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EVALUATION OF SHELLDYNE-H FUEL FOR GAS TURBINE ENGINE USE

Robert S. McCarty and Edward L. Brandys
AiResearch Manufacturing Company of Arizona,
A Division of The Garrett Corporation

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FOREWORD

This final technical report describes work performed under Contract F33615-69-C-1864, Project 139A-63217F, from June to November of 1969. Contract performance was accomplished by the AiResearch Manufacturing Company of Arizona, a division of The Garrett Corporation, located at 402 South 36th Street, Phoenix, Arizona 85034. The contract was issued by the Air Force Systems Command, Aeronautical Systems Division, Wright-Patterson AFB, Ohio 45433. The USAF program monitoring organization was AGM-86A SPO, and the project engineer was W. Woeste, ASZV. This report was submitted in December 1969.

AiResearch project activity covered by this report was conducted by Theodore E. Sarphie on the fuel control, and by Charles G. Mackay on combustion, and was supervised and directed by P. Engel, SCAD Project Engineer; F. L. Roberts, Senior Project Engineer, Fan and Jet Engines; and R. Bodemuller SCAD Program Manager.

This report is identified by the contractor as AiResearch Technical Report PE-8067.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

ARCHIE L. WOOD, Colonel, USAF
Director, AGM-86 SPO
Deputy for Development Planning

ABSTRACT

Shelldyne-H* fuel was evaluated with an AiResearch Model GTP30 Gas Turbine Engine, and some of its components. Fuel properties data supplied by Shell Oil Company were verified. Elevated-temperature aging tests of various elastomers indicated that Viton A, LS-53, and Buna N are compatible with Shelldyne-H fuel, and that materials containing straight silicone compounds are incompatible with Shelldyne-H fuel. Fuel control tests, including fuel-pump tests were performed at temperatures down to minus 65°F. Low temperature pump cavitation was experienced. Ignition was a problem, but combustion tests revealed good efficiency and temperature distribution after combustion was achieved. Engine starts with Shelldyne-H fuel could be made above plus 10°F with the use of a cartridge starter gas system. Engine starts could be made above minus 40°F, if ignition was initiated with MIL-T-5624 Grade JP-4 fuel. A system problem, identified at low temperatures, was a means to get all usable fuel from the fuel tank to the engine because fuel adhered to the tank walls.

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SECTION I

INTRODUCTION

1. OBJECTIVE. Aircraft generally tend to be gross-weight-limited. Aircraft range is usually determined as a compromise between takeoff or landing fuel weight and payload weight.

In direct contrast to aircraft subject to the foregoing gross-weight limitation, a class of vehicles including air-breathing missiles have been conceived that are volumetrically limited rather than gross-weight-limited. The fuel carried aboard these missiles is limited by the fuel tank available volume. Consequently, increases in energy content per unit volume of the fuel (Btu per gallon) will provide an increased range for such a vehicle.

Shelldyne-H*, a hydrocarbon fuel, has a volumetric heating value of approximately 161,200 Btu per gallon in comparison to MIL-T-5624, Grade JP-4, fuel, which has a volumetric heating value of approximately 120,000 Btu per gallon. Direct substitution of Shelldyne-H fuel for Grade JP-4 fuel in a volumetrically limited vehicle would provide an ideal or theoretical range increase on the order of 15 to 20 percent, depending upon the vehicle mass fraction and external aerodynamic configuration.

The program reported herein was conducted to:

(a) Determine the applicability of Shelldyne-H fuel to the current technology for gas turbine engines.

(b) Define current gas turbine engine technology or conceptual deficiencies that could preclude the use of Shelldyne-H fuel for turbofan or turbojet engines.

2. SCOPE. This report describes fuel tests conducted on an AiResearch Model GTP30 Gas Turbine Engine and some of its fuel components during the period from 15 June 1969 to 15 November 1969. The tests were conducted by the AiResearch Manufacturing Company of Arizona, a division of The Garrett Corporation, located at 402 South 36th Street, Phoenix, Arizona 85034.

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*Shelldyne-H is a trademark of the Shell Oil Company.

3. SUMMARY. This program consisted of three major segments: fuel handling and control component testing, combustion rig testing, and engine testing. An AiResearch Model GTP30-67 Auxiliary Power Unit (APU) with a nominal rating of 50 horsepower was used. Components of this engine model were used in conducting subsystem and component tests.

The program segment for fuel handling and control component testing consisted of

(a) Fuel physical properties evaluation

(b) Materials compatibility tests

(c) Fuel pumping characteristics evaluation

(d) Determination of fuel control low-temperature operating limits.

The physical properties of Shelldyne-H fuel were found to be in close agreement with preliminary data supplied by the Shell Oil Company.

Materials compatibility tests indicated that all metallic and elastomeric materials tested, except elastomers containing silicone compounds, were compatible with Shelldyne-H fuel. Materials containing silicone compounds exhibited excessive swelling characteristics and were therefore considered to be unusable with Shelldyne-H fuel. All elastomeric materials used in the Model GTP30 APU were found to be compatible with Shelldyne-H fuel and thereby negated any requirement for material substitution prior to either fuel control or engine testing.

Fuel-pump tests indicated that the high viscosity of Shelldyne-H fuel improved pump volumetric efficiency but increased pump inlet losses. Increased pump supply pressures were required to eliminate pump cavitation and to offset increased viscosity-induced inlet losses at the lower inlet temperatures. Fuel-control tests revealed that the "existing parts list" control would function satisfactorily with Shelldyne-H fuel for engine endurance testing at prevailing ambient temperatures.

Reduced-temperature testing indicated that the control would not function adequately over the entire governor range of temperatures below minus 35°F. However, the control was adequate for cold-start and no-load operation at temperatures down to minus 65°F.

The combustion-rig testing portion of the program consisted of:

(a) The design and fabrication of a combustor suitable for use with either Grade JP-4 fuel or Shelldyne-H fuel.

(b) Evaluation and comparison of combustion performance characteristics for Grade JP-4 fuel and Shelldyne-H fuel.

(c) Evaluation of the ignition characteristics of Shelldyne-H fuel.

A "Shelldyne-H combustor" based on preliminary combustion test data obtained from two existing combustors was designed and fabricated. The combustor was placed in test 4 weeks after receipt of contract. Test results revealed that combustion efficiency with Shelldyne-H fuel was somewhat less than with Grade JP-4 fuel; however, the combustor pattern factor at temperature-distribution factor (TDF) for both fuels is practically identical. The combustion stability limits for Shelldyne-H fuel are significantly larger than for Grade JP-4 fuel. This is exemplified by the fact that the Shelldyne-H fuel minimum limiting combustion pressure was on the order of 4 mm Hg absolute, in comparison to 8 mm Hg absolute for Grade JP-4 fuel. With a conventional spark igniter, Shelldyne-H fuel is markedly more difficult to ignite than Grade JP-4 fuel, and requires a combustor inlet air temperature of 265°F as compared to the 8°F required for Grade JP-4 fuel. Significant reductions in minimum required combustor inlet air temperature were obtained by using a small "lead" of Grade JP-4 fuel or injecting cartridge starter gases into the combustor, or both. Use of these techniques allowed ignition of Shelldyne-H fuel at temperatures down to minus 5°F, which is only 15°F above the steady-state combustion limiting temperature, at start-air and fuel-flow conditions, of minus 20°F.

The engine testing segment of the program consisted of endurance and cold-start engine testing, during which 60 hours of endurance running were accumulated, together with 54 start-cycles. Post-test teardown inspection indicated that all engine components were in excellent condition except for a failed gearbox pinion bearing. The bearing failure is not connected in any way with the fuel used to run the engine, and therefore cannot be attributed to the use of Shelldyne-H fuel. There were no observable signs of distress, wear, or corrosion on any of the hot rotating or stationary parts.

Carbon deposits that were not observed inside the combustor during combustion-rig testing were observed during the endurance test. These carbon deposits did not affect the engine or the conduct of the test. The deposit was clearly undercut or eroded in areas of air impingement. Although Shelldyne-H fuel did produce carbonaceous deposits, they can be eliminated by judicious metering of air into sensitive areas within the combustor.

For purposes of conducting the endurance test, the engine was started with a 2.5-cubic-centimeter lead of Grade JP-4 fuel in the fuel line directly ahead of the combustor. Therefore, although ignition was initiated with Grade JP-4 fuel, the engine accelerated and attained governed speed on Shelldyne-H fuel.

Cold-start testing of the engine in a cold tank revealed that the engine could be started on pure Shelldyne-H fuel at 10°F with the use of the cartridge starter gas system. By filling the fuel line between the fuel control and combustor with Grade JP-4 fuel, successful starts were obtained at minus 20°F. Under these conditions, the combustor was burning Grade JP-4 fuel at light-off and during the first part of the acceleration schedule and was burning Shelldyne-H fuel during the latter part of the start. In addition, a successful start with a long "lead" of Grade JP-4 fuel was made at minus 40°F; however, an electrical failure shut the engine down 5 seconds after it had reached governed speed. It was not possible to ascertain whether Shelldyne-H fuel was actually burned during this start. It should be noted that during both the minus 20°F and minus 40°F starts Shelldyne-H fuel was being pumped and metered by the unit fuel control.

There were no fundamental gas turbine technology or state-of-the-art deficiencies uncovered by this program that would preclude the application of Shelldyne-H fuel as a gas turbine fuel. However, two potential propulsion system problems were observed that could seriously compromise the advantages offered by Shelldyne-H fuel. These problems were not pursued or evaluated, as they were considered to be beyond the scope of the contract task.

At low temperatures, Shelldyne-H fuel was observed to adhere to metallic surfaces much in the way that honey clings to the inside of a jar. Consequently, as a fuel tank is depleted, fuel will cling to the tank walls and slosh baffles. The amount of this unavailable fuel or "carry-over" could conceivably be a significant portion of the total fuel tank volume.

The second problem relates to the fuel-pickup and boost-pump system. Although it has been shown that Shelldyne-H fuel can be used in a gas turbine engine at temperatures down to minus 65°F, the fuel must still be removed from the fuel tank and transferred to the engine. Fuel boost-pump inlet cavitation, or the system compromises required to suppress it, could also negate much of the advantage offered by Shelldyne-H fuel. Several approaches can be propounded for solving these problems, among which are the use of fuel additives or blending agents, fuel tank heating, and the use of positive expulsion or bladder tankage. However, these system problems are not encountered in applications to long-range supersonic (Mach 2 to Mach 4) air-breathing vehicles because of the high skin temperatures associated with these flight conditions. In addition, the high volumetric heat release, low vapor pressure, better lubricity, and increased combustion stability characteristics of this fuel would make it an excellent fuel for such applications.

SECTION II

SHELLDYNE-H FUEL VERIFICATION

1. FUEL VERIFICATION. Investigation of the chemical and physical properties of Shelldyne-H fuel was conducted for purposes of verification, receiving inspection, and batch-property identification. Tests were performed to establish fuel properties that would be of concern during engine tests of the fuel. Three tests for each property were performed to assure accuracy. The test results were compared with Shell Oil Company physical property data for Shelldyne-H fuel.

1.1 Distillation Temperatures. Temperatures at the following distillation points were determined:

(a) Initial boiling point

(b) 5 percent evaporated

(c) 10 through 90 percent evaporated, in 10 percent increments

(d) 95 percent evaporated

(e) End point

The amount of residue, the heavy distillate left in the flask, and the amount of distillation loss following each test were also determined in accordance with ASTM Test Method D-86.

1.2 Viscosity. The kinematic viscosity of Shelldyne-H fuel was determined by use of ASTM Test Method D-445. The viscosity was determined at 100° and 210°F. Values at zero °F and minus 30°F were established by extrapolation. Three different viscometers with slightly different orifice calibrations were used to determine one set of data for each of the test temperatures--100°F and 210°F.

1.3 Density. The specific gravity of the test batch of Shelldyne-H fuel was established by means of a glass hydrometer in accordance with ASTM Test Method D-287. The gravity was determined in triplicate at 60°F.

1.4 Pour Point. Since Shelldyne-H fuel was reported to not possess a freezing point (it becomes increasingly more viscous at lower temperatures but does not freeze), the pour point was determined. The pour point, defined as 5°F above the temperature at which the fuel fails to flow, was determined by means of ASTM Test Method D-97. A cloud and pour point test apparatus was used for this determination. A low-temperature bath utilized with this apparatus consisted of a mixture of methanol and dry ice capable of attaining temperatures down to minus 95°F.

1.5 Heat of Combustion. The heat of combustion of the test batch of Shelldyne-H fuel was determined by use of ASTM Test Method D-240. An oxygen-bomb calorimeter was used. Both Btu per pound and Btu per gallon were calculated from the test results.

1.6 Sulfur Content. The sulfur content of Shelldyne-H fuel was determined by analyses conducted on the residues from the heat of combustion tests. The test procedures followed were those specified in ASTM Test Method D-1266. The sulfur content was determined by a Gravimetric precipitation method with use of barium chloride ($BaCl_2$).

2. CONCLUSIONS

2.1 Fuel Verification Tests. The results of all tests conducted for purposes of verification, receiving inspection, and fuel batch-property identification are presented in Table I. The test results show excellent reproducibility and agreement with the preliminary data supplied by Shell Oil Company. Consequently, it is concluded that the fuel received was Shelldyne-H fuel.

Determination of the actual pour point could not be carried to completion because of limitations of the test apparatus. Tests were conducted to the minimum temperature capability of the test apparatus which was minus 95°F. The fuel still showed signs of flow at this temperature. Therefore, the pour point is reported to be less than minus 90°F (the pour point being 5°F above the minimum observed temperature).

TABLE I

SHELLDYNE-H FUEL CHEMICAL AND PHYSICAL PROPERTIES VERIFICATION TEST RESULTS

Test	Test Results			Shell Data
	Set 1	Set 2	Set 3	
1. Distillation (corrected to 760 mm)				
Initial BP, Temperature °F	507	508	508	509
5%	512	512	512	-
10%	513	513	513	513
20%	513	513	513	513
30%	513	513	513	-
40%	514	514	514	-
50%	514	515	514	515
60%	515	515	515	-
70%	515	515	515	-
80%	516	516	516	-
90%	517	517	517	517
95%	519	519	519	-
End point	527	528	529	525
Distillation Loss, %	1.3	1.2	1.2	1.4
Residue, %	0.7	0.8	0.8	0.6
2. Viscosity, cs at				
210°F	3.25	3.23	3.25	-
100°F	13.7	13.6	13.7	13
0°F (extrapolated)	260	260	260	215
-30°F (extrapolated)	1,250	1,250	1,250	1,200
3. Specific gravity, gm/cc 60°F/60°F	1.080	1.080	1.080	1.081
4. Pour point, °F	<-90	<-90	<-90	-
5. Heat of combustion				
Btu/lb	17,900	17,870	17,870	17,890
Btu/gal	161,300	161,100	161,100	161,400
6. Sulfur content, %	0.01	0.01	0.01	0

BP = boiling point

SECTION III

MATERIALS

1. ORGANIC MATERIALS COMPATIBILITY. Selected elastomers, used in gas turbine fuel pump and fuel-control apparatus, were exposed to Snelldyne-H fuel at elevated temperatures. The effect of the fuel on the organic materials was determined by examination of the change in weight, volume, tensile strength and elongation, hardness, and compression set after exposure. The test methods used were as follows:

(a)	Change in weight	Federal Test Standard No. 601, Method 6251
(b)	Change in volume	Federal Test Standard No. 601, Method 6211
(c)	Change in tensile strength and elongation	ASTM D-1414
(d)	Change in hardness	ASTM D-676
(e)	Change in compression set	ASTM D-395

The elastomers tested in the forms of O-rings and buttons (used for hardness test only) were as follows:

	Elastomer	Type
(a)	Viton A	Fluorocarbon
(b)	LS-53	Fluorosilicone
(c)	EMS53084*	Silicone
(d)	Buna N	Butadiene-acrylonitrile
(e)	EMS53015*	Silicone

The test specimens were immersed in Shelldyne-H fuel in large, sealed test tubes that were positioned in a Comet** heat-aging block. The test specimens were exposed to the fuel

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*AiResearch specification.

**Comet is a trade name.

for 70 hours at 350°F, except that Buna N was tested at 250°F and that all compression-set tests were conducted on specimens exposed for 22 hours. Permanent set of the test specimens was evaluated after the specimens had been allowed to stabilize for 1 hour after having been compressed.

Triplicate tests were conducted with a total of 150 specimens tested. All elastomer test specimens representing one test group were immersed together. Each set of like specimens, however, was kept separate during the compression set tests.

2. ORGANIC MATERIALS COMPATIBILITY TEST RESULTS. Table II presents the results of the compatibility tests between Shelldyne-H fuel and the selected elastomers. Because of excessive weight gain, volume change (swell), and loss of hardness during compression set testing, two elastomers were found to be unacceptable when exposed to Shelldyne-H fuel. These elastomers contain silicone materials and are identified as EMS53084 and EMS53015. The other three elastomers (Viton A, LS-53, and Buna N) were found to be compatible with Shelldyne-H fuel and are recommended for use.

Figures 1, 2, and 3 illustrate the condition of representative O-ring test specimens before and after compression set testing. It should be noted that compression set test results of the three acceptable elastomers showed positive values indicating a certain amount of permanent set. These results were expected and are considered normal. The two unacceptable elastomers, EMS53084 and EMS53015, exhibited negative compression set test values indicating undesirable and abnormal swelling of sufficient magnitudes to preclude their use as O-rings or seals in machined parts. The asterisked values of "compression set" for EMS53084 and EMS53015 in Table II are noticeably larger than the rest of the data. Although post-test investigation did not reveal an obvious explanation for these discrepancies, the data is considered to be questionable. Technician error is postulated as the reason for these anomalies.

All elastomeric materials used in the fuel-handling components of the GTP30 Gas Turbine Engine were found to be compatible with Shelldyne-H fuel.

TABLE II

ORGANIC MATERIALS COMPATIBILITY WITH SHELLDYNE-H FUEL
TEST RESULTS

			Tensile			Elongation			Hardness,	
Material	Weight Change %	Volume[1] Change %	Before psi	After psi	Change %	Before %	After %	Change %	Before pts	Afte pt
Viton A	2.7	5.3	1420	1400	-1.4	225	176	-21.8	72	68
	2.4	5.5	1420	1450	+2.1	225	230	+2.2	75	71
	2.7	5.9	1420	1310	-7.8	225	184	-18.2	73	70
LS-53	6.4	9.6	912	478	-47.6	207	185	-10.6	59	48
	6.5	10.0	912	667	-26.8	207	212	+2.4	57	46
	6.4	9.9	912	691	-24.2	207	203	-1.9	60	47
EMS53084	33.3	49.8	884	599	-32.2	176	180	+2.3	73	51
	33.5	50.1	884	599	-32.3	176	172	-2.3	73	50
	34.5	51.5	884	667	-13.2	176	176	0	73	48
Buna N[3]	7.3	9.3	1750	1600	-8.6	257	198	-22.9	72	69
	7.6	10.0	1750	1980	+13.1	257	194	-23.5	71	66
	7.7	10.2	1750	1620	-7.4	257	189	-26.4	73	69
EMS53015	38.9	51.3	848	437	-48.5	150	119	-20.7	72	50
	41.5	58.7	848	463	-45.4	150	123	-18.0	74	52
	39.8	56.8	848	402	-52.6	150	110	-26.7	70	46

NOTES: [1] Volume change = swell

[2] Negative compression set indicates swell; positive indicates loss i resilience; 22 hours exposure.

[3] Buna N tested at 250°F for 70 hours; all others tested at 350°F.

---

*Questionable data

A

B

TABLE II

ORGANIC MATERIALS COMPATIBILITY WITH SHELLDYNE-H FUEL TEST RESULTS

eight hange %	Volume[1] Change %	Tensile Before psi	Tensile After psi	Tensile Change %	Elongation Before %	Elongation After %	Elongation Change %	Hardness, Shore A Before pts	Hardness, Shore A After pts	Hardness, Shore A Change pts	Compression Set[2] %
2.7	5.3	1420	1400	-1.4	225	176	-21.8	72	68	-4	21.4
2.4	5.5	1420	1450	+2.1	225	230	+2.2	75	71	-4	23.5
2.7	5.9	1420	1310	-7.8	225	184	-18.2	73	70	-3	28.4
6.4	9.6	912	478	-47.6	207	185	-10.6	59	48	-11	14.3
6.5	10.0	912	667	-26.8	207	212	+2.4	57	46	-11	10.6
6.4	9.9	912	691	-24.2	207	203	-1.9	60	47	-13	11.6
33.3	49.8	884	599	-32.2	176	180	+2.3	73	51	-22	-163*
33.5	50.1	884	599	-32.3	176	172	-2.3	73	50	-23	-25.1
34.5	51.5	884	667	-13.2	176	176	0	73	48	-25	-24.2
7.3	9.3	1750	1600	-8.6	257	198	-22.9	72	69	-3	24.4
7.6	10.0	1750	1980	+13.1	257	194	-23.5	71	66	-5	26.1
7.7	10.2	1750	1620	-7.4	257	189	-26.4	73	69	-4	25.0
38.9	51.3	848	437	-48.5	150	119	-20.7	72	50	-22	-189*
41.5	58.7	848	463	-45.4	150	123	-18.0	74	52	-22	-32.3
39.8	56.8	848	402	-52.6	150	110	-26.7	70	46	-24	-37.7

lume change = swell

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uestionable data

A

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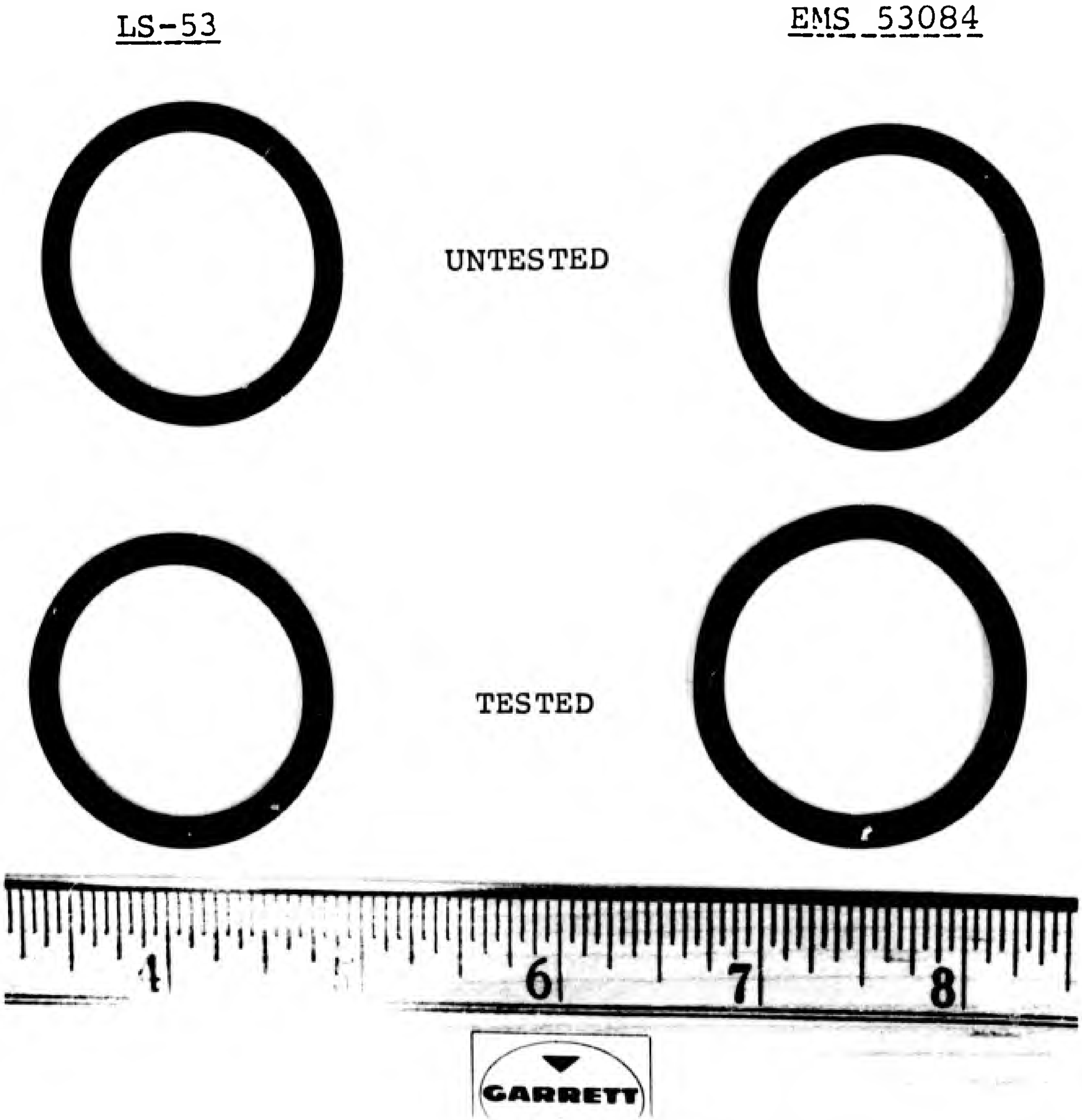

