Ratio</u>	<u>CO ppm</u>	<u>CO₂ %</u>	<u>HC ppm</u>	<u>NO ppm</u>	<u>NO_x ppm</u>
0.00	45.0	4.05	5.4	195.0	211.7
0.25	55.0	3.43	-	83.3	83.3

APPENDIX E

ANALYSIS OF THE EFFECT OF A SPECIFIC GRAVITY SETTING
OF 0.72 ON MAIN FUEL CONTROL PERFORMANCE WITH EMULSIFIED FUEL

OBJECTIVES:

1. Determine the effect of MFC specific gravity setting of 0.72 on the Acceleration Schedule Limit (ASL).
2. Compare ASL to emulsion flow required to operate the engine at INT power with a water/fuel ratio of 0.30.

ASSUMPTIONS:

1. INT power rating fuel flow (W_f) of 10250 lb/hr will not be affected by the water in the emulsion.
2. INT power rating combustor pressure P_b of 180 psia will not be affected by the water in the emulsion.
3. Maximum fluid flow rate through the MFC varies linearly with the MFC specific gravity setting. The effect of actual fluid density is neglected because it is not a factor in this situation.
4. An emulsion water/fuel ratio of 0.30 is required to control the test cell exhaust plume opacity to a value of 20 percent.

ANALYSIS:

1. The following data were obtained from Figure 12 of this report for a water/fuel ratio of 0.30.

<u>MFC Specific Gravity Setting (SGS)</u>	<u>ASL (LB/HR/PSIA)</u>
0.85	62.2
0.82	64.2
0.79	64.4

The equation for the best straight line for these data determined by the method of Least Squares Analysis is:

$$ASL = 121.7 - 70 \text{ SGS}$$

Substituting for a SGS of 0.72, the ASL value is 71.3 LB/HR/PSIA. This value represents the maximum that could be achieved with the MFC SGS of 0.72 and a water/fuel ratio value of 0.30 at the ambient conditions of test shown in Figure 12.

2. Maximum water/fuel ratio possible at INT power with an ASL equal to 71.3 and a 180 psia combustor pressure value is determined as follows:

$$ASL = \frac{W_{\text{fuel}} + W_{\text{water}}}{P_b}$$

$$W_{\text{water}} = (ASL)(P_b) - W_{\text{fuel}} = (71.3)(180) - 10250 = 2584 \text{ lb/hr}$$

$$W_{\text{water}}/W_{\text{fuel}} = \frac{2584}{10250} = 0.25$$

3. The ASL value required for the MFC to meter a 0.30 water/fuel ratio emulsion at INT power is calculated as follows:

$$ASL = \frac{W_{\text{fuel}} + W_{\text{water}}}{P_b} = \frac{10250 + 10250(0.30)}{180} = 74.0 \text{ lb/hr/psia}$$

4. The combustor pressure required in order to meter an emulsion having a water/fuel ratio of 0.30 and an ASL of 71.3 is:

$$ASL = \frac{W_{\text{fuel}} + W_{\text{water}}}{P_b} = 71.3 = \frac{10250 + 10250(0.30)}{P_b}$$

$$P_b = 187 \text{ psia}$$

CONCLUSIONS:

1. The ASL value (74) required to meter an emulsion having a water/fuel ratio of 0.30 at INT power is greater than the maximum ASL value (71.3) possible with this engine at a MFC SGS setting of 0.72.
2. The maximum water/fuel ratio emulsion that can be injected into this engine at INT power is 0.25. Based on Figure 17 of this report, the 0.25 water/fuel ratio corresponds to a visible opacity of 25 percent which is unsatisfactory.
3. A 4 percent increase in combustor pressure would be required to raise the ASL ratio to 74.0, which is the value necessary to meter an emulsion with 0.30 water/fuel ratio at INT power.