REPRESENTATIVE O-RING TEST SPECIMENS
AFTER EXPOSURE TO SHELLDYNE-H FUEL
FOR 70 HOURS AT 350°F

FIGURE 1

MP-24164

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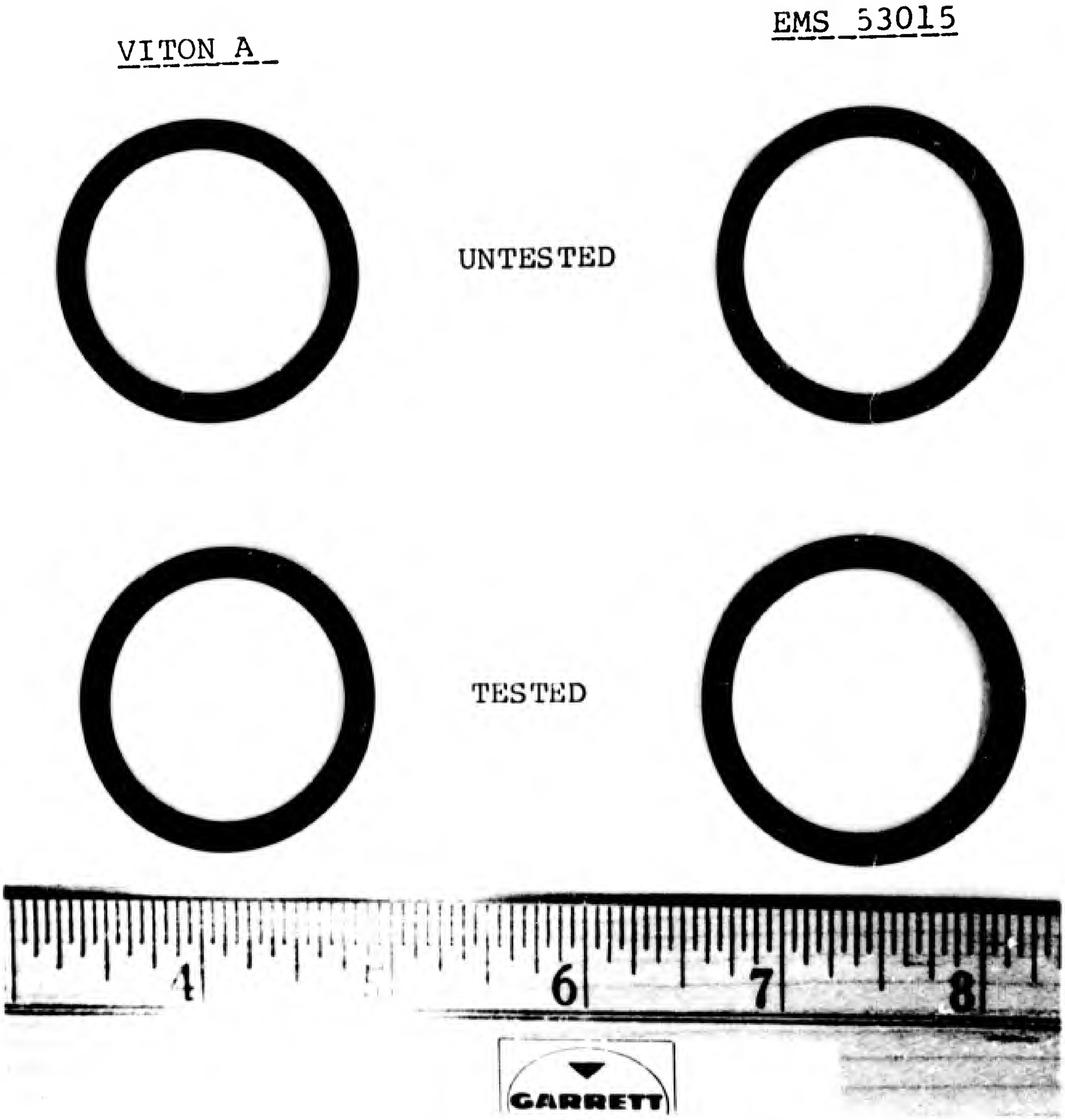
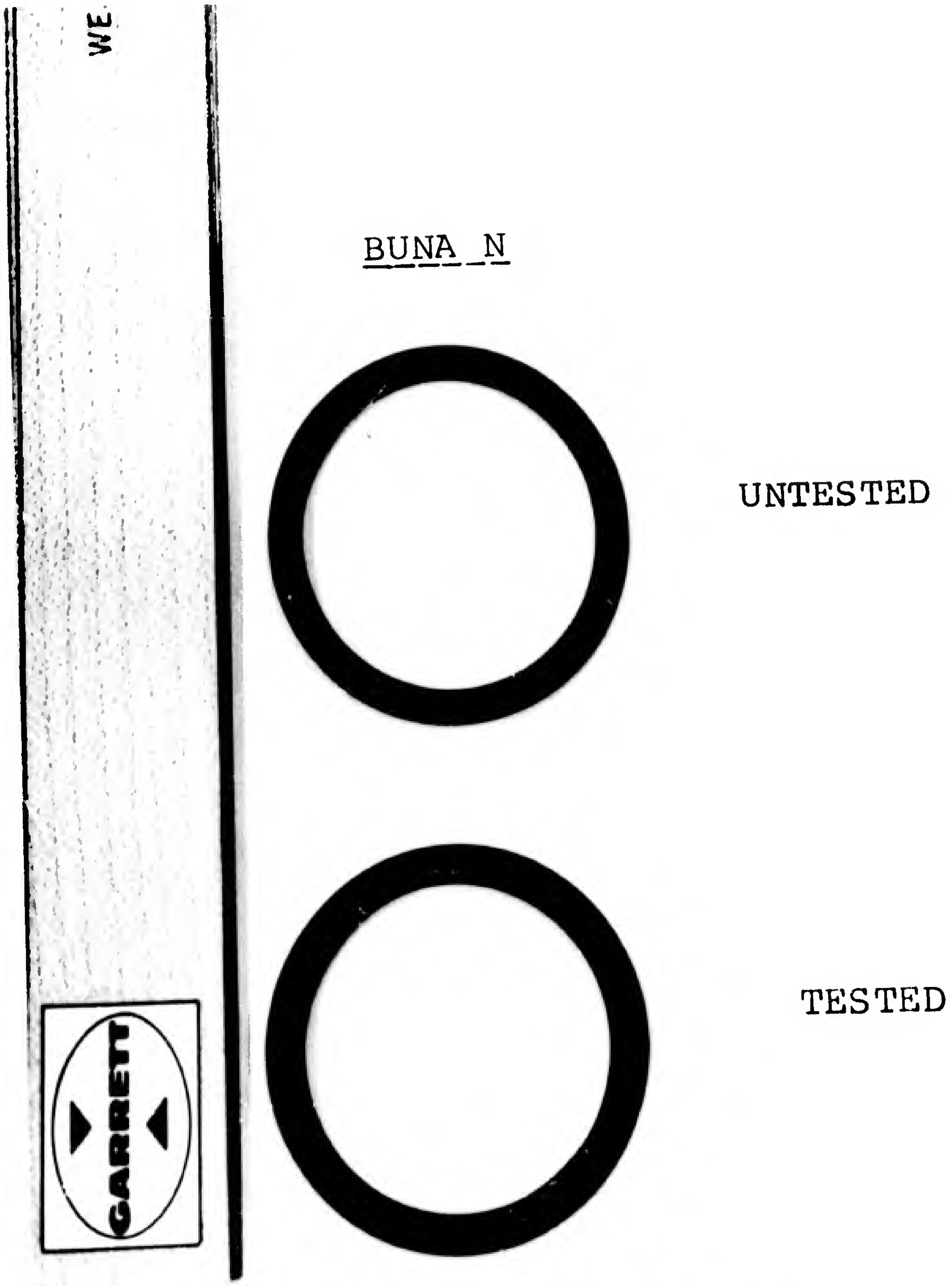


REPRESENTATIVE O-RING TEST SPECIMENS
AFTER EXPOSURE TO SHELLDYNE-H FUEL
FOR 70 HOURS AT 350°F

FIGURE 2

MP-24163



REPRESENTATIVE O-RING TEST SPECIMENS AFTER EXPOSURE TO SHELLDYNE-H FUEL FOR 70 HOURS AT 250°F

FIGURE 3

3. METALS COMPATIBILITY TEST. The corrosion and oxidation effects of Shelldyne-H fuel on various metals, including several commonly employed in high-speed turbomachinery, were tentatively investigated in accordance with Federal Test Method 5308.

Small, highly polished metal samples were weighed and were immersed in a bath of Shelldyne-H fuel at 350°F for 72 hours. The samples were then reweighed and visually inspected for changes in surface luster.

Following this tentative investigation, an additional long-term test was conducted by reimmersing the unaltered samples in Shelldyne-H fuel at room temperature until the conclusion of the program (a period of approximately 3 months) and repeating the measurements. The results of these tests are presented in Table III. The weight change is given as a fraction of the exposed surface area of the sample.

TABLE III

WEIGHT CHANGE EFFECTS OF SHELLDYNE-H FUEL

Material	Weight Change Milligrams per Square Centimeter After a: 72-Hour Immersion in Shelldyne-H Fuel at 350°F	3-Month Exposure at Room Temperature
Copper	0.00	+0.02
Silver	0.00	+0.08
Iron	0.00	+0.02
Aluminum	0.00	+0.03
Magnesium	0.00	0.00
*Inconel 718	0.00	+0.03
*INCO 713	-0.01	+0.02
*IN-100	0.00	+0.03
**Waspaloy	0.00	+0.04

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*Trademark of International Nickel Company
**Trademark of United Aircraft Company

The 72-hour portion of this test is normally applied to oils and is generally more severe than similar tests for fuels. The maximum acceptable weight change allowed by this Federal test is plus or minus 0.4 milligrams per square centimeter for the 72-hour period.

The largest weight change experienced after 3 months of exposure was plus 0.08 milligrams per square centimeter for the silver sample, and a slight reduction in surface luster accompanied this weight gain. All other samples retained their original high luster.

In conclusion, all materials tested were found to be completely compatible with Shelldyne-H fuel and are recommended for use.

4. MISCIBILITY TEST. The Shelldyne-H fuel distillation data reported in Paragraph 1.1 of Section II of this report indicated the lack of "front ends" or compounds that evaporate at lower temperatures. A means of providing these properties and improving the ignition characteristics of Shelldyne-H fuel without severely reducing its high-density characteristic would be through the addition of a small amount of some high-volatility fuel. In order to determine the miscibility of Shelldyne-H fuel with such fuels, 2.5 milligrams for each of nine candidate fuels were added in separate vials to 22.5 milligrams of Shelldyne-H fuel. These mixtures were vigorously agitated for several minutes and then allowed to remain undisturbed for 66 hours. The following observations were then made:

(a) 10% MIL-T-5624, Grade JP-4, Aviation Turbine Fuel - complete mixing.

(b) 10% MIL-T-5624, Grade JP-5, Aviation Turbine Fuel - complete mixing.

(c) 10% MIL-G-5572, Aviation gasoline - complete mixing.

(d) 10% Aviation Kerosene - complete mixing.

(e) 10% DF-2 - complete mixing, slight discoloration.

(f) 10% Petroleum ether - complete mixing.

(g) 10% Acetone - complete mixing.

(h) 10% Benzene - complete mixing.

(i) 10% Methanol - total separation, no mixing during agitation.

With the exception of methanol, all organic fluids tested exhibited complete miscibility with Shelldyne-H fuel.

SECTION IV

FUEL CONTROL COMPONENT TESTING

The fuel control for the AiResearch Model GTP30 Gas Turbine Engine was tested with Shelldyne-H fuel on a fuel-control test stand. These tests were conducted at fuel control and fuel temperatures down to and including minus 65°F.

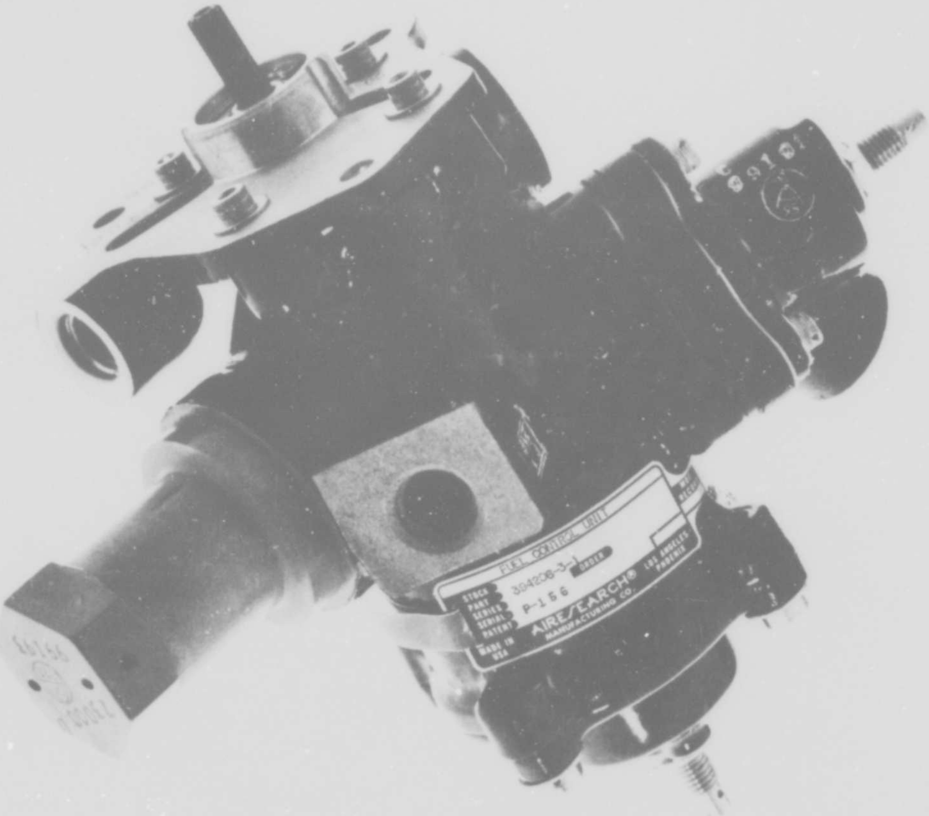
1. TEST OBJECTIVES. Three series of tests were conducted to determine (a) the pumping characteristics of Shelldyne-H fuel at reduced temperatures, (b) the minimum temperature at which an existing control would retain structural and functional integrity, and (c) whether modifications would be required to provide a control that could support the engine endurance testing and cold-start evaluation segments of the program.

2. SUMMARY OF RESULTS. The pumping characteristics of Shelldyne-H fuel were found to be better than the more conventional JP class of fuels. These characteristics are attributed to the higher viscosity of Shelldyne-H fuel and what appears to be a better lubricity characteristic of this fuel. The net positive suction head (NPSH) requirements, at the pump inlet, increased as the fuel temperature was reduced, as would be expected. The fuel control was found to have both structural and functional integrity at fuel and prevailing ambient temperature down to and including minus 65°F.

3. FUEL CONTROL DESCRIPTION. A photograph of the Model GTP30 Gas Turbine Engine Fuel Control Unit Part 394206-3 is shown in Figure 4. The major components of this fuel control are a fuel pump, a filter (removed for tests), an acceleration limiter, and a governor. Figure 5 is a schematic diagram of this control, which depicts the components and their related functions.

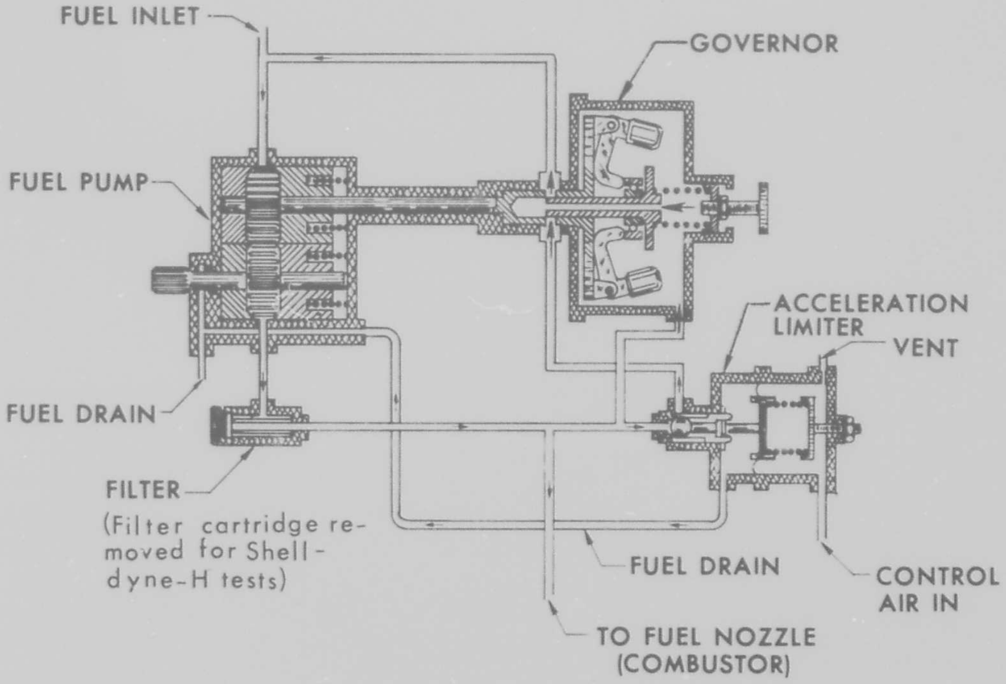
3.1 Fuel Pump. The fuel pump is integral with the fuel-control assembly and is a two-gear positive-displacement pump. The pump consists of a drive gear, which is attached to the fuel-control input drive shaft, and a driven gear, which is attached to the governor shaft. The two gears are sandwiched between spring-loaded bushings that compensate for normal gear and bushing wear.

Fuel passes from the pump through the high-pressure filter. The fuel is directed from the filter to the speed governor, the acceleration limiter, and the fuel nozzle.



FUEL CONTROL UNIT
394206-3

FIGURE 4



MODEL GTP30 ENGINE
FUEL CONTROL SCHEMATIC

FIGURE 5

The fuel filter cartridge was removed from the fuel control for purposes of this program because of the excessive pressure drop across the filter that would have been incurred with Shelldyne-H fuel at reduced temperatures.

3.2 Governor. The governor consists of a pair of spring-counterpoised ball-bearing-pivoted flyweights, which directly modulate the position of a spool valve. The flyweights and spool valve are so arranged that increases in governor speed cause the flyweights to open the valve against the force of the governor spring. Consequently, as the governor speed is increased, more fuel from the pump discharge is bypassed by the valve back to the pump inlet.

The action of the governor in conjunction with the fuel pump and fuel nozzle can best be described by the following example. Assume that the engine is operating at governed speed under no-load conditions. Under these conditions a certain amount of fuel from the pump discharge is being bypassed by the governor, back to the pump inlet. The amount of bypass flow is such that the remainder of the pump discharge flow delivered to the combustor is the appropriate amount to maintain governed speed. Addition of load to the engine will tend to reduce the engine speed, which simultaneously causes the governor flyweights to react by closing the spool valve and consequently reduces the amount of bypass flow. The net result is that more fuel is delivered to the combustor, until the fuel flow, engine speed, and engine load again reach equilibrium. Therefore, as the engine load is increased, the speed will tend to decrease or "droop." Conversely, as the engine load is decreased, the speed will tend to increase. The amount of "droop" or reduction in speed for a given increase in engine load is a measure of the control system "gain."

3.3 Acceleration Limiter. The acceleration limiter is an adjustable diaphragm-actuated bypass ball valve, which is used to maintain a fixed relationship between engine compressor discharge pressure and fuel delivery pressure. The valve consists of a ball and seat. The diaphragm is spring-loaded and loads the ball toward its seat. The valve action is such that the spring-loaded diaphragm force exerted on the ball is continually balanced by the fuel pressure acting on the ball. Consequently, the ball is continually repositioned to maintain a desired system fuel pressure, the resultant fuel pressure being a function of the combined forces of the spring and control air pressure acting on the diaphragm.

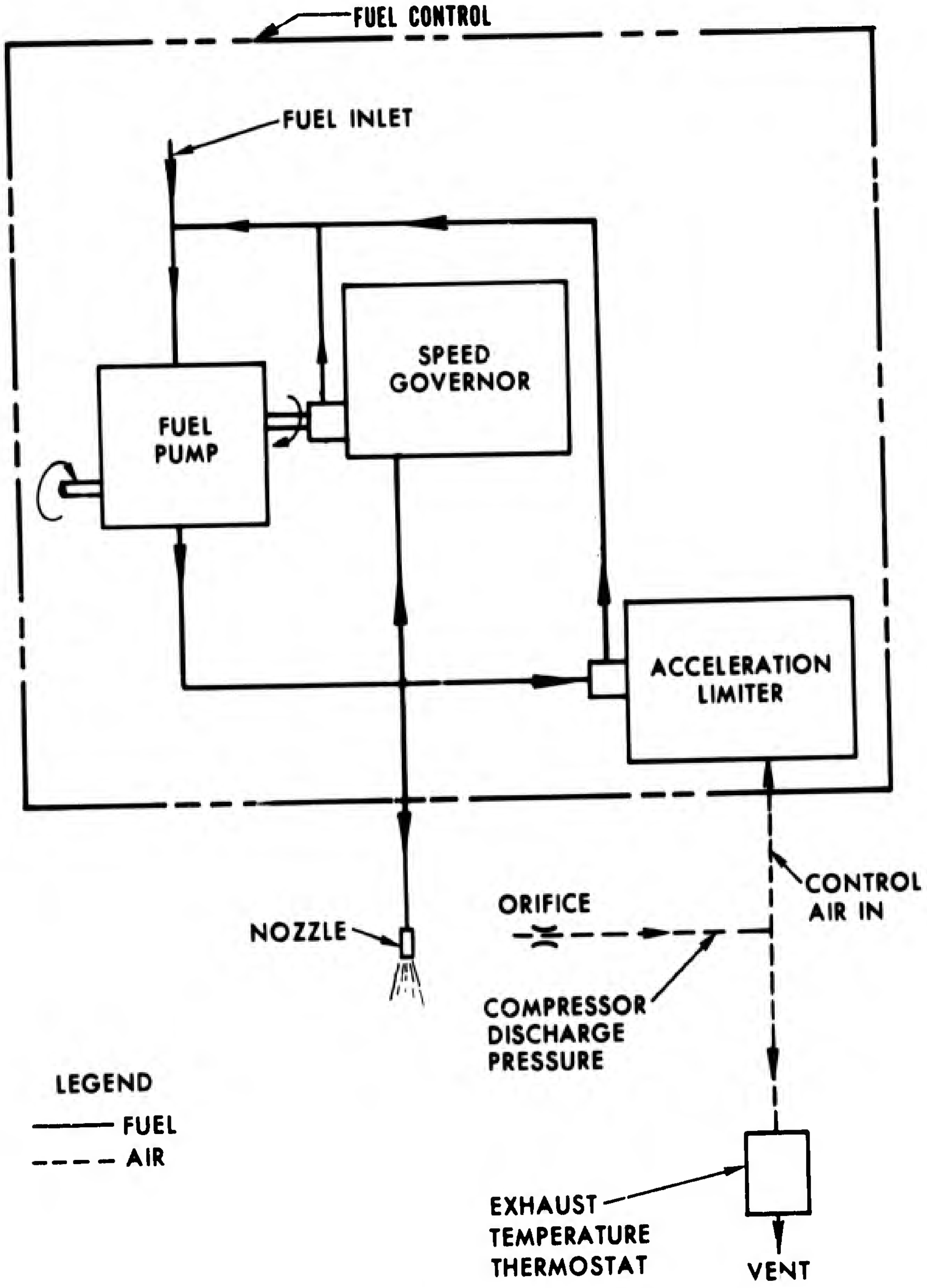
The acceleration-limiter relationship to the governor and fuel pump in conjunction with the affected engine-control system components (fuel nozzle, compressor discharge pressure, and exhaust temperature thermostat) is shown schematically in Figure 6. Engine compressor discharge air pressure is supplied to the acceleration-limiter control-air port through an orifice. During an engine start, the compressor discharge-air transient pressure, which is a function of engine speed, is applied to the acceleration-limiter diaphragm. The result is to control fuel pressure as a function of engine speed. The fuel flow delivered to the engine combustor during a start is "scheduled" to regulate the acceleration and, consequently, the turbine inlet temperature during the start transient. The acceleration-limiter function is to provide fuel-flow regulation until the engine accelerates to governed speed, at which time the governor controls the engine.

A protective override feature is built into the control system in the form of an exhaust temperature thermostat that is located in the engine exhaust. This device is a normally closed thermally actuated pneumatic valve. The valve port of the thermostat is connected in parallel with the acceleration-limiter control-air port. Therefore, when the valve in the thermostat opens, the control-air pressure supplied to the acceleration limiter is reduced. The reduction in pressure causes the acceleration-limiter ball valve to open, thereby reducing fuel flow to the combustor. This system provides engine overtemperature protection both during engine accelerations and during inadvertent overload conditions at governed speed.

4. TEST EQUIPMENT. Three test setups were assembled to attain a satisfactory test system. The initial test setup was fabricated from available laboratory equipment.

Although the initial test setup was deficient in some capabilities, it provided rapid exposure to the conditioning and handling problems associated with Shelldyne-H fuel. Consequently, the overall lead time for development of a fully workable test system was reduced significantly.

The second test system, although improved in overall capabilities, was fuel-temperature-limited at approximately minus 40°F. Therefore, in order to satisfy the requirements to test at fuel temperatures of minus 65°F, a third system was fabricated. The lower temperature limit of this system was not established; however, it appears to be significantly lower than minus 65°F.



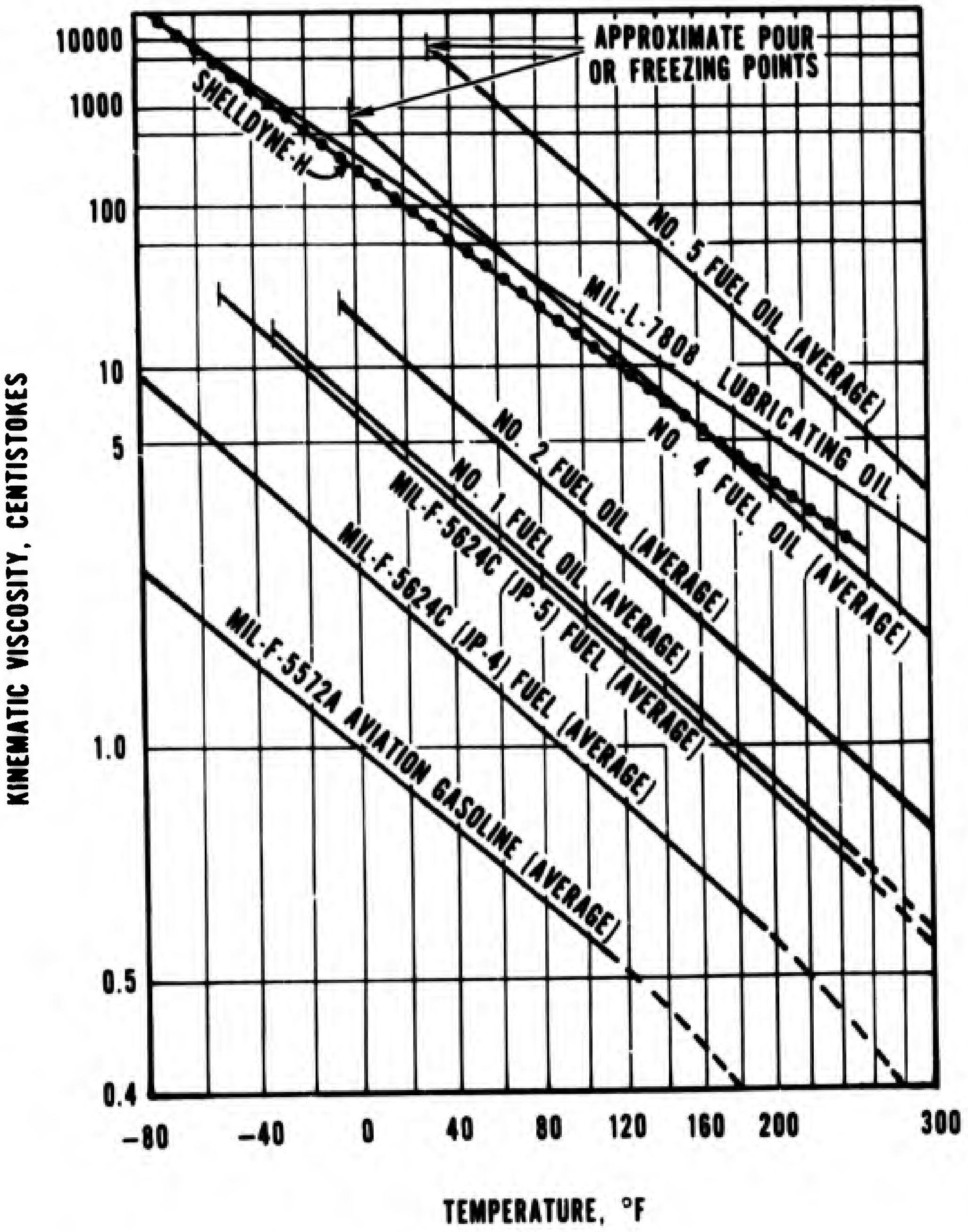
SCHEMATIC OF ACCELERATION LIMITER RELATIONSHIP

FIGURE 6

4.1 Effects of Viscosity. The viscosity characteristics of Shelldyne-H fuel are similar to those of diesel fuel No. 4 (DF-4), and together with viscosity data for several other fuels, are shown in Figure 7. The viscosity limit for fuels normally used in AiResearch gas turbines is on the order of 15 centistokes--a value that is well above the viscosity of JP-4 fuel at minus 65°F. However, the temperature of Shelldyne-H fuel corresponding to a viscosity of 15 centistokes is on the order of 90°F. The 15-centistoke limit is established primarily because of fuel measurement requirements. The effects of viscosity on fuel-flow measurement (rotameters, turbine flowmeters) accuracies are significant at viscosities greater than 12 to 15 centistokes. For this reason, a test setup utilizing direct-flow-measurement equipment must be so designed that flow measurements are made at a point in the system where the fuel viscosity is in the calibration range of the flowmeter being utilized. Alternately, an indirect flow measurement system may be employed wherein a less viscous fluid is used to displace Shelldyne-H fuel on an equal-volume basis. The first and third test setups incorporated the direct flow measurement concept. The second setup incorporated the positive displacement concept.

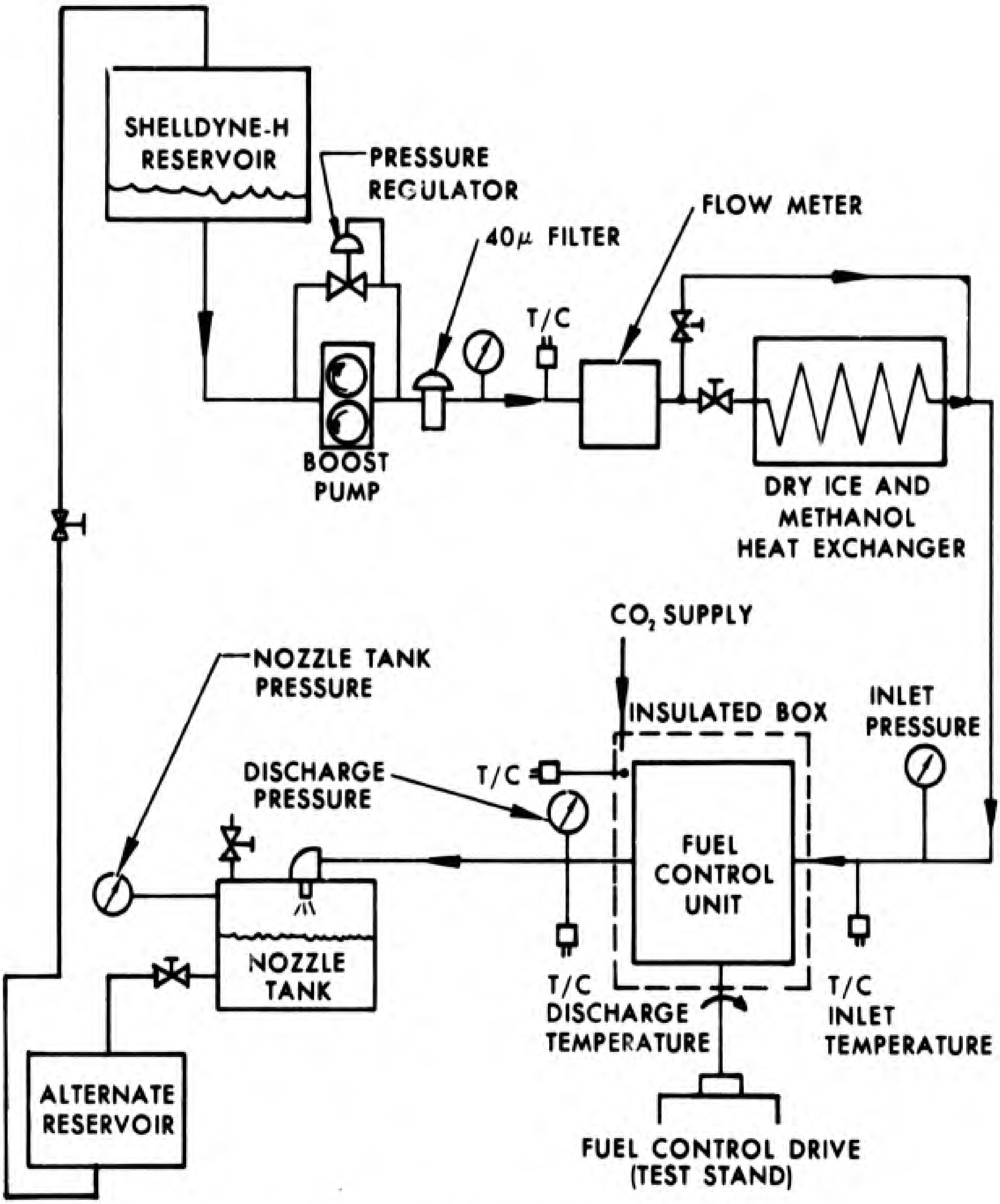
4.2 First Test Rig. The first Shelldyne-H fuel test rig was assembled from available laboratory equipment that had been used for similar fuel tests. This rig was used primarily to determine the characteristics of the Model GTP30 Engine fuel control with Shelldyne-H fuel. A schematic diagram of this system is shown in Figure 8. Fuel was routed from the reservoir, through a boost pump, a 40-micron filter, a flowmeter, a heat exchanger, and into the fuel control unit. A dry-ice methanol mixture was used to chill the fuel as it passed through the heat exchanger. The fuel-control unit was enclosed in an insulated box that was maintained at the same temperature as the fuel entering the control. Fuel leaving the fuel-control unit was discharged into a nozzle tank which drained into an alternate reservoir.

The flowmeter was placed in the circuit upstream of the dry-ice methanol heat exchanger so that the viscosity of the Shelldyne-H fuel could be held within the calibrated range of the flowmeter.



CHARACTERISTICS OF SHELLDYNE-H
AND SEVERAL OTHER FLUIDS

FIGURE 7



FIRST TEST SETUP SCHEMATIC

FIGURE 8

The 10-micron filter normally used in the fuel-control unit was removed because of the excessive pressure drop that would have been experienced across the filter at reduced Shelldyne-H fuel temperatures. However, the 40-micron facility filter was located upstream of the flowmeter at a point where the fuel temperature was maintained in excess of 70°F.

The low-temperature capability of this setup was limited by the heat-exchanger size and heat-transfer characteristics. Because of the high viscosity at reduced temperatures, the Reynolds number of the Shelldyne-H fuel was extremely low. Consequently, the heat-transfer coefficients were reduced and flow pressure drops were large (50 psi).

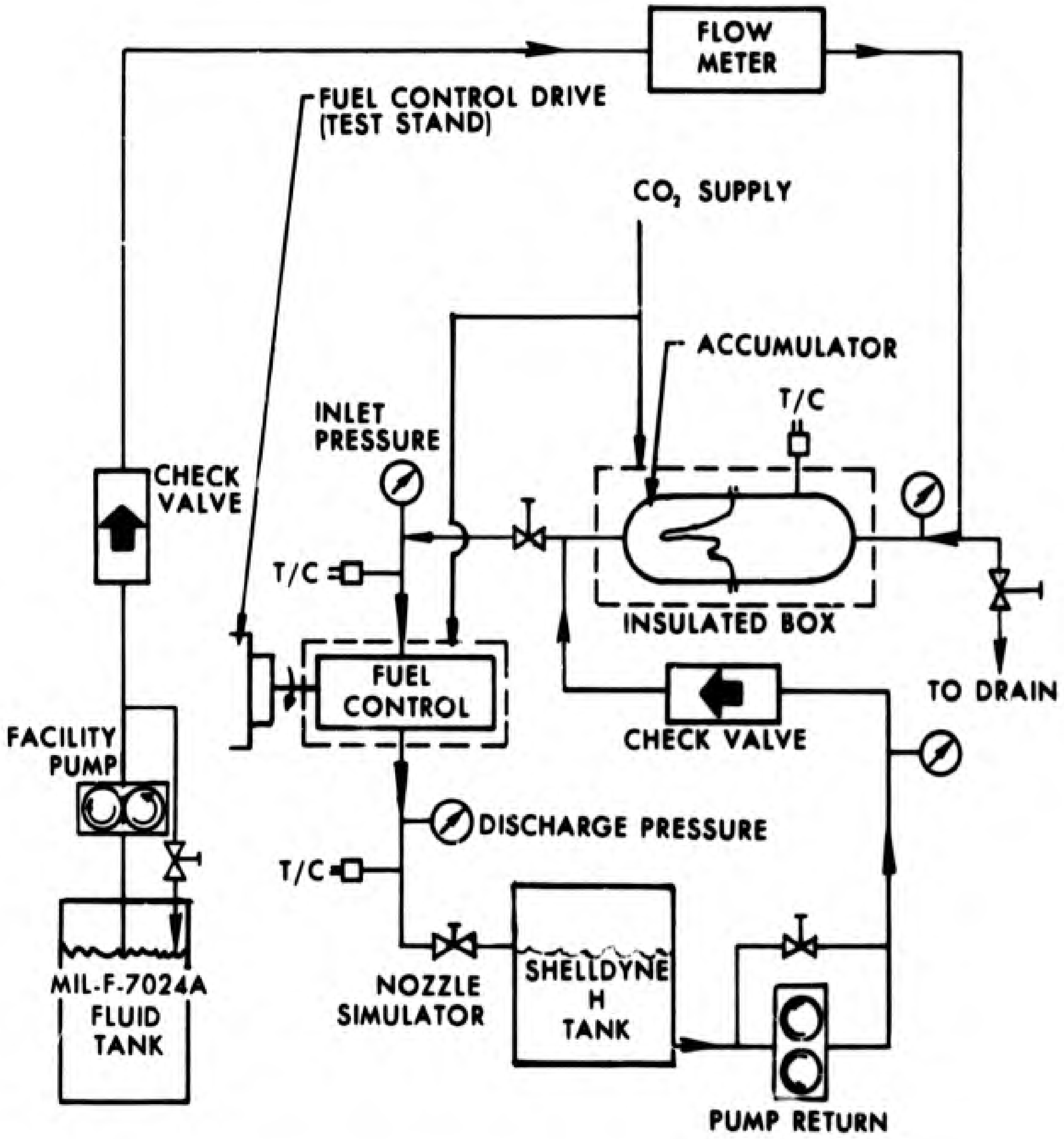
For minimum control fuel-flow rates, the minimum temperature of the Shelldyne-H fuel leaving the heat exchanger was zero °F, with the methanol/dry-ice mixture at minus 100°F. Attempts to increase the fuel-flow rates resulted in higher fuel temperatures. Calculations derived from this data indicated that the size of a heat exchanger and the associated pressure drop required to achieve minus 65°F operation were prohibitive.

Results of fuel-control-unit testing with the first setup system revealed that the control was capable of operation at temperatures down to zero °F. The originally predicted lower temperature capability of the existing fuel-control unit operating with Shelldyne-H fuel was on the order of 40°F to 50°F.

4.3 Second Test Rig. The second test rig is shown schematically in Figure 9.

The system includes an accumulator with a separating diaphragm. The accumulator is filled completely with Shelldyne-H fuel and MIL-F-7024A fluid (a nonflammable JP-4 simulation fuel) is then applied to the other side of the accumulator to expel the Shelldyne-H fuel. The diaphragm functions simply as a positive seal between the two fluids and carries no load. The positive seal system was utilized to preclude contamination of Shelldyne-H, which is expensive and in limited supply.

The volume of Shelldyne-H fuel expelled is measured directly by the volume of MIL-F-7024A fluid pumped into the accumulator. MIL-F-7024A fluid was selected as the secondary fluid because of the availability of flowmeters that are accurately calibrated for this fluid. Most of the basic



SECOND TEST SETUP SCHEMATIC

FIGURE 9

system was derived from existing equipment previously developed for an AiResearch-sponsored fuel-evaluation test on tetrahydromethylcyclopentadiene dimer (TH-MCPD) fuel that was documented in AiResearch Test Report PE-5130-R.

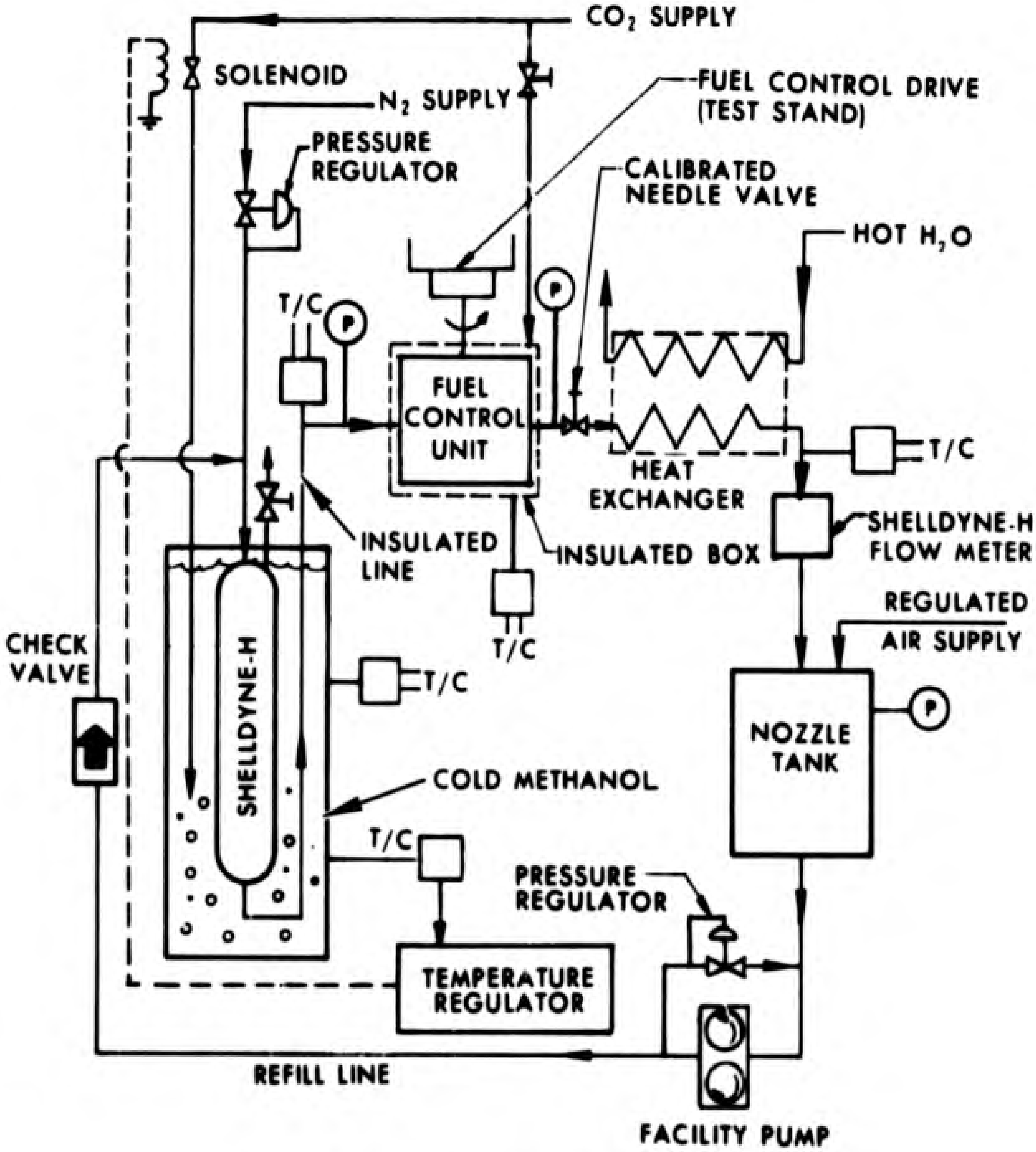
The fuel-control unit and the accumulator were enclosed in separate insulated boxes and were chilled with CO_2 gas. MIL-F-7024A fluid was pumped by a gear pump through a check valve and flowmeter into one side of the accumulator. An equivalent volume of Shelldyne-H fuel was discharged from the other side of the accumulator, through the fuel control, through a nozzle simulator, and into a Shelldyne-H fuel receiving tank.

To recharge the accumulator, Shelldyne-H fuel was withdrawn from the Shelldyne-H tank and pumped through a check valve and into the accumulator. The MIL-F-7024A fluid was expelled from the other side of the accumulator to the test stand drain.

The accumulator diaphragm was made of Buna N rubber which remains flexible at temperatures down to minus 45°F. At temperatures below minus 45°F Buna N becomes brittle, and flexing of the diaphragm causes it to rupture. Alternate materials were investigated in an attempt to find a diaphragm material capable of operation at minus 65°F. Materials possessing the proper mechanical properties at these temperatures were found to contain Silicone compounds similar to those in EMS53084 and EMS53015. Use of diaphragms made from these materials was precluded by the results from the materials compatibility testing, which showed these materials to be incompatible with Shelldyne-H fuel (see Section III).

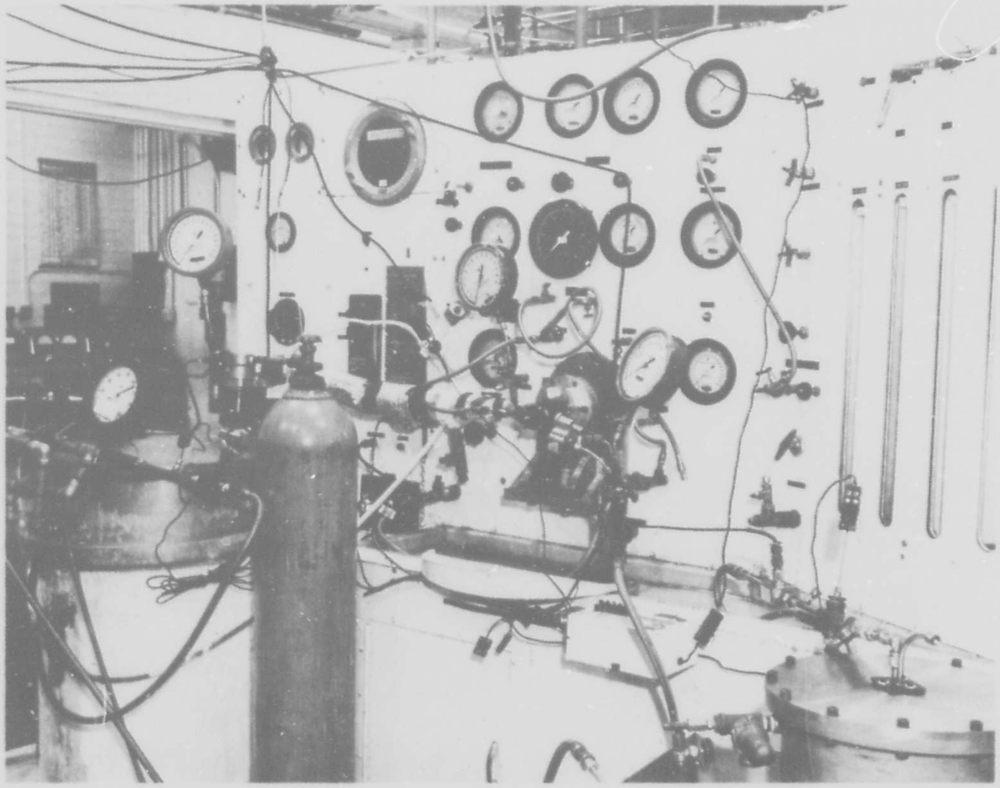
Test results obtained with this test setup indicated functional and structural integrity of the fuel control at temperatures down to minus 40°F. An additional problem was identified during this segment of the testing. Gaseous carbon dioxide used to thermally condition the fuel accumulator would solidify on expansion into the insulated box. Consequently, the temperature within the box surrounding the accumulator was the sublimation temperature of almost minus 100°F. Under these conditions, it was impossible to maintain a closely controlled Shelldyne-H temperature.

4.4 Third Test Rig. The third test rig was assembled from laboratory equipment and apparatus fabricated especially for these tests. A schematic diagram of this system is shown in Figure 10. The test setup is shown in Figures 11 and 12.



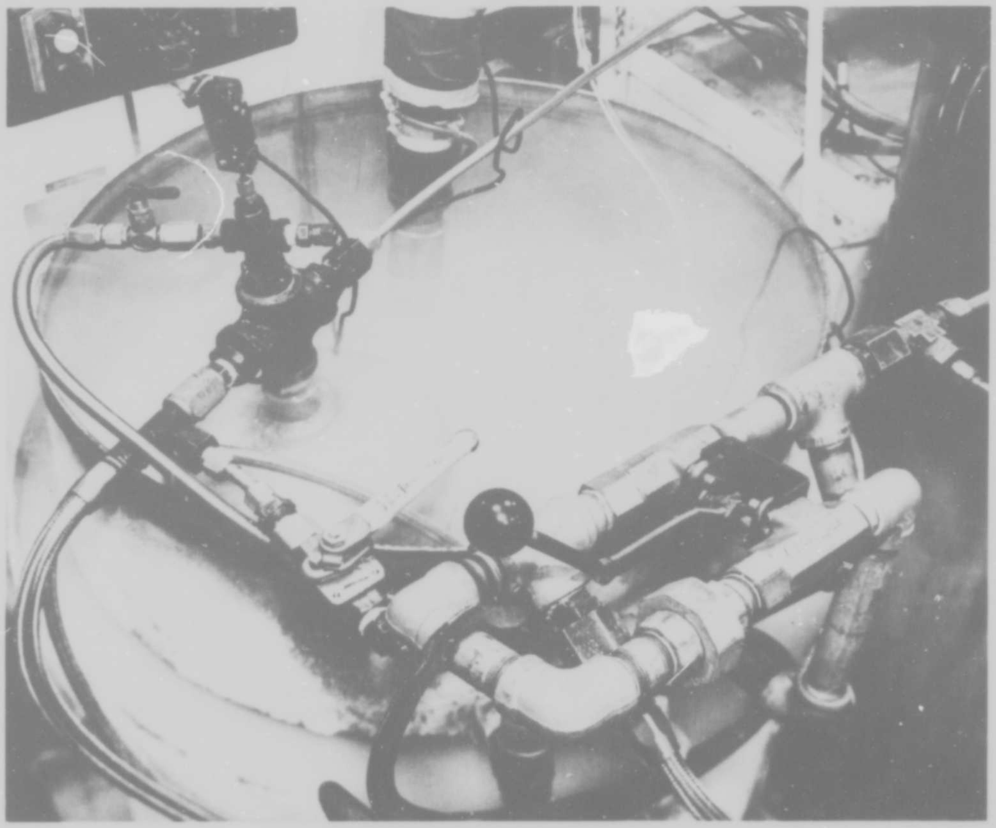
THIRD TEST SETUP SCHEMATIC

FIGURE 10



THIRD TEST SETUP
FOR SHELLDYNE-H COOLING

FIGURE 11



METHANOL TANK FOR
THIRD TEST SETUP

FIGURE 12

The system includes a pressure vessel that contains Shelldyne-H fuel. The vessel is immersed in a tank containing methanol. The methanol, pressure vessel, and Shelldyne-H fuel were initially chilled with dry ice. Carbon dioxide was then bubbled through the methanol and used to maintain the desired bath and Shelldyne-H fuel temperature. Carbon dioxide flow was automatically regulated by a thermocouple temperature-regulator solenoid valve system. Gaseous nitrogen was used to pressurize the chilled Shelldyne-H fuel tank and thereby force the Shelldyne-H fuel through an insulated line to the fuel-control-unit inlet.

After discharge from the fuel-control unit and a back-pressure valve, the Shelldyne-H fuel was heated in a hot-water to fuel heat exchanger. The heat exchanger raised the fuel temperature so that the fuel viscosity entering the downstream flowmeter was maintained within the flowmeter calibration limits. The fuel leaving the flowmeter was then passed to the nozzle tank.

To refill the system, Shelldyne-H fuel was transferred from the nozzle tank by a facility pump, through a check valve, and into the Shelldyne-H pressure vessel. The Shelldyne-H pressure vessel volume was 5 gallons.

Use of this system indicated that the fuel-control unit would function at Shelldyne-H fuel temperatues down to minus 65°F. In addition, the operating characteristics of the test setup indicated capability for handling viscous fuels and oils at temperatures down to minus 100°F with carbon dioxide and methanol utilized as the coolant bath. Further reductions in temperature are possible by utilizing lower temperature cryogenic liquids such as nitrogen bubbled through ethyl alcohol. This combination would allow temperatures down to minus 170°F.

5. TEST RESULTS.

Tests of Shelldyne-H fuel with the control components of the GTP30 Gas Turbine Engine revealed that current engine-fluid handling technology and the state of the art would not preclude the application of Shelldyne-H fuel as a gas turbine engine fuel.

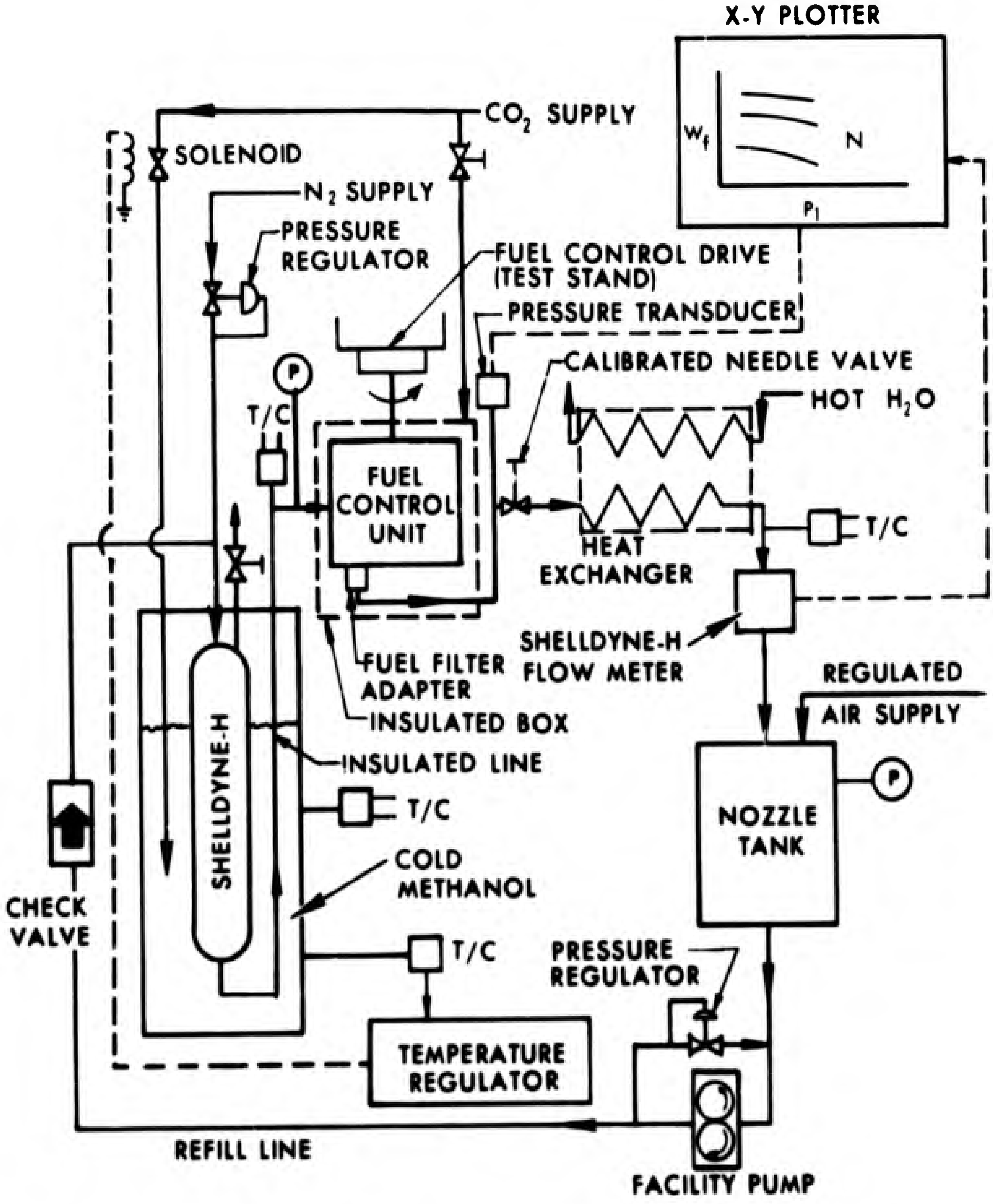
In some respects the Shelldyne-H fuel handling characteristics are superior to those of the more conventional class of fuels such as MIL-T-5624, Grades JP-4 and JP-5. The lubrication qualities of Shelldyne-H fuel seem to be significantly improved over that of JP-4 or JP-5 class fuels. Although direct lubricity measurements, such as with a Hohman wear tester, were not made, the general appearance of the fuel-control elements indicated that Shelldyne-H fuel lubricity characteristics are superior. The very low vapor pressure characteristics of Shelldyne-H fuel also reduce the cavitation tendency of high-speed pumping elements at elevated fuel temperatures.

Conversely, the high-viscous properties of Shelldyne-H fuel create a tendency toward cavitation at low fuel temperatures. In general, the higher fuel viscosity characteristics of Shelldyne-H fuel will tend to have some detrimental effects on the fuel handling system.

5.1 Fuel Pump Test. The pumping characteristics of Shelldyne-H fuel were determined by use of the basic test system shown in Figure 10. However, this system was modified to include an X-Y plotter, which was connected to fuel-pump discharge pressure and fuel flow measurement instrumentation as shown in Figure 13.

Use of this plotter provided direct presentation of pump flow versus discharge pressure data and also permitted obtainment of transient data. The system shown in Figure 13 utilized a fixed-volume, or batch, fuel chilling concept. Therefore, a given test run was limited in duration both by the volume of fuel contained in the Shelldyne-H fuel vessel and by the fuel flow rate. Consequently, by establishing the fuel temperature conditions and setting a pump speed, the entire range of fuel flow versus pump discharge pressures could be obtained by simply adjusting the needle valve located between the fuel-control unit and the heat exchanger. The more conventional quasi-steady-state method of obtaining these data would have yielded only a single datum point per run.

The GTP30 Gas Turbine Engine fuel pump is integral with the fuel-control unit as discussed and described previously in Section IV. To obtain fuel-pump performance characteristics, a fuel filter adapter was installed on the fuel-control



FUEL CONTROL UNIT PUMP TEST SETUP SCHEMATIC

FIGURE 13

unit in place of the fuel filter. The adapter capped off an internal fuel delivery port and provided an external port for connecting directly to the pump discharge flow.

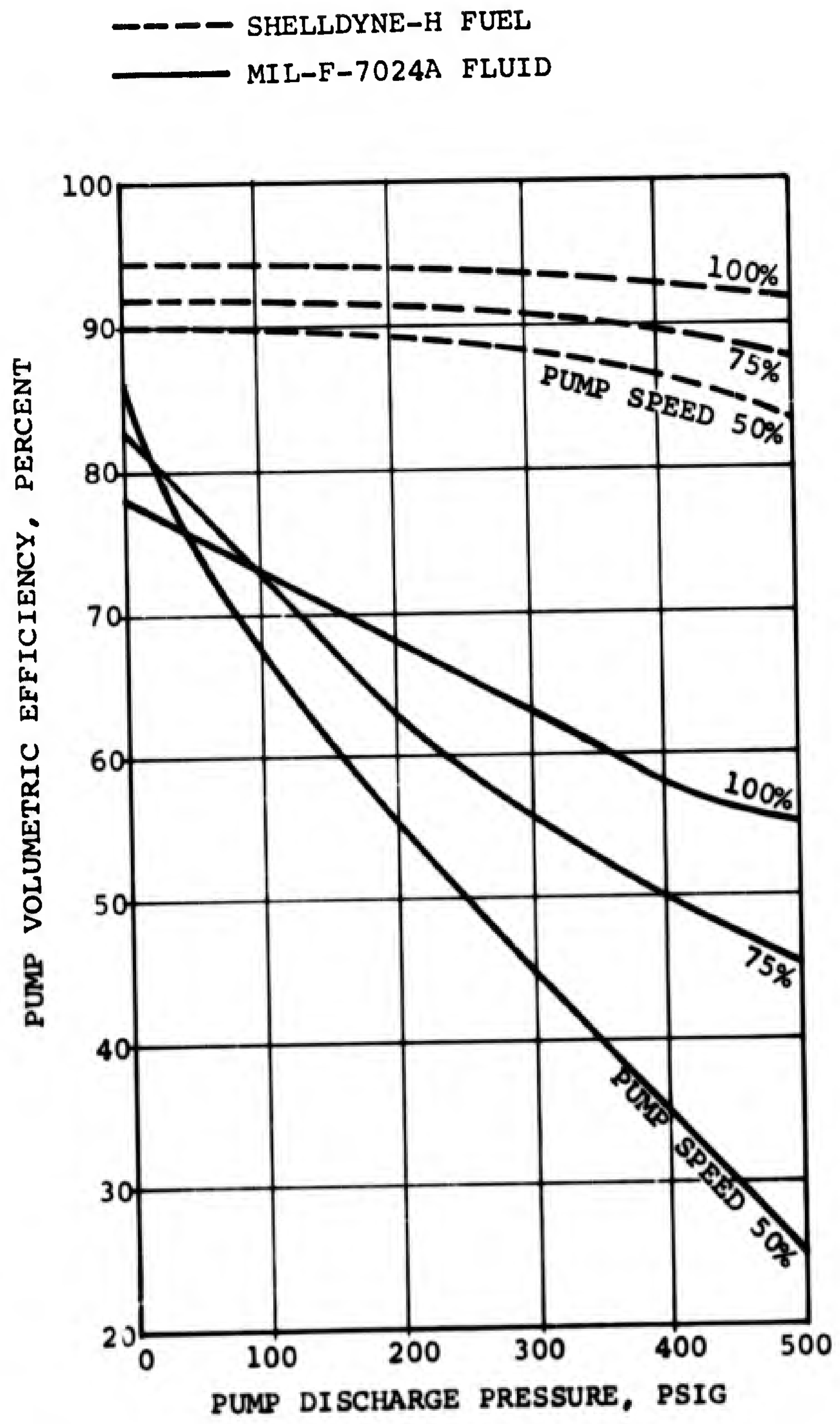
A series of pump calibration runs were made with Shelldyne-H fuel at temperatures of 75°F, zero °F, and minus 65°F and with MIL-F-7024A fluid at 75°F. The results of these tests are shown in Figures14 and 15.

Figure 14 presents comparative data for the pump operating with MIL-F-7024A fluid and Shelldyne-H fuel. Data was obtained with a fuel temperature of 75°F and at a pump inlet pressure of 15 psig. The pump body ambient temperature was maintained at the fuel supply temperature for all tests. A marked improvement in pump volumetric efficiency was noted with the use of Shelldyne-H fuel and is attributed to the higher viscosity of this fuel. Gear pump volumetric efficiency is controlled for the most part by tip and side leakage. The higher viscosity fuel displayed less leakage around the pump elements; consequently, the volumetric efficiency characteristic of the pump was improved.

The data presented in Figure 15 relates the performance characteristics of the pump operating with Shelldyne-H fuel at temperatures of 75°F, zero °F, and minus 65°F. The performance characteristics of the pump were relatively insensitive to temperature except that at minus 65°F the pump exhibited flow-capacity limits that were dependent upon the fuel supply pressure.

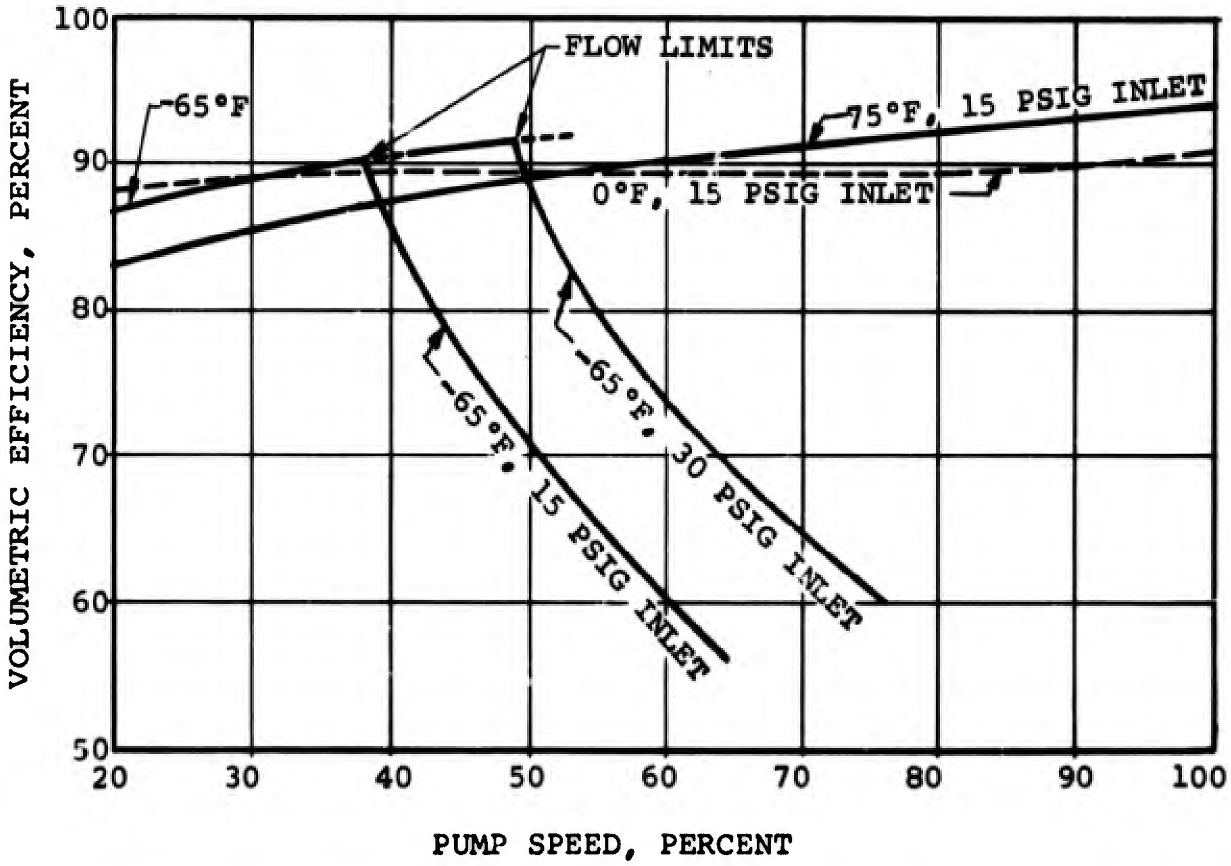
The fuel delivery rate of the pump became limited at 38 percent pump speed at a fuel supply pressure of 15 psig. By increasing the fuel supply pressure to 30 psig, the pump delivery rate continued to increase with increasing pump speed up to a speed of 49 percent.

A pump capacity limitation that is dependent on the inlet supply pressure is a phenomenon that is a characteristic of pump cavitation. Cavitation tendency normally is associated with increasing pump inlet fluid temperatures or conditions under which the fluid vapor pressure increases at constant supply pressure. The mechanism of low-temperature cavitation is analogous. Consider the fluid at point A in Figure 16 being at a supply pressure of P_1. In order to flow from A to B, a certain head drop, Δh, must be available. If, for the prevailing flow rate, this head drop becomes the total head available, then the pressure at B becomes the vapor pressure of the fluid (or some higher pressure, if air leakage is present in the system). Under these conditions, fluid cannot be delivered to the pump gears at a faster rate, independent



PUMP PERFORMANCE WITH SHELLDYNE-H FUEL
AND MIL-F-7024A FLUID SUPPLY AT 75°F AND 15 PSIG

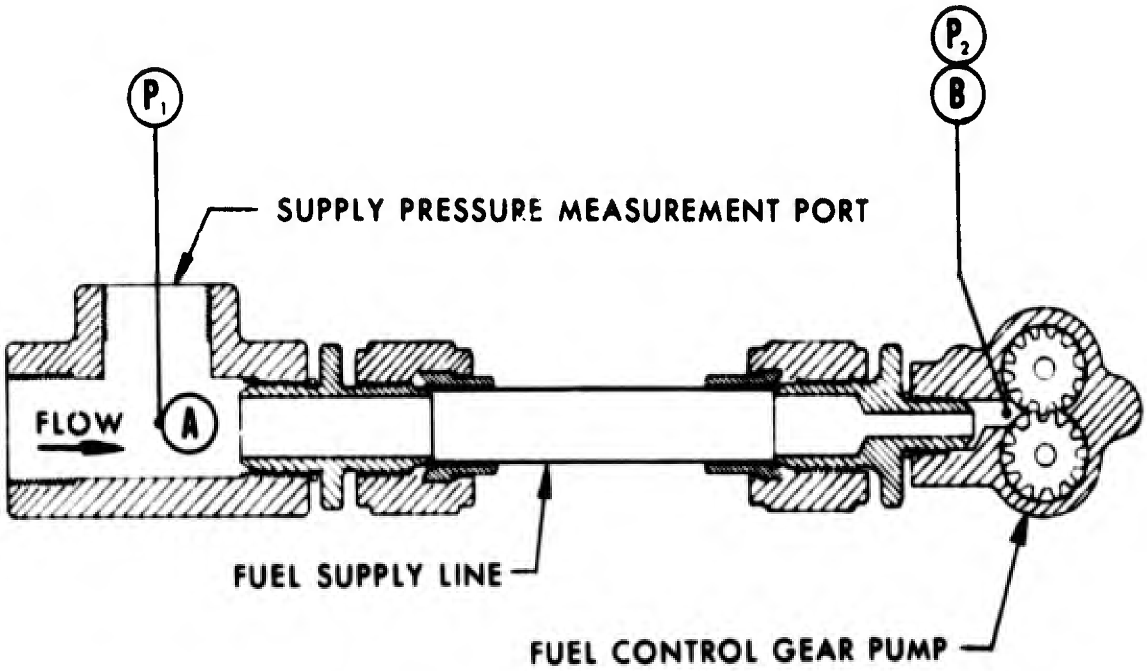
FIGURE 14



PUMP DISCHARGE
PRESSURE 200 PSIG

PUMP PERFORMANCE WITH
SHELLDYNE-H FUEL

FIGURE 15



CROSS SECTION OF PUMP AND INLET CONNECTIONS USED FOR EVALUATING SHELLDYNE-H FUEL PUMPING CHARACTERISTICS

FIGURE 16

of gear speed, unless the supply pressure, P_1, is increased. Consequently, the pump gear teeth do not fill with fluid, and the pump cavitates. For fluids that exhibit highly viscous characteristics, low-temperature cavitation will result simply because of the increased flow losses incurred in the pump inlet with decreasing temperature.

This phenomenon can be verified analytically by relating the limiting flows of Figure 15 to supply pressure.

Fluid head drop in flow is:

$$\Delta h = f \frac{L}{D} \frac{V^2}{2g} \quad \text{(Reference } ^1\text{)} \qquad (1)$$

where

f = Moody friction factor

L = length of flow path

D = flow-path characteristic dimension, usually diameter

V = velocity flow

g = gravitational acceleration

ρ = fluid density

μ = fluid viscosity (absolute)

From the Blasius correlation for friction factor at Reynolds numbers up to 100,000:

$$f = \frac{0.316}{R^{1/4}} \quad \text{(Reference}^2\text{)} \qquad (2)$$

$$R\text{, Reynolds number} = \frac{VD\rho}{\mu}$$

Combining

$$\Delta h = 0.316 \left(\frac{\mu}{VD\rho}\right)^{1/4} \frac{L}{D} \frac{V^2}{2g} \qquad (3)$$

$$\Delta h = 0.316 \left(\frac{\mu}{D\rho}\right)^{1/4} \frac{L}{D} \frac{V^{1.75}}{2g} \qquad (3a)$$

For the case under consideration, all fluid properties and the flow paths are identical. Consequently, the fluid head drops can be related to fluid velocities in the following manner:

$$\frac{\Delta h_1}{\Delta h_2} = \left(\frac{V_1}{V_2}\right)^{1.75} \tag{4}$$

Letting Condition 1 be at a supply pressure of 30 psig and Condition 2 at a supply pressure of 15 psig, the ratio of velocities is the ratio of flows and

$$\left(\frac{V_1}{V_2}\right)^{1.75} = \left[\frac{(0.914)\,(0.4\overset{*}{9})}{(0.903)\,(0.38)}\right]^{1.75} = 1.592 \tag{5}$$

The ratio of head drops for these two conditions is

$$\frac{\Delta h_1}{\Delta h_2} = \frac{30.0 + 14.0}{15.0 + 14.0} = 1.518 \tag{6}$$

The ratios in (5) and (6) above are in close agreement indicating that the pump inlet, in fact, limits the flow supplied to the pump.

The results of these tests indicate that the pumping characteristics of Shelldyne-H fuel are somewhat different than those of the more conventional JP class of fuels. Shelldyne-H fuel is a more viscous fluid, thereby providing for higher positive-displacement-pump volumetric efficiencies. The higher viscosity, however, also has the deleterious effect of requiring higher pump-inlet pressures at reduced temperatures for suppression of low-temperature cavitation. The effects of this characteristic can be minimized by careful design of the pump inlet and fuel supply line.

5.2 <u>Fuel-Control-Unit Tests.</u> Fuel-control-unit testing was accomplished by using the test system previously described, and shown in Figure 10. The test-stand fuel-control-unit installation is shown in Figures 11 and 12. Preliminary testing was accomplished with use of MIL-E-7024A fluid to verify the functional and mechanical integrity of the fuel-control unit. The control was then subjected to detailed testing and verification of the control function with Shelldyne-H fuel at reduced temperatures.

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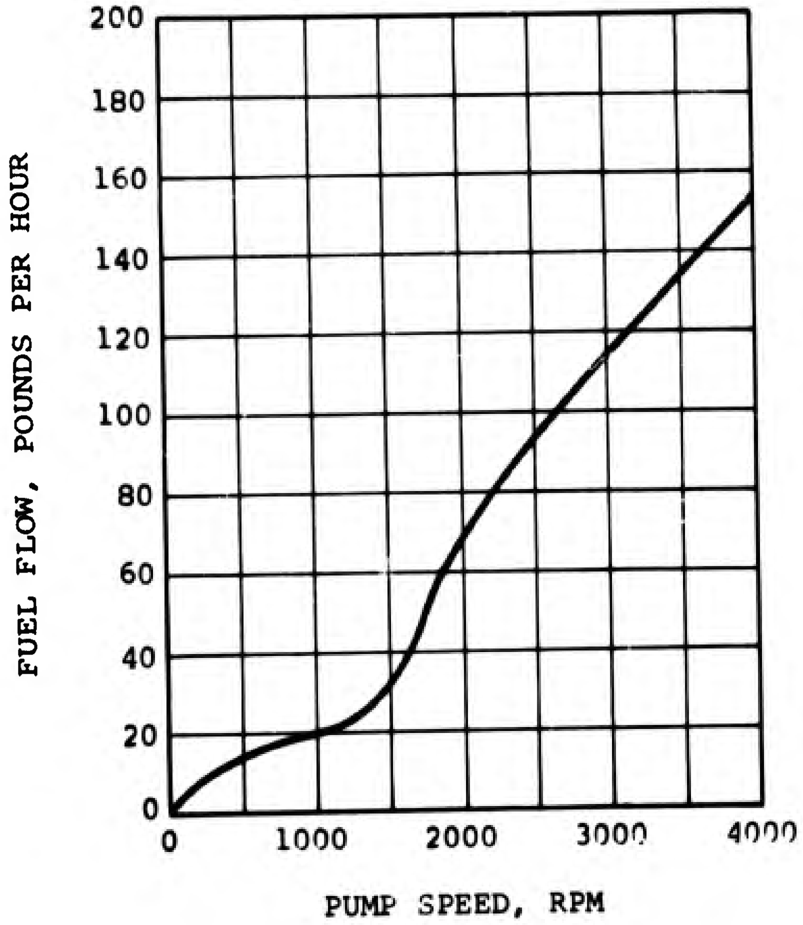
*Data taken from Figure 15, Page 37.

5.2.1 Preliminary Testing. The control was calibrated in accordance with standard production test procedures. These test procedures, which are conducted on the standard fuel-test bench with use of MIL-F-7024A calibration fluid, include various internal and external leakage checks, pump discharge pressure fluctuation checks, acceleration limiter checks, and governor checks.

The results of the preliminary calibration indicated that the fuel-control unit was functionally sound and that the acceleration-limiter valve had been adjusted to the crack pressure specified by the production test instructions. The resulting acceleration or start-flow schedule obtained from these tests is presented in Figure 17 as a curve of fluid flow versus fuel-pump speed. It should be observed that the characteristic slope change of this curve at approximately 1200 rpm pump speed is due to opening of the flow divider in the fuel atomizer assembly.

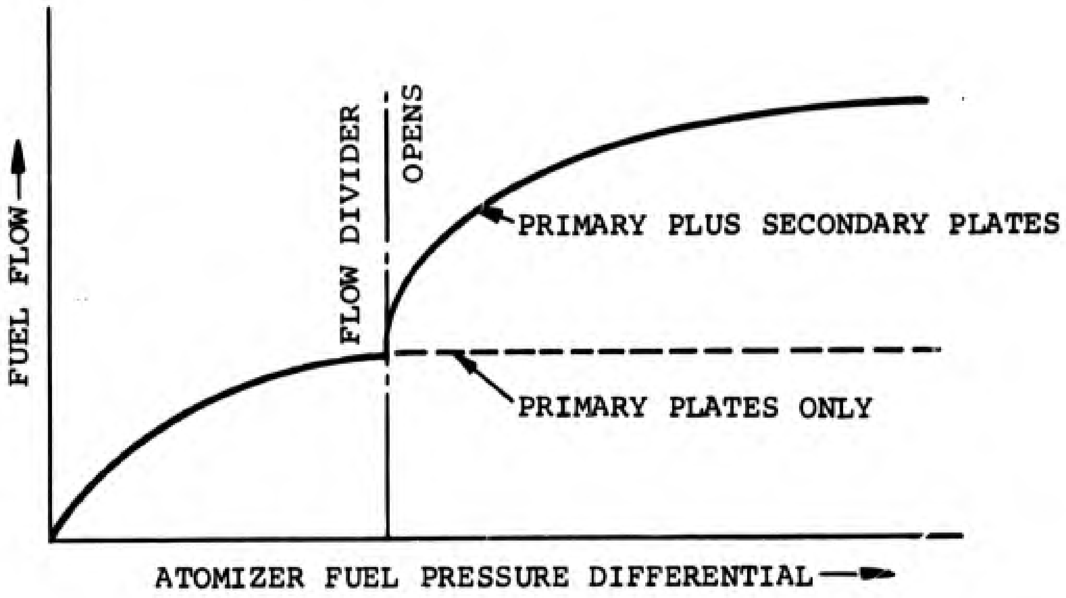
The Model GTP30 Engine standard combustor employs a duplex fuel nozzle. This nozzle consists of a primary and secondary set of spray plates and a pressure relief valve, which is referred to as the "flow divider."

During engine operating conditions that require low fuel-flow rates, the flow-divider or relief valve is closed, which forces all of the fuel to enter the combustor through the primary spray plates. The primary spray plates are designed to provide the high fuel velocities and atomization characteristics required at the low flow rates that occur during an engine start transient. As engine speed increases, the amount of fuel delivered by the fuel control increases. This results in an increasing pressure drop across the primary nozzle. At a preset pressure drop the flow divider opens, allowing the fuel to flow through the secondary spray plates. The secondary plates are designed to provide proper atomization characteristics at the higher fuel-flow rates required at governed speed. The resulting fuel-flow scheduling characteristics incorporated in the atomizer are shown in representative curve form on Page 43.



ACCELERATION SCHEDULE WITH
MIL-F-7024A FLUID AT 75°F

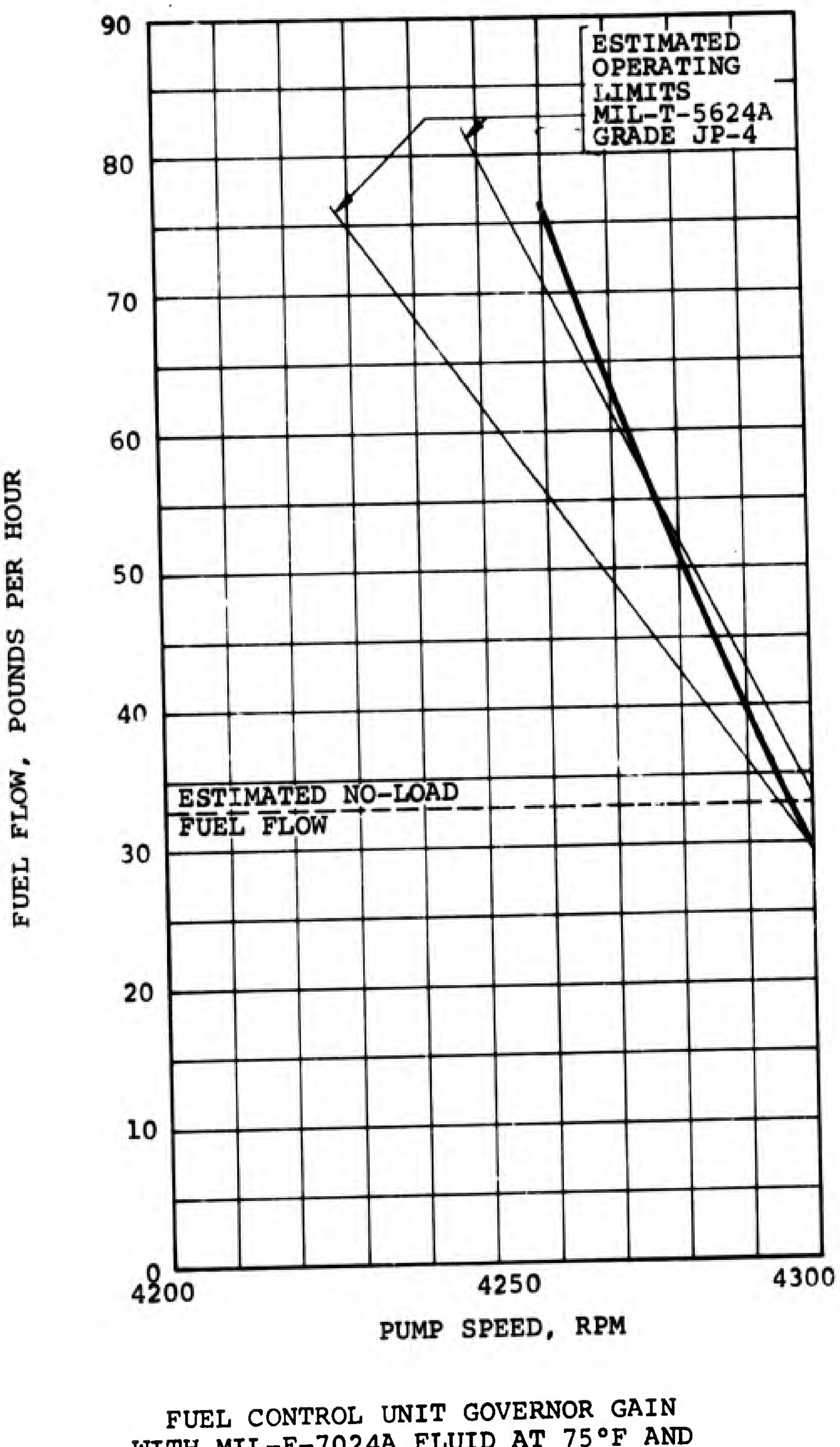
FIGURE 17



The resulting acceleration schedule shown in Figure 17 is normal and would provide satisfactory fuel flows to accelerate the Model GTP30 Engine with MIL-T-5624 Grade JP-4 fuel.

Governor tests indicated that the governor spring rate (30 pounds per inch) was too low for use with MIL-T-5624 Grade JP-4 fuel. Figure 18 shows the resulting fuel flow rates delivered by the control over the range of pump speeds for which the governor is normally operative. Also shown are the upper and lower operating limits as defined by the production test instructions. The governor curve is linear; however, the slope or gain is considerably higher than normal.

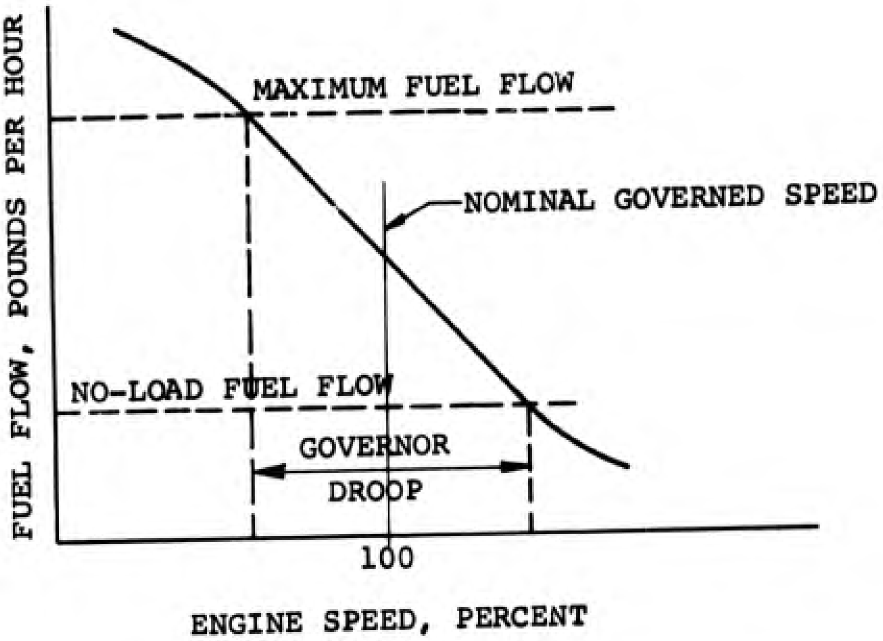
The governor used in this fuel-control unit is a proportional control device. Consequently, a speed error is required to change the fuel flow and the change in fuel flow is "proportional" to the engine speed deviation. The speed deviation, in percent, from no load to full load is called governor "droop."



FUEL CONTROL UNIT GOVERNOR GAIN
WITH MIL-F-7024A FLUID AT 75°F AND
30-POUND-PER-INCH GOVERNOR SPRING

FIGURE 18

A curve of engine fuel flow versus engine speed as shown below reflects the important steady-state characteristics of the control.



The slope or rate of fuel flow change for a given speed change is termed governor gain. Consequently, the higher the gain the lower the droop. Also, it is desirable to maintain a constant governor gain, which requires that the fuel flow versus engine speed characteristic be a straight line.

For a single speed operating point such as is used for the Model GTP30 Engine it is desirable to have as little speed deviation or "droop" as possible. Consequently, the control gain must be high. However, a general tendency of proportional controls is that as the control gain is increased the propensity toward instability or speed cycling increases. The control gain characteristics shown in Figure 18 reflect the upper and lower allowable governor set-point limits.

A governor gain line that falls within these limits will provide an acceptable engine speed and a stable control. On the Model GTP30 Engine fuel control, the governor set point is adjusted by increasing or decreasing the load on the governor spring with an adjusting screw. The gain of the control is adjusted by changing the spring rate of the governor spring. This is accomplished by physical substitution of the governor spring with one possessing the proper spring rate.

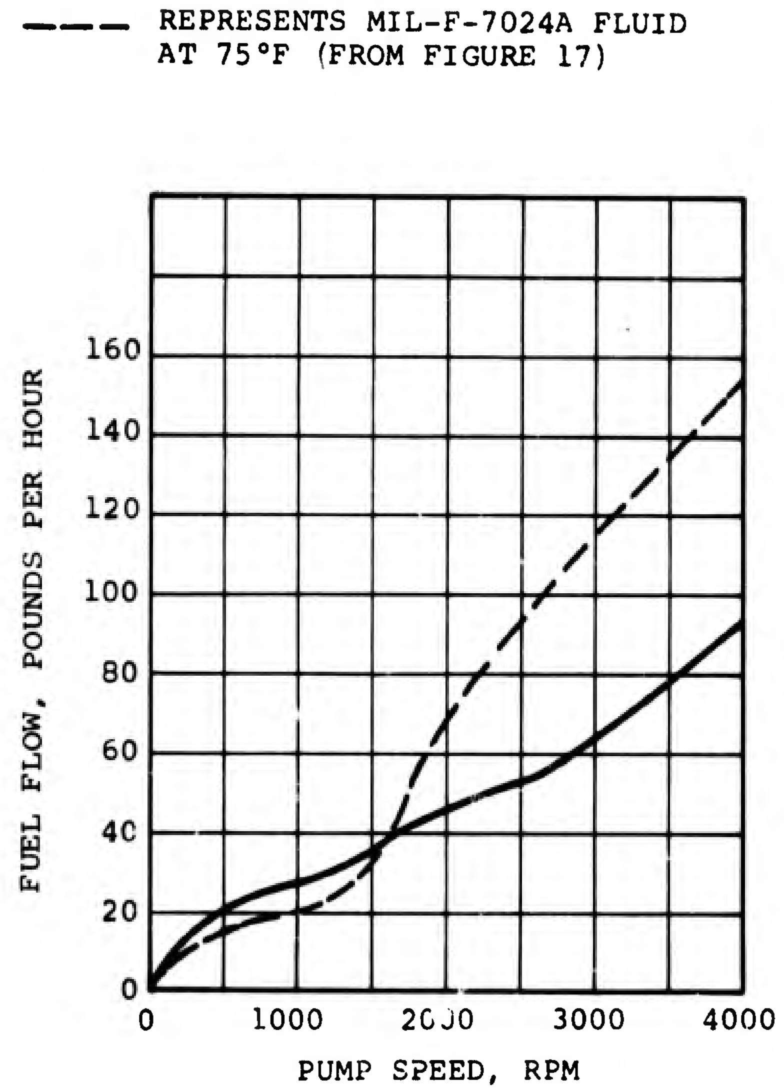
The governor characteristics shown in Figure 18 indicate that the governor gain is too high and that the engine would probably be unstable if operated on MIL-T-5624 Grade JP-4 fuel. Preliminary estimates had, however, indicated that the governor gain would be considerably different with Shelldyne-H fuel, necessitating a governor spring change. Consequently, the performance shown in Figure 18 was not altered prior to testing with Shelldyne-H fuel.

5.2.2 Shelldyne-H Fuel Tests. The acceleration or start-flow tests with Shelldyne-H fuel were conducted with use of the test setup shown in Figures 10, 11, and 12. The test was accomplished by increasing the fuel-pump speed in 500-rpm increments from 500 rpm to 4000 rpm. For these tests, the acceleration-limiter pneumatic input signal was simulated by a regulated air supply. The pneumatic simulation was accomplished by scheduling air pressure as a function of the governor speed that was representative of compressor discharge pressure-speed characteristics experienced during an engine start. Fuel flow, compressor air pressure, fuel-control discharge pressure, pump speed, and fuel temperature were recorded for each speed. The crack pressure setting of the acceleration-limiter valve obtained during initial tests with MIL-F-7024A fluid was retained for the Shelldyne-H fuel tests. Data obtained from this test at 75°F is presented in Figure 19.

Comparison of the data for MIL-F-7024A fluid shown in Figure 17 with the data for Shelldyne-H fuel shown on Figure 19 is made on Figure 19. This comparison shows that Shelldyne-H fuel flows between zero and approximately 1500 rpm pump speed are somewhat higher than MIL-F-7024A fluid flows, and Shelldyne-H fuel flows between approximately 1500 and 4000 rpm pump speed are lower.

The difference in acceleration schedule characteristics results from the fuel-injection system and not the acceleration limiter itself. The fuel-injection system used with the Model GTP30 Engine combustor incorporates a duplex nozzle as described in Paragraph 5.2.1. The combustor incorporated for this program utilizes a fixed downstream restriction which causes the acceleration flow-schedule to have different characteristics. The flows obtained with Shelldyne-H fuel were, however, considered to be adequate for acceleration of the Model GTP30 endurance engine.

As the fuel and ambient temperatures were lowered, the output of the fuel-control unit increased because of increased pump volumetric efficiency and reduced acceleration-



ACCELERATION SCHEDULE WITH
SHELLDYNE-H FUEL AT 75°F

FIGURE 19

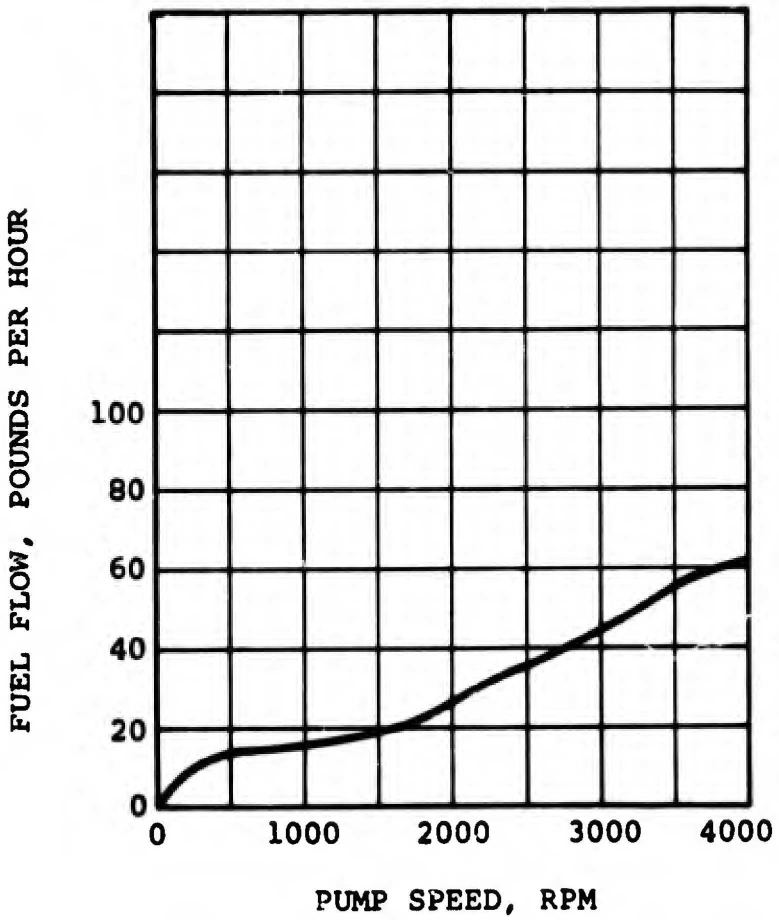
limiter-valve flow capacity. These effects were caused by increased fuel viscosity as the temperature was reduced. This condition was corrected by closing the downstream orifice and thereby increasing the back pressure on the control. The acceleration schedules obtained at temperatures of minus 45°F and minus 65°F are shown in Figures 20 and 21 respectively. The fuel-flow acceleration schedules obtained were equal to or less than those obtained at 75°F. The settings of the downstream orifice were recorded for each fuel temperature so that adjustments can be made during reduced-temperature start tests on the engine.

These acceleration tests clearly revealed that a more sophisticated control is required in the application of Shelldyne-H fuel as a gas turbine engine fuel. Automatic fuel viscosity or density compensation is considered a mandatory feature for such a control. Compensation techniques have been developed and are employed on many fuel controls presently in production.

Initial governor tests with Shelldyne-H fuel at 90°F with use of a 30-pound-per-inch governor spring produced the results shown in Figure 22. This data indicated that the governor characteristic was nonlinear at pump speeds down to 4250 rpm (52,200 rpm engine speed). At pump speeds lower than 4250 rpm the governor gain was excessively high.

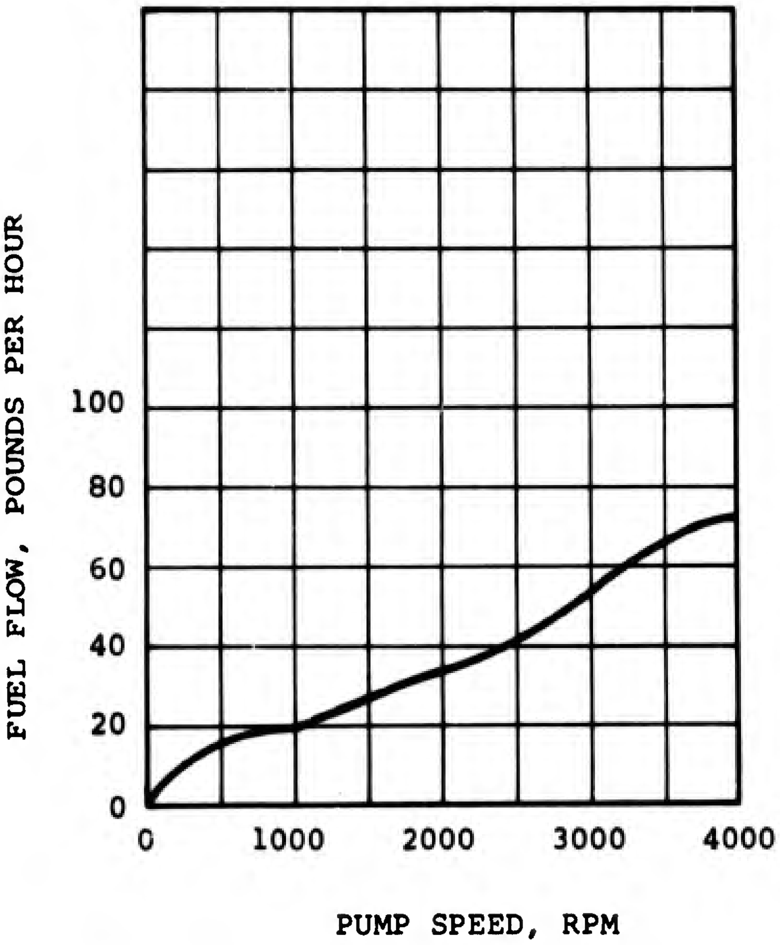
Two additional tests were run with 35- and 45-pound-per-inch governor springs to reduce the governor gain. Test results with the 35-pound-per-inch spring are shown in Figure 23. This data indicates a reduction in the governor nonlinearity characteristic compared to the data shown in the previous figure as well as a significant reduction in governor gain. Governor characteristics utilizing a 45-pound-per-inch spring are given in Figure 24 and indicate even further reductions in nonlinearity and gain.

The governor set point adjustment has the effect of moving the governor characteristic line vertically upward, for increased governed speed, or downward for decreased governed speed. Even though the gain characteristics obtained with the 45-pound-per-inch spring are the most linear and provide an almost ideal governor gain, this spring rate is unusable. Figure 25 shows the effect of varying the governor set point with a 45-pound-per-inch spring. By raising the governor set point, to achieve maximum no-load fuel flow (shown as line A), the engine will experience excessive droop as the load is increased. At full power the droop would be twice that allowable.



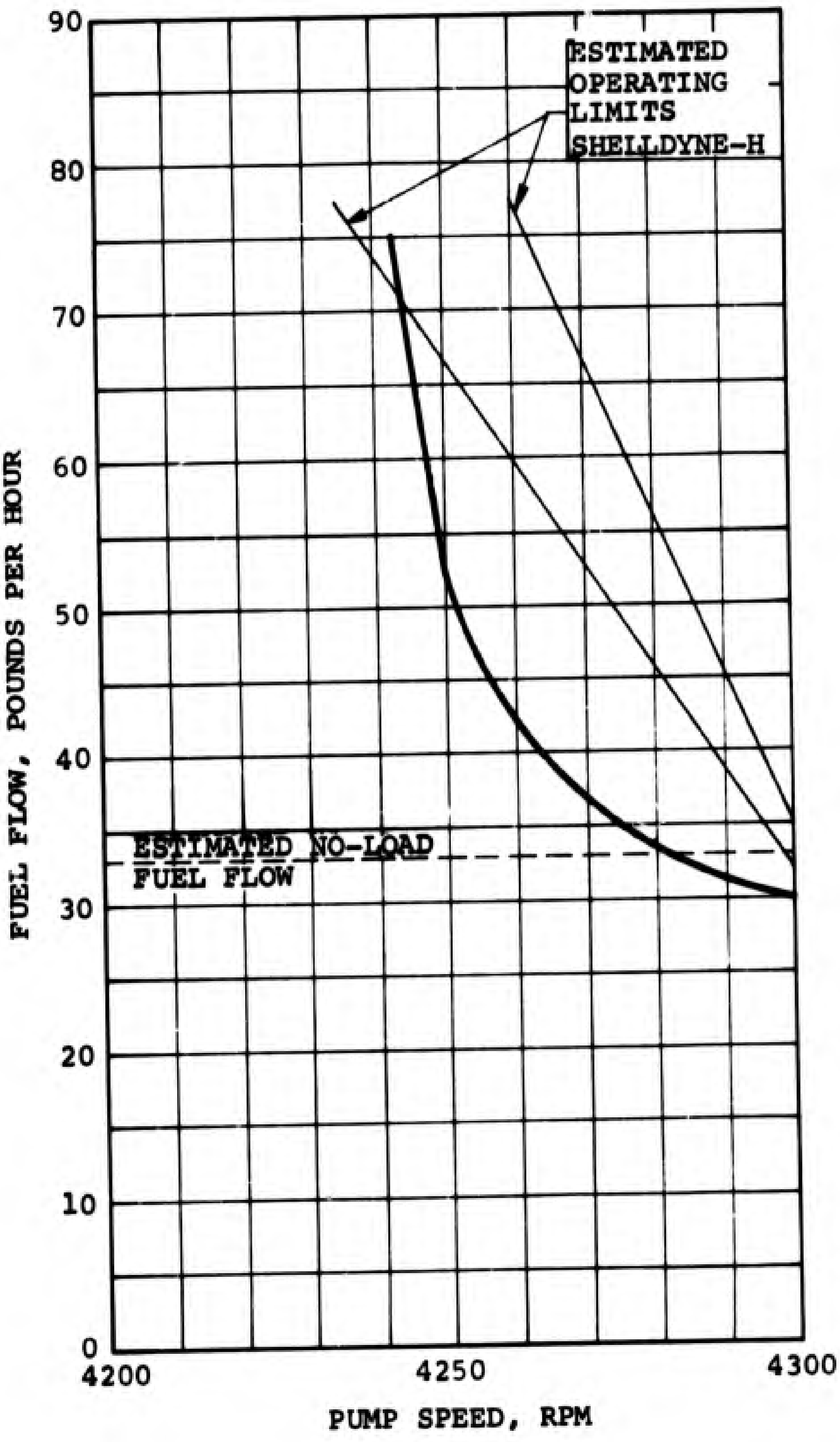
ACCELERATION SCHEDULE WITH
SHELLDYNE-H FUEL AT -45°F

FIGURE 20



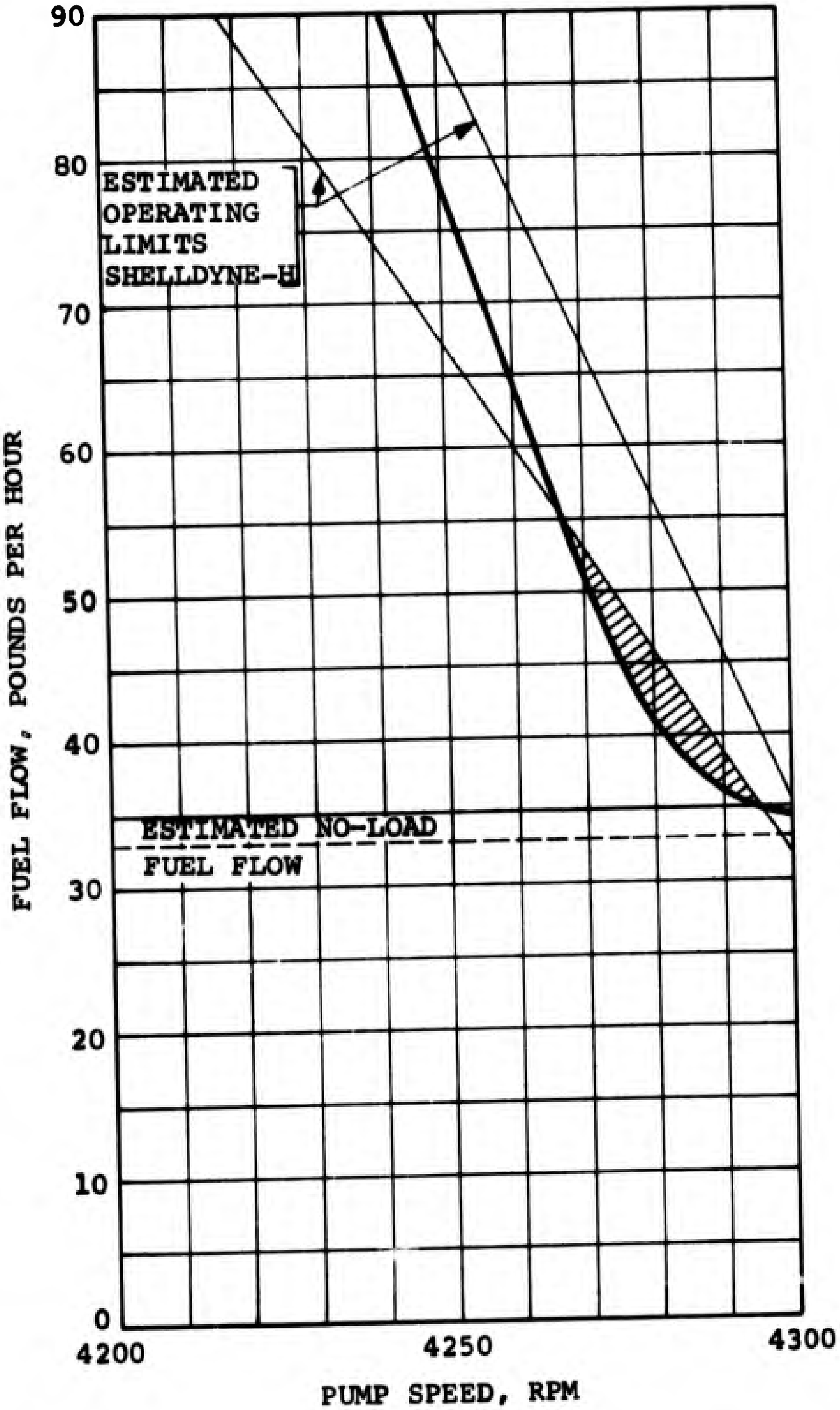
ACCELERATION SCHEDULE WITH
SHELLDYNE-H FUEL AT -65 °F

FIGURE 21



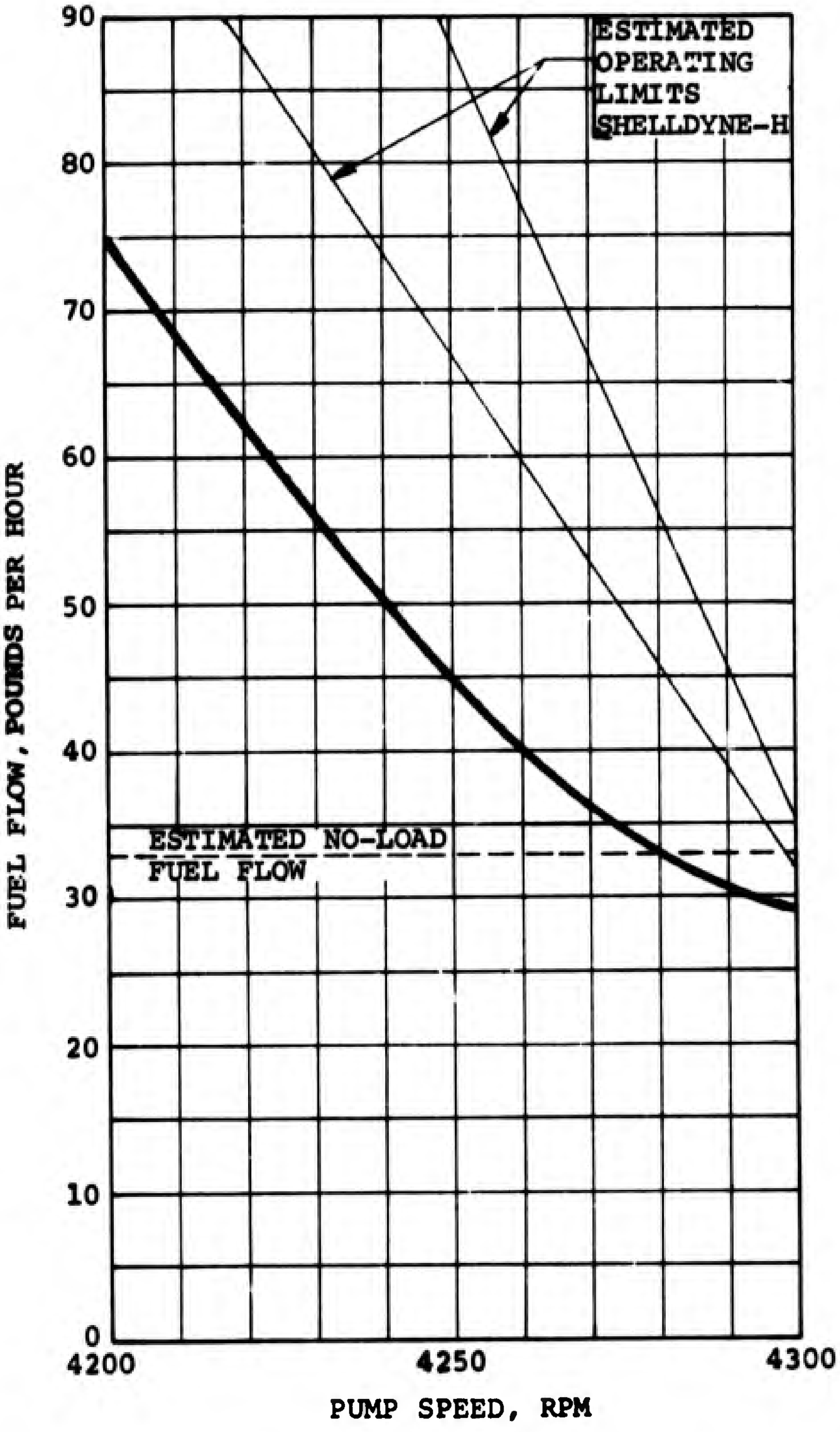
FUEL CONTROL UNIT GOVERNOR GAIN WITH SHELLDYNE-H FUEL AT 90°F AND 30-POUND-PER-INCH GOVERNOR SPRING

FIGURE 22



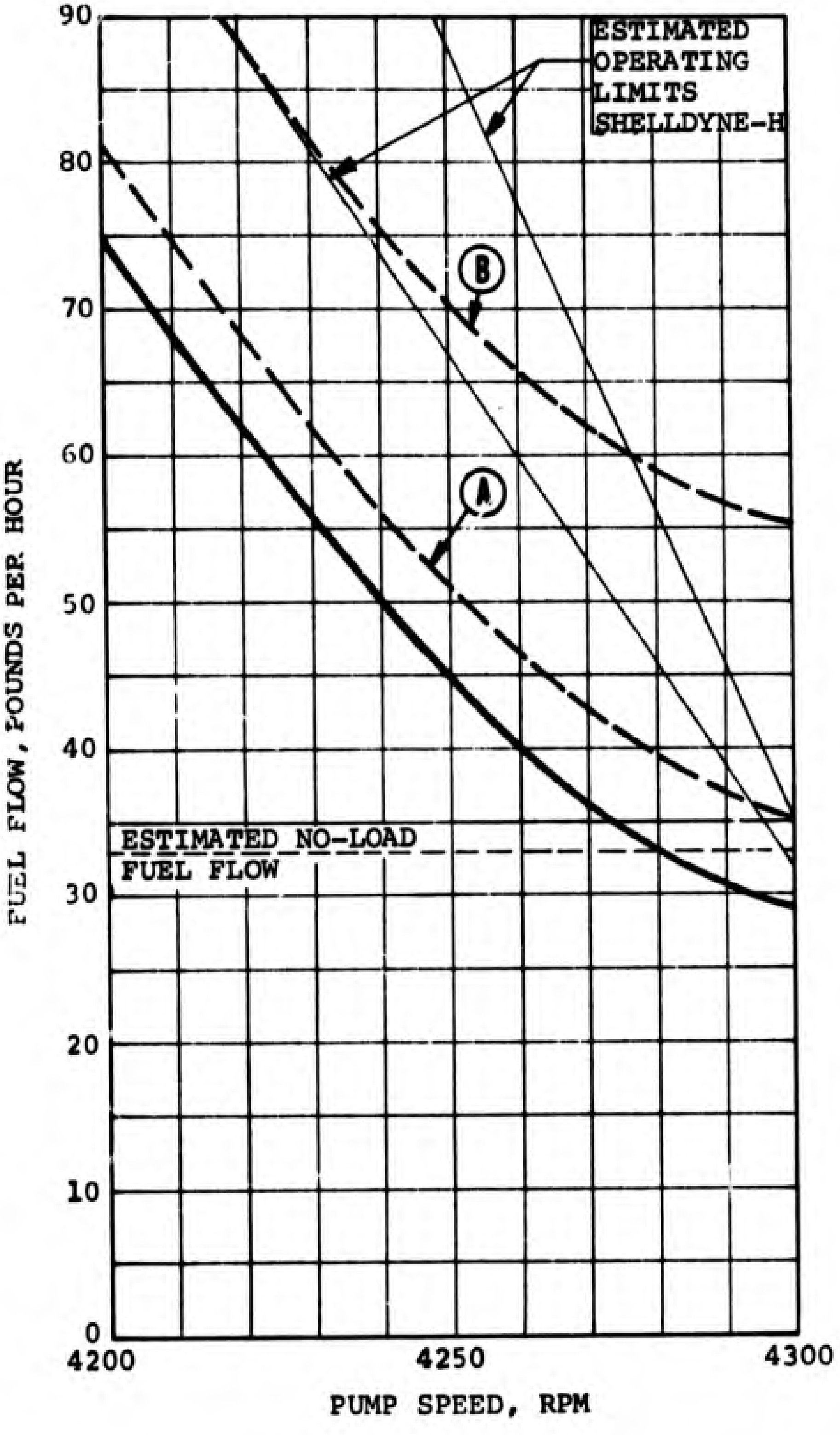
FUEL CONTROL UNIT GOVERNOR GAIN WITH SHELLDYNE-H FUEL AT 80°F AND 35-POUND-PER-INCH GOVERNOR SPRING

FIGURE 23



FUEL CONTROL UNIT GOVERNOR GAIN WITH SHELLDYNE-H FUEL AT 90°F AND 45-POUND-PER-INCH GOVERNOR SPRING

FIGURE 24



FUEL CONTROL UNIT GOVERNOR GAIN WITH SHELLDYNE-H FUEL AT 90°F AND 45-POUND-PER-INCH GOVERNOR SPRING

FIGURE 25

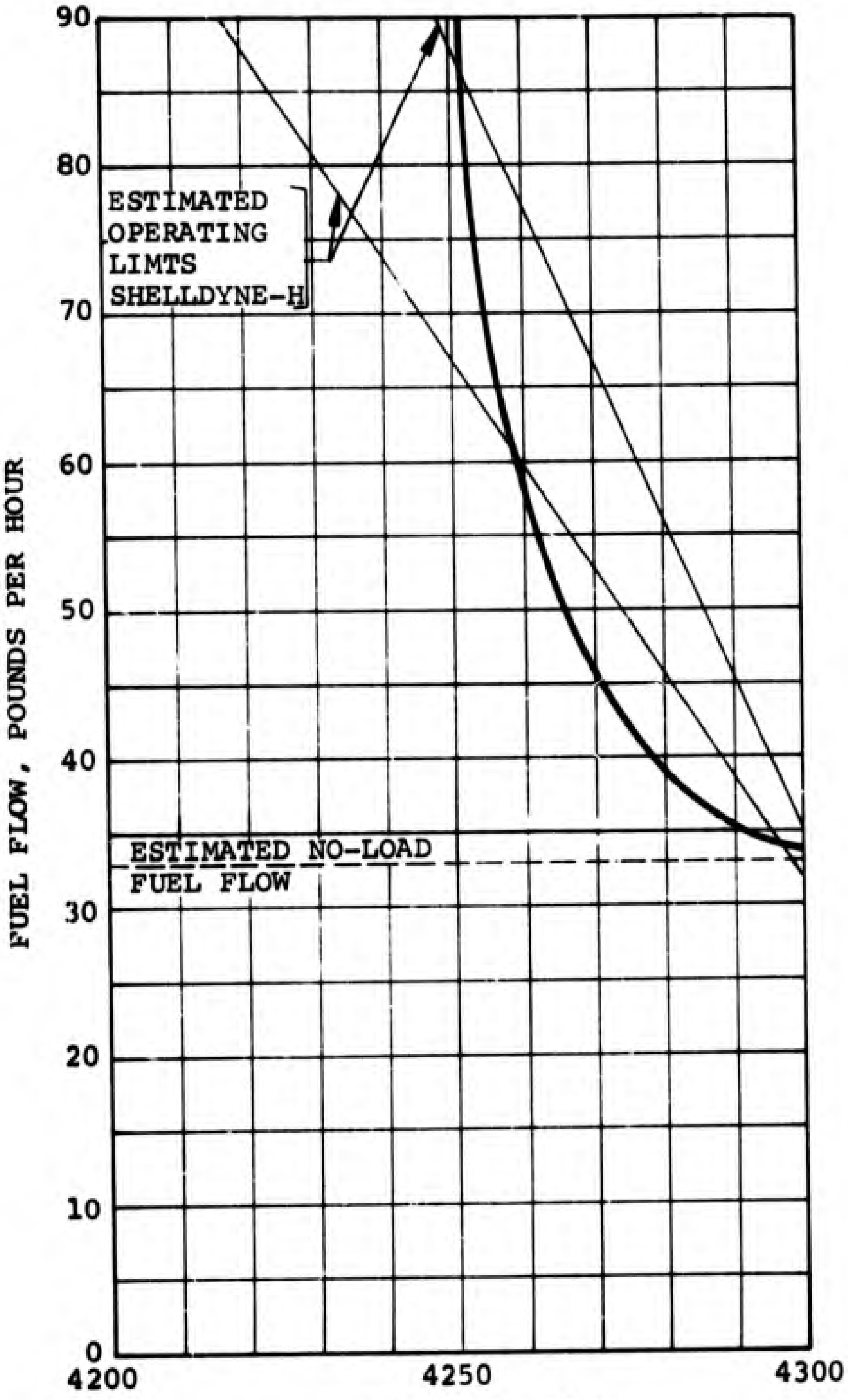
By increasing the governor set point to achieve the allowable droop characteristics as shown by line B would mean that the no-load speed would increase past the physical speed limitations of the engine. Consequently, the 45-pound-inch spring rate would not provide adequate control.

The data presented in Figure 23 (35-pound-per-inch spring) indicates that the no-load fuel flow requirements are satisfactory, as are the high-load fuel flow requirements. Even though the governor gain at high flow rates is somewhat high it is not excessive. The nonlinearity of this governor, however, has the effect of causing excessive "droop" as shown by the shaded area between pump speeds of 4268 and 4300 rpm.

The nonlinear characteristics observed at low output flows (high bypass flows) were attributed to the limiting size of the bypass port in the governor valve. The port size could not readily be increased without structurally weakening the governor shaft which also drives the governor flyweight mechanism. The mechanical loads carried by the governor shaft are already higher than are normally experienced because of the increased resistance to rotation of the flyweights in the more viscous Shelldyne-H fuel.

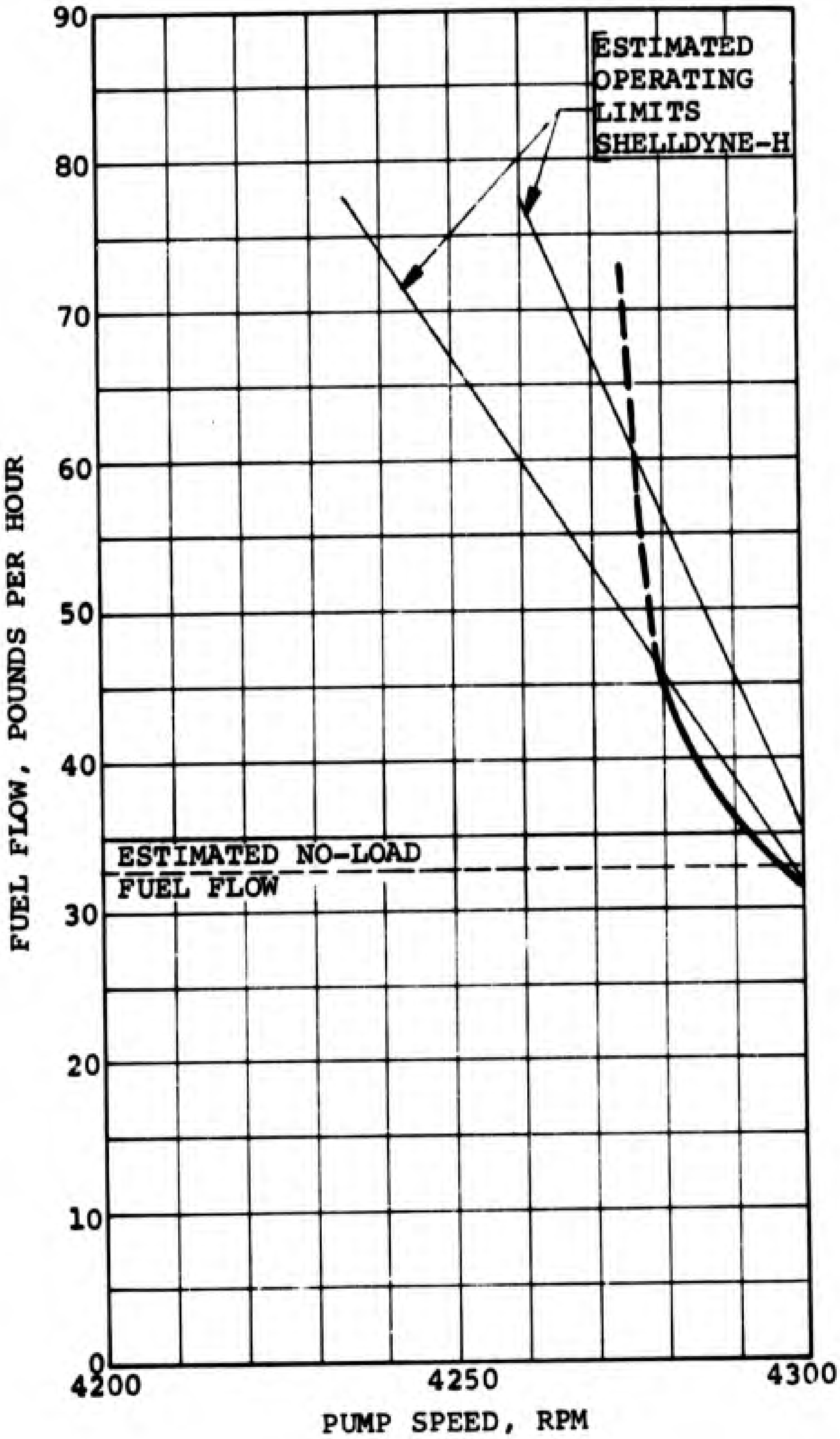
The nonlinear characteristic observed, although not desirable, was considered to be acceptable, since the output flow continued to decrease with increasing speed and the no-load flow rates were acceptable. Consequently, the control utilizing the 35-pound-per-inch spring was considered satisfactory for the endurance testing of a complete Model GTP30 Gas Turbine Engine with Shelldyne-H fuel.

The performance characteristics of this control at reduced temperatures of minus 35°F to minus 40°F are shown in Figure 26 and at a reduced temperature of minus 65°F are shown in Figure 27. Both Figure 26 and Figure 27 show high governor gains at the high output flows and the same nonlinear behavior experienced previously at the low output flow rates. The data indicates that as the temperature of the fuel is decreased, the gain and nonlinearity of the control increases significantly. Examination of the data reveals that these control characteristics would not be adequate to allow engine overall operation at reduced temperatures. However, it should also be noted that the governor characteristics at high pump speeds (no-load conditions) would provide adequate control.



FUEL CONTROL UNIT GOVERNOR GAIN WITH SHELLDYNE-H FUEL AT -35°F TO -40°F AND 35-POUND-PER-INCH GOVERNOR SPRING

FIGURE 26



FUEL CONTROL UNIT GOVERNOR GAIN WITH SHELLDYNE-H FUEL AT -65°F AND 35-POUND-PER-INCH GOVERNOR SPRING

FIGURE 27

Since engine cold-start testing requires only adequate acceleration-schedule and speed-governing functions under no-load conditions, the control used for the endurance testing will also be used for cold-start testing.

Examination of the control during and at the conclusion of these tests revealed no deleterious effects of Shelldyne-H fuel on the control. All O-rings and diaphragms retained their integrity after several weeks of continuous exposure to the fuel.

6. CONCLUSIONS. The overall results of this effort have indicated that the viscous characteristic of Shelldyne-H fuel will have a significant effect on the design of a fuel control. However, control techniques for the viscosity and density compensation have been developed and are incorporated on many production engines. Based on the results of this reported effort, there are no observed fundamental engine fuel handling and control component problems originated by the characteristics of Shelldyne-H fuel that would preclude its use as a gas turbine engine fuel.

SECTION V

COMBUSTION

An airblast-injection combustor (referred to as the Shelldyne-H combustor) capable of burning either MIL-T-5624, Grade JP-4, fuel or Shelldyne-H fuel was designed, fabricated, tested, and incorporated in the GTP30 Auxiliary Power Unit (APU) test engine. This combustor was used to replace the standard GTP30 atomizing combustor for purposes of this test program.

1. TEST OBJECTIVES. Tests were conducted on the Shelldyne-H combustor to (a) verify the mechanical and functional integrity of the combustor prior to its incorporation in the GTP30 Test Engine, (b) evaluate the comparative steady-state combustion characteristics of Grade JP-4 and Shelldyne-H fuels, (c) determine the ignition characteristics of Shelldyne-H fuel, and (d) evaluate the lean- and rich-blowout characteristics of Shelldyne-H fuel. These objectives were oriented to evaluation of the fuel and to determining the feasibility of defining a single combustion system for use of either Grade JP-4 or Shelldyne-H fuel.

2. SUMMARY OF RESULTS. The combustor designed for test purposes satisfied both the structural and functional integrity requirements of a GTP30 Auxiliary Power Unit combustor.

> NOTE: The program intent was to evaluate Shelldyne-H fuel characteristics rather than to develop an engine or production combustion system for Shelldyne-H fuel. Consequently, little detailed combustion system development was undertaken. Therefore, care should be exercised in interpretation of the data presented in the subsequent combustion subsections because the data obtained on the partially developed combustor does not indicate the absolute or limiting obtainable performance characteristics.

Combustion efficiency* with the use of Grade JP-4 fuel was somewhat better than with the use of Shelldyne-H fuel, and combustor exhaust temperature profiles for both fuels were practically identical. The direct ignition of Shelldyne-H fuel was more difficult than ignition of Grade JP-4 fuel. The combustion stability characteristics of Shelldyne-H fuel were better than those of Grade JP-4 fuel.

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*Combustion efficiency η_c, is defined as the actual combustor temperature rise divided by the ideal temperature rise. See Appendix I.

3. PRELIMINARY TESTS. A series of preliminary tests were performed at the start of the program to determine the general combustion characteristics of Shelldyne-H fuel. These tests consisted of a glow-plug ignition test, a flame speed-determination test, and combustion tests in existing combustor configurations.

3.1 Glow-Plug Ignition Test. A conventional glow plug was coated with a small amount of Shelldyne-H fuel. The fuel ignited slowly and burned with a sooty flame, which indicated that Shelldyne-H fuel would be difficult to ignite.

3.2 Flame Speed-Determination Tests. A flame speed test with use of a Bunsen burner apparatus revealed that the flame speed for Shelldyne-H fuel-to-air mixtures is approximately 7 percent higher than for MIL-T-5624, Grades JP-4 and JP-5, fuel-to-air mixture. A summary of the data obtained from this test is tabulated below.

	MIL-T-5624 Grade JP-5	Shelldyne-H Fuel
Pressure, atmospheres	1	1
Fuel temperature, °F	560	540
*Equivalence ratio	1.72	1.65
**Flame speed, feet per second	4.1	4.4

*Equivalence ratio is the ratio of observed fuel-to-air ratio to the stoichiometric fuel-to-air ratio.

**The indicated flame speeds are considered to be high as compared to other published data for MIL-T-5624, Grades JP-4 and JP-5, fuels. The reason given for this disparity is that flame height measurements were made directly. Data used from the literature was obtained by shadowgraph flame-height measurements. The relationship between Shelldyne-H fuel and Grade JP-5 fuel flame speeds is considered valid.

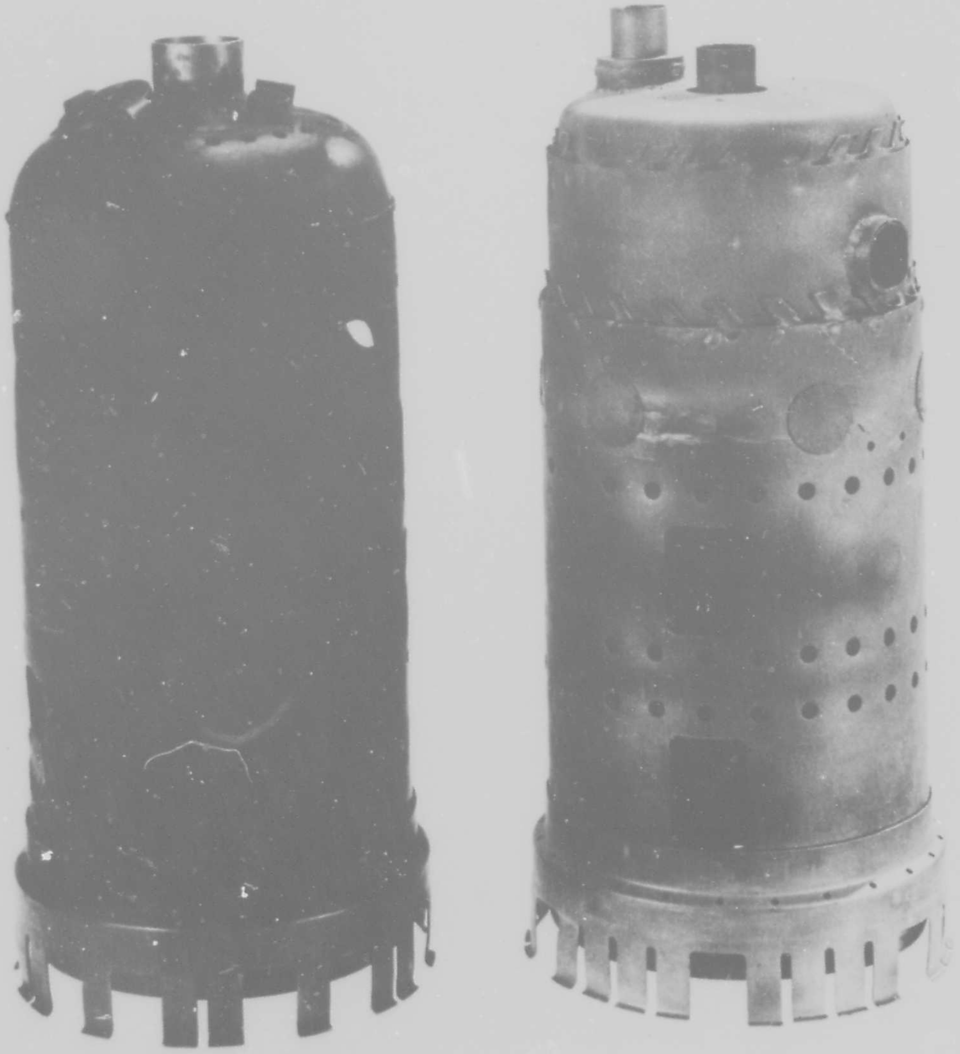
Flame characteristics observed during execution of the test indicated that the Shelldyne-H fuel flame was clear and blue, with a bright yellow core. Smoke emanated from the core stream tube. In comparison, the Grade JP-5 fuel flame was clear and blue throughout and produced no smoke.

3.3 Tests with Existing Combustors. Two existing combustors, one utilizing an atomizing fuel-injection system and the other utilizing an airblast-injector system, were tested with Shelldyne-H fuel. Both of these combustors are designed to be used interchangeably, for development purposes, in another AiResearch engine--the Model TSCP700-1, which is an APU for the Douglas DC-10 Airplane. Both of these combustors are shown in Figure 28. Testing was accomplished by mounting the combustors on the vacuum test rig as shown in Figure 29. The advantage of using this test configuration is that the combustor is exposed, and direct visual examination of the combustion process can be made by viewing the flame through the holes in the combustion liner.

Shelldyne-H fuel could not be ignited directly. Therefore, the test was conducted by starting and operating the combustor with Grade JP-4 fuel and blending in Shelldyne-H fuel in a continuously increasing quantity while simultaneously reducing the Grade JP-4 fuel quantity. The atomizing combustor sustained combustion on pure Shelldyne-H fuel but the airblast-injector combustor would not. The flame in both combustors became increasingly white and luminescent as the percentage of Shelldyne-H fuel increased. The airblast-injector combustor continued to sustain combustion until the mixture became approximately 95 percent Shelldyne-H fuel, at which time the combustor became unstable and the flame extinquished. The atomizing combustor continued to function when the fuel became pure Shelldyne-H fuel but required a 130-psig fuel pressure as compared to a 30-psig fuel pressure required for Grade JP-4 fuel.

4. SHELLDYNE-H COMBUSTOR DESIGN.

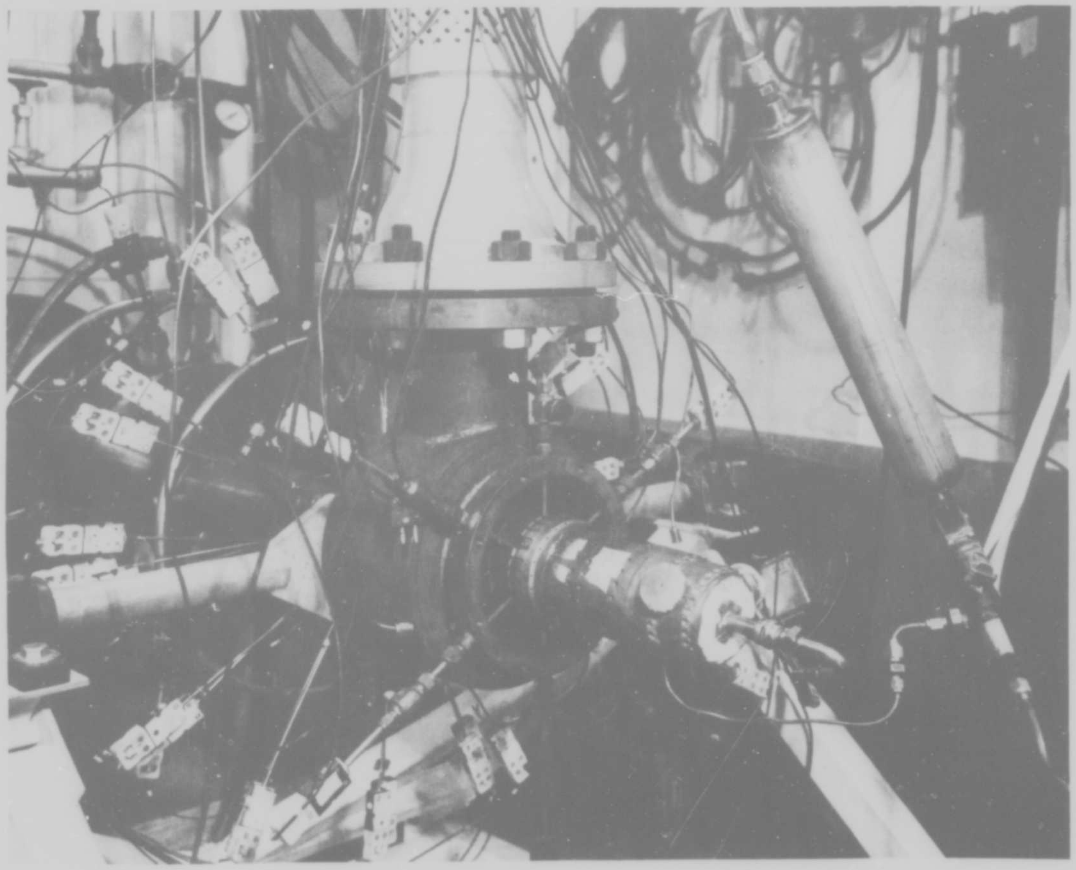
Although the preliminary combustion tests described above were qualitative in nature, the results provided significant discernment of Shelldyne-H fuel combustion characteristics. Initial results with the use of an atomizing combustor were more favorable than those with the use of an airblast-injector combustor. However, the injector supply pressures required with an atomizing combustor are considered excessive, since the preliminary tests were accomplished at prevailing ambient temperatures of approximately 95°F. The fuel viscosity at this temperature is on the order of 15 centistokes. The viscosity of Shelldyne-H fuel at minus 65°F is on the order of 10,000 centistokes. Fuel droplet size generated by an atomizer is related by an empirical relationship to the following Sauter Mean Diameter (SMD):



ATOMIZING FUEL - INJECTION COMBUSTOR (LEFT)
AIRBLAST-INJECTOR COMBUSTOR (RIGHT)

FIGURE 28

MP-25698



COMBUSTOR VACUUM TEST RIG

FIGURE 29

$$\text{SMD} = 220\,\frac{W^{0.209}\,\mu^{0.215}}{\Delta P^{0.458}} \quad \text{(Reference}^{3}\text{)}$$

where:

W = fuel flow
μ = fuel viscosity
ΔP = atomizer pressure drop

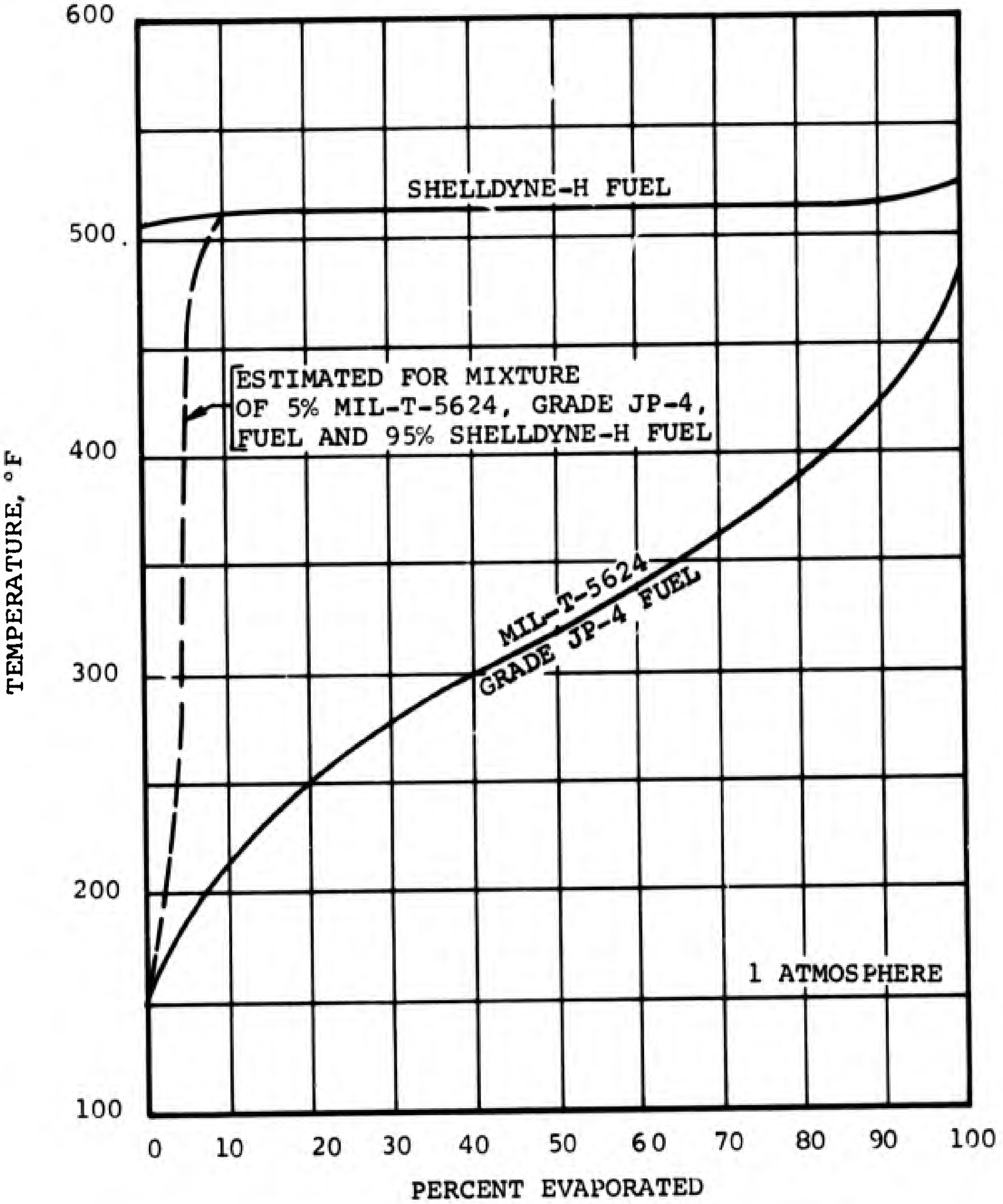
Therefore, in order to retain a given droplet diameter at constant fuel flow, the pressure drop required is a function of the fuel viscosity, which is:

$$\frac{\Delta P_1}{\Delta P_2} = \left(\frac{\mu_1}{\mu_2}\right)^{0.469}$$

The atomizer pressure drop required for Shelldyne-H fuel at minus 65°F is therefore approximately 21 times the pressure drop required at 95°F. Based on the fact that Shelldyne-H fuel would not burn at a 30-psig atomizer supply pressure but would burn at a 130-psig atomizer supply pressure, the fuel supply pressure at minus 65°F would have to be greater than 630 psig and less than 2730 psig. Although not impractical, pressures of such a magnitude are considered excessive and not consistent with conventional fuel practice. Consequently, atomizing combustor designs were considered impractical for purposes of this program.

The results obtained with the airblast-injector combustor indicated that only a small amount of Grade JP-4 fuel in the Shelldyne-H fuel would allow the combustor to work. Shelldyne-H fuel is essentially a pure compound and thus evaporates within a narrow temperature band at any given pressure, whereas Grade JP-4 fuel is a mixture of many compounds and evaporates or fractionates over a large temperature band. This difference between the fuels was postulated as the reason that Shelldyne-H fuel would not burn in the TSCP700 airblast-injector combustor whereas a mixture of 5 percent Grade JP-4 fuel and 95 percent Shelldyne-H fuel would. The fractionation characteristics of Shelldyne-H fuel and Grade JP-4 fuel are compared on Figure 30, together with the estimated fractionation characteristics of a mixture of 5 percent Grade JP-4 fuel and 95 percent Shelldyne-H fuel.

The mechanisms of combustion with Grade JP-4 fuel are such that the light fractions (front ends) of the fuel evaporate at relatively low temperatures and burn. The subsequent heat release causes the remaining fuel to be heated, thereby evaporating heavier fractions, and so on, until the



FUEL FRACTIONATION CHARACTERISTICS

FIGURE 30

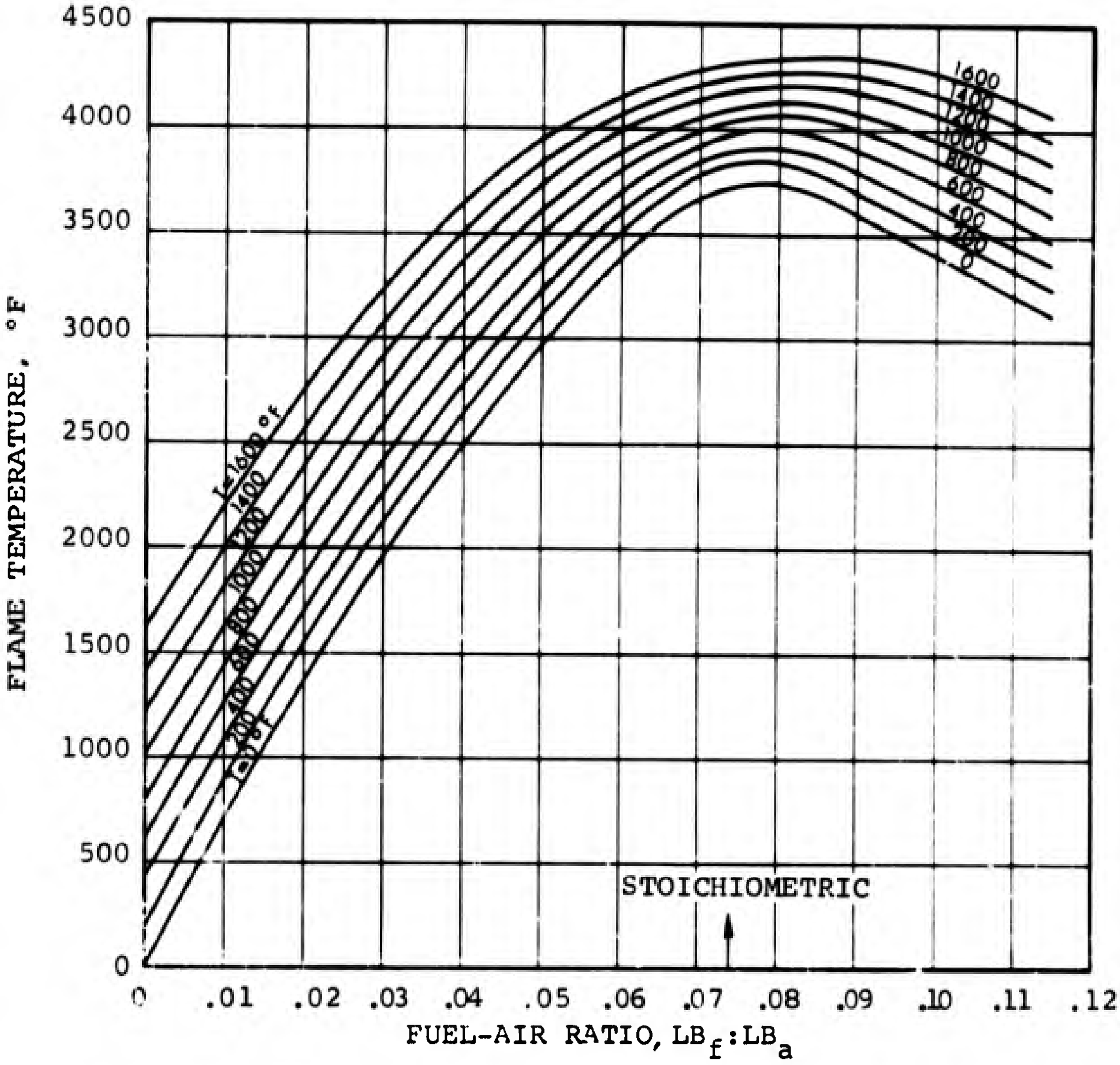
fuel has been completely vaporized. The process with Shelldyne-H fuel is the same except that there is very little, if any, fractionation. Consequently, vaporization of the fuel is delayed in the combustor (lack of light fractions); and once vaporization starts, it occurs rapidly (lack of heavy fractions). Therefore, if the evaporation zone is located downstream of the primary recirculation zone, combustion products are not carried back into the primary zone to evaporate the fuel, and combustion ceases.

The fact that a mixture of approximately 5 percent of Grade JP-4 fuel provided enough light fractions to allow sustained combustion indicated that the recirculating zone for a Shelldyne-H fuel combustor should be located slightly downstream as compared to a combustor designed for Grade JP-4 fuel.

Flame temperature-rise parameters for Shelldyne-H fuel were calculated (see Appendix I) as shown in Figure 31. This data, together with fuel evaporation criteria derived from NACA Report 1087, aided in establishing the combustor design shown in Figure 32. Also shown in this figure are the percentages of airflow entering the process, together with equivalent overall fuel-to-air ratios at various locations along the combustor. A comparison between the Shelldyne-H fuel combustor (Part PAP214161) and the conventional GTP30 combustor (Part 892493), which it replaced, is shown in Figure 33. Provision for two igniter locations was included in the design. One was located at the same axial distance and rotated 120 degrees from the fuel inlet and primary pipe. The igniter was physically placed in an ignition chamber, which was attached to the side of the combustor as shown in Figure 34. The second, or alternate, igniter location was in the combustor dome facing the primary pipe discharge, also shown in the above figure. The resulting Shelldyne-H fuel combustor components are shown in Figures 35 and 36.

Figure 35 is an end view of the Shelldyne-H fuel combustor and shows the location of the primary fuel pipe, booster strip, cooling bands, corrugated strips, and dilution ports. Most of these features and the ignition chamber and mounting tabs are shown in the overall view in Figure 36.

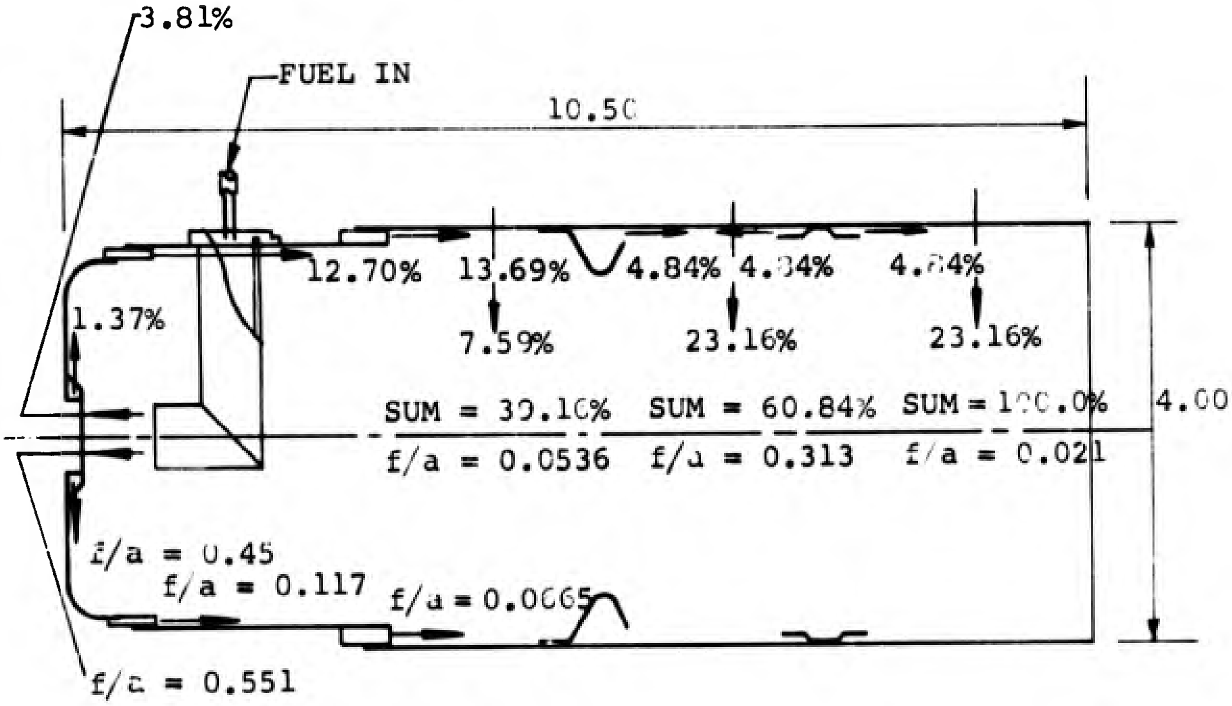
5. COMBUSTION TESTS. Testing of the Shelldyne-H fuel combustor was accomplished in four segments: (a) initial testing, (b) verification testing, (c) performance testing, and (d) ignition testing.



NOTES:
1. SHELLDYNE-H FUEL
2. LOWER HEATING VALUE = 17,890 Btu PER POUND
3. CARBON-TO-HYDROGEN RATIO, 9.05:1
4. STOICHIOMETRIC FUEL-TO-AIR RATIO, 0.072576:1
5. COMBUSTION PRESSURE = 1.0 ATMOSPHERE
6. DISSOCIATION EFFECTS INCLUDED

SHELLDYNE-H FUEL FLAME TEMPERATURE

FIGURE 31

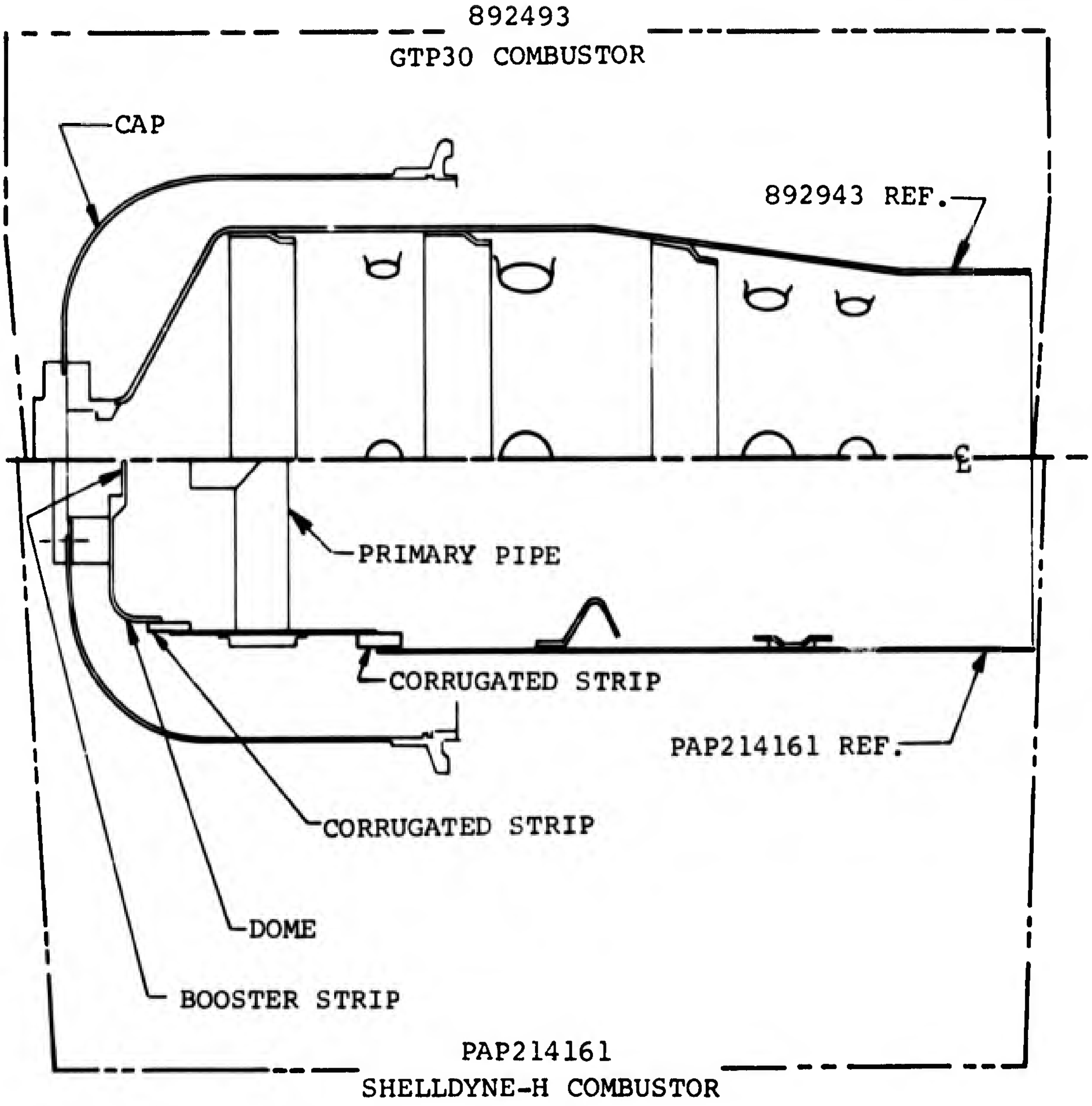


NOTES: Airflow in %
f/a = fuel-to-air ratio

REF. PAP 21461

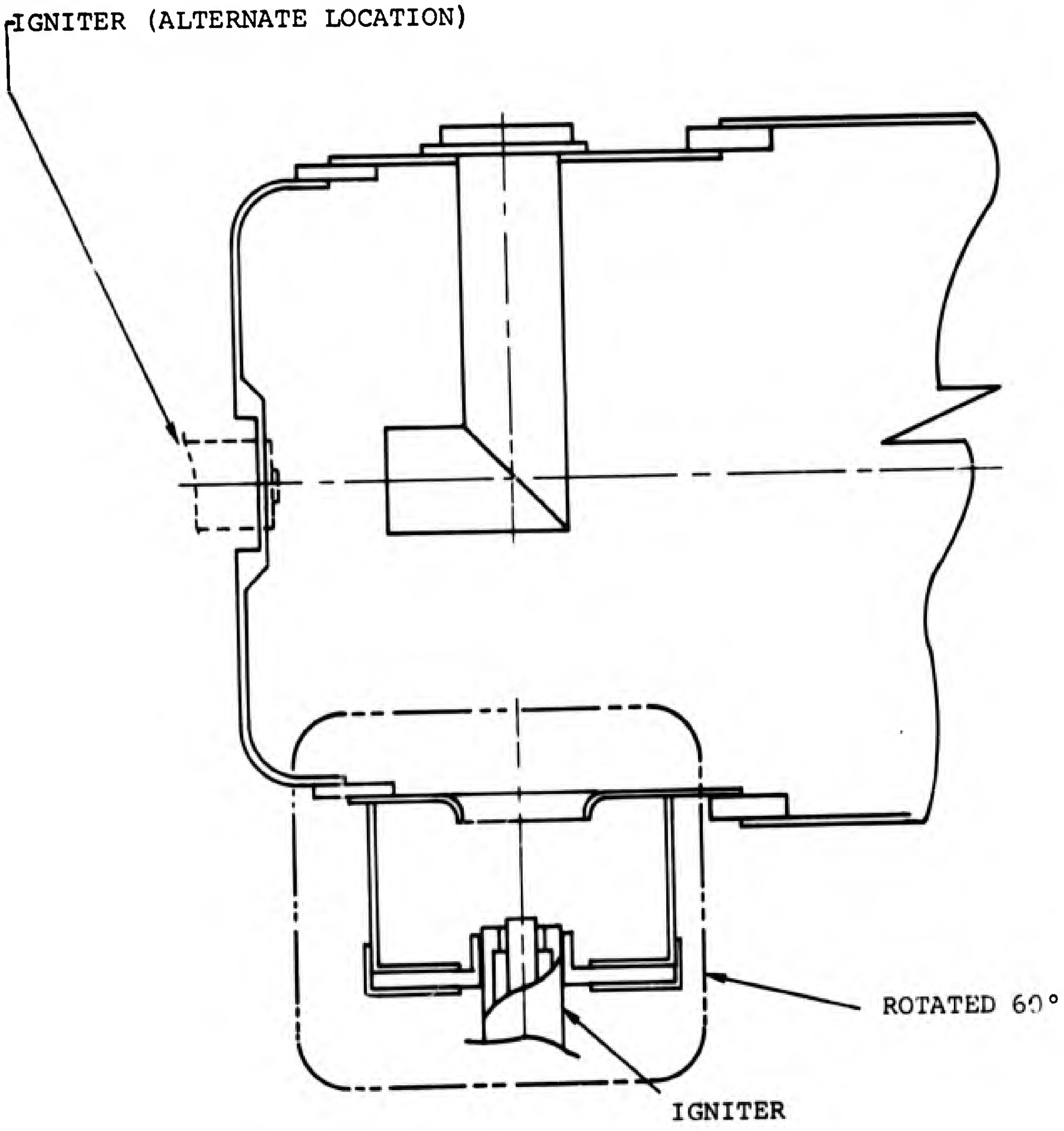
SHELLDYNE-H COMBUSTOR
AIR DISTRIBUTION AND LOCAL FUEL-TO-AIR RATIOS

FIGURE 32



COMPARISON OF GTP30 COMBUSTOR (SHOWN ABOVE ℄)
AND SHELLDYNE-H COMBUSTOR (SHOWN BELOW ℄)

FIGURE 33



SHELLDYNE-H COMBUSTOR
IGNITER LOCATIONS

FIGURE 34

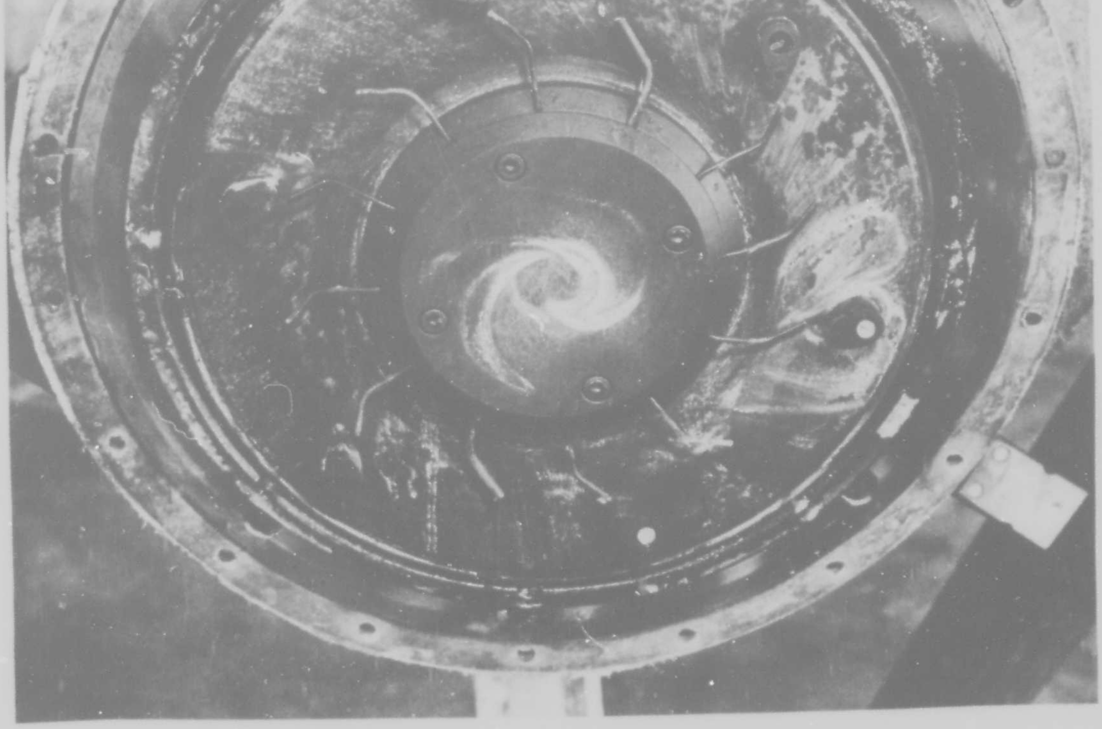
INSIDE VIEW
SHELLDYNE-H COMBUSTOR

FIGURE 35

OVERALL VIEW
SHELLDYNE-H COMBUSTOR

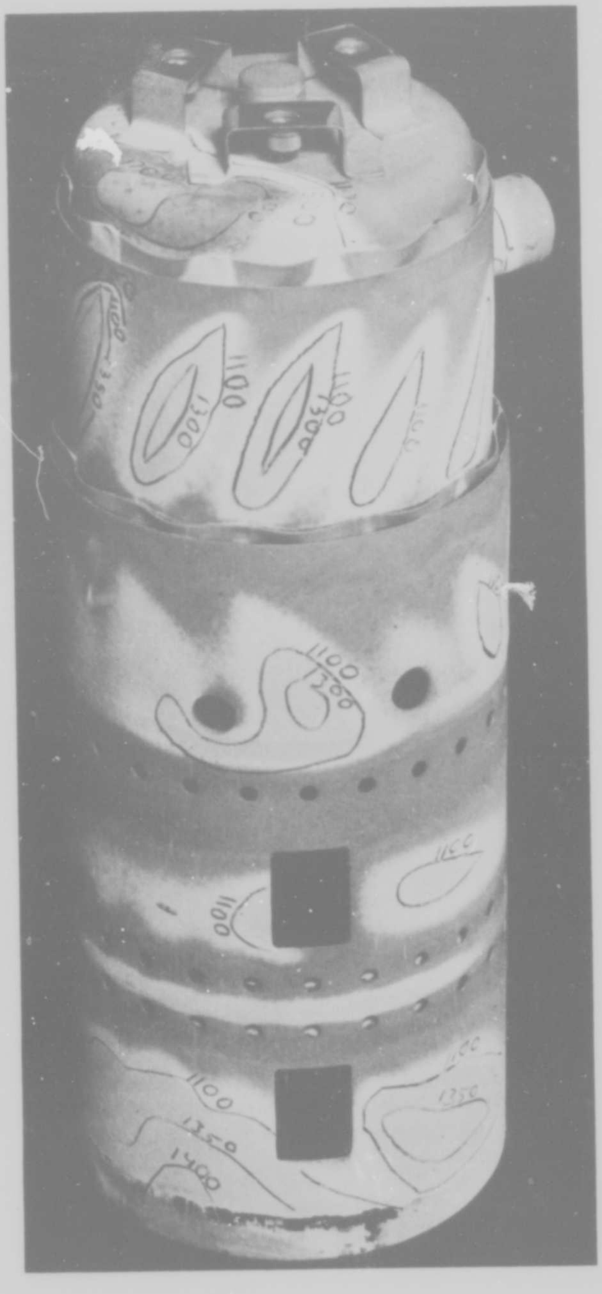
FIGURE 36

MP-25218



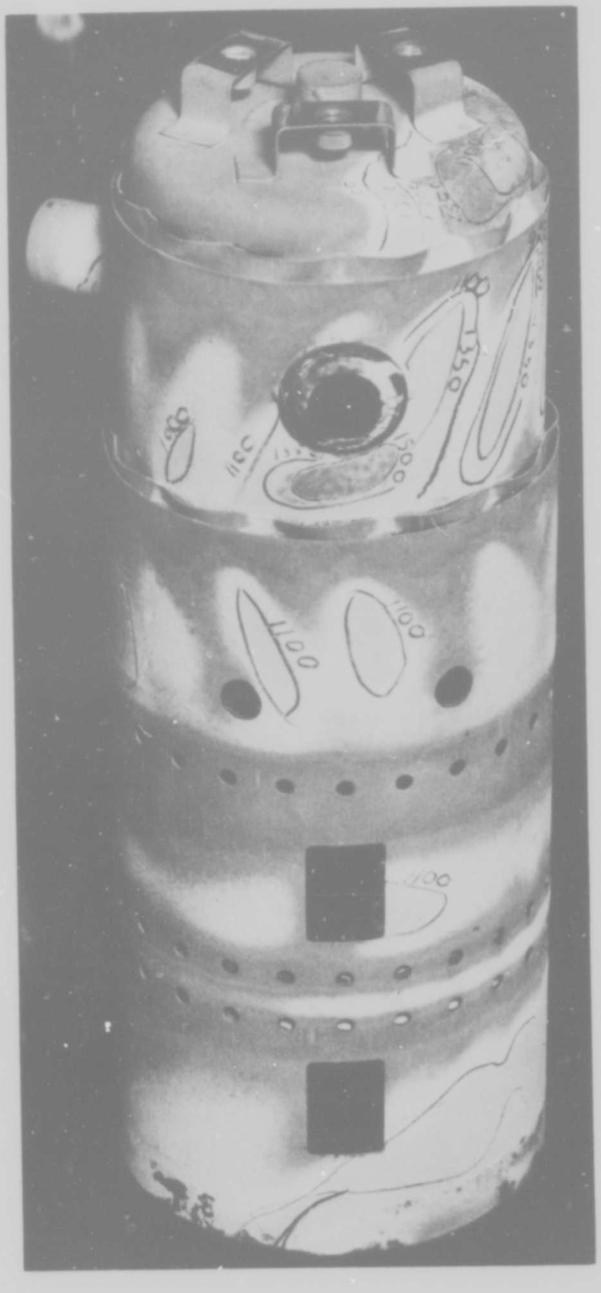
TURBINE INLET TEMPERATURE
SENSING THERMOCOUPLES

FIGURE 39



SHELLDYNE-H COMBUSTOR ISOTHERMS

FIGURE 40



SHELLDYNE-H COMBUSTOR ISOTHERMS

FIGURE 41

5.1 Initial Tests. Initial tests were conducted on one vacuum test rig for purposes of initial combustor development. This testing was performed to evaluate the gross characteristics of the Shelldyne-H fuel combustor, such as flame stability, flame length, and general visual appearance of the combustion process. Airflow measurements on this test rig are inherently crude because there cannot be an airflow-measurement section upstream of the combustor under test. This limitation, dependent on airflow combustion parameters such as efficiency and lean-limit blowout, cannot be evaluated accurately. Therefore, this testing is primarily qualitative in nature.

Results obtained from these tests indicated that the Shelldyne-H fuel combustor would sustain combustion equally well on Grade JP-4 or Shelldyne-H fuel. The temperature distribution factors (TDF's) observed during these tests were approximately the same, with the Shelldyne-H fuel TDF being somewhat less than that of the Grade JP-4 fuel. The TDF is defined as

$$\mathrm{TDF} = \frac{T_{MAX} - T_{AV}}{T_{AV} - T_{IN}}$$

where: T_{MAX} = the maximum observed temperature

T_{AV} = the averaged discharge temperature

T_{IN} = combustor inlet air temperature

During this series of tests, it was found that the elimination of twelve 0.050-inch-diameter holes surrounding the primary pipe reduced the combustor TDF, and the addition of six 0.375-inch-diameter holes at the end of the primary zone reduced the TDF and improved combustor stability. The introduction of secondary pipes in the combustor dome resulted in reduced Shelldyne-H fuel combustion capabilities.

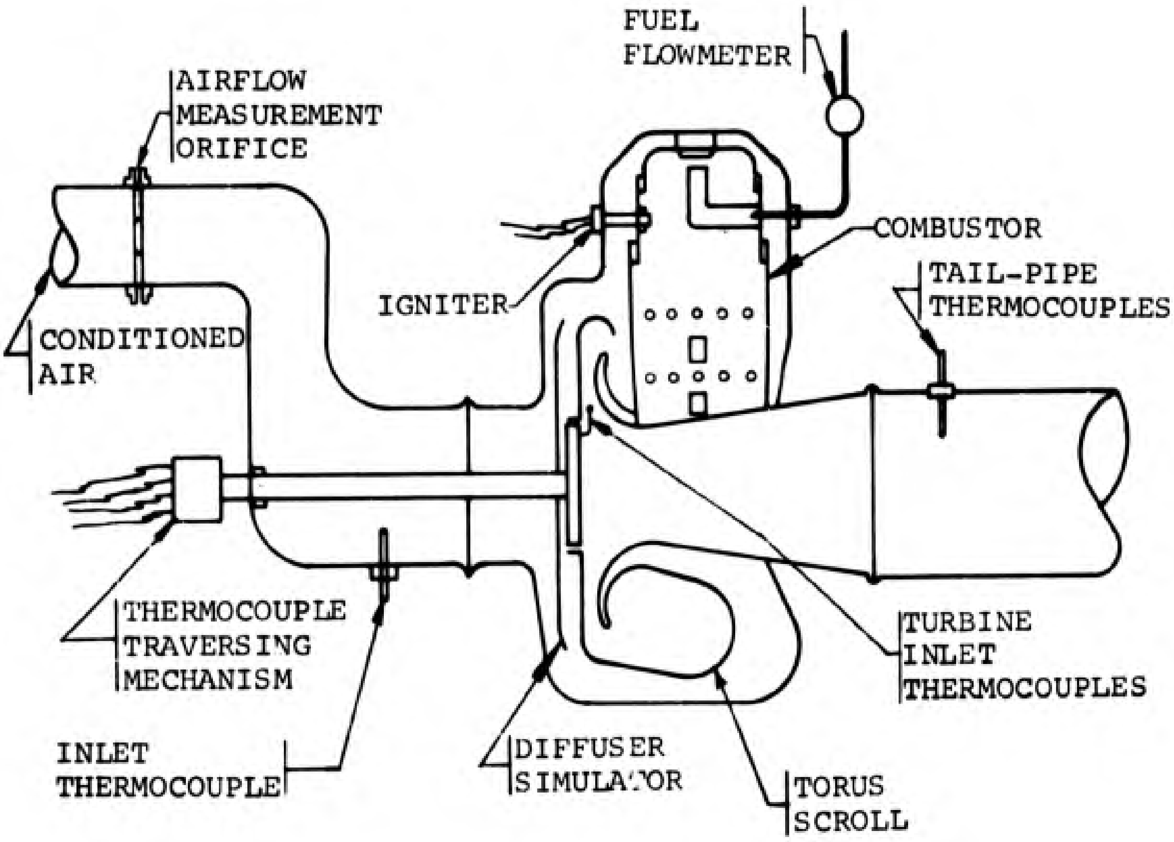
Ignition testing of the combustor on the vacuum test rig revealed that Grade JP-4 fuel could be ignited readily with a conventional spark igniter. Ignition attempts with Shelldyne-H fuel, however, were unsuccessful. It was observed during ignition testing with Shelldyne-H fuel that the igniter would ignite the Shelldyne-H fuel mixture in the combustion chamber (Figure 34). A short-duration flame resulted, which extended into the combustor primary zone. Minute particles of fuel could be observed throughout the primary zone; nevertheless, the flame did not propagate, and ignition did not occur. Based on these observations, modifications were made to the ignition chamber in an attempt to extend the duration of the flame emanating from the chamber. Although ignition delay, flame size, and flame duration could be varied with the geometry and configuration of the ignition chamber, none of the tests resulted in successful direct ignition of Shelldyne-H fuel.

Ignition attempts with the igniter alternately located in the dome produced similar results, with the exception that no flame whatsoever was observed.

It was observed during this series of tests that even small amounts of Grade JP-4 fuel mixed with Shelldyne-H fuel would provide successful ignition at the prevailing ambient temperature of 90°F. During several ignition attempts with Shelldyne-H fuel, which followed tests with Grade JP-4 fuel, ignition was accomplished. However, these results were not repeatable on subsequent Shelldyne-H fuel ignition attempts. Though the combustor and fuel lines had been thoroughly drained between the Grade JP-4 fuel and Shelldyne-H fuel tests, enough residual Grade JP-4 fuel remained in the fuel system to effect ignition on the initial attempt. During subsequent attempts the Grade JP-4 fuel residue had been purged from the system, and ignition was not effected.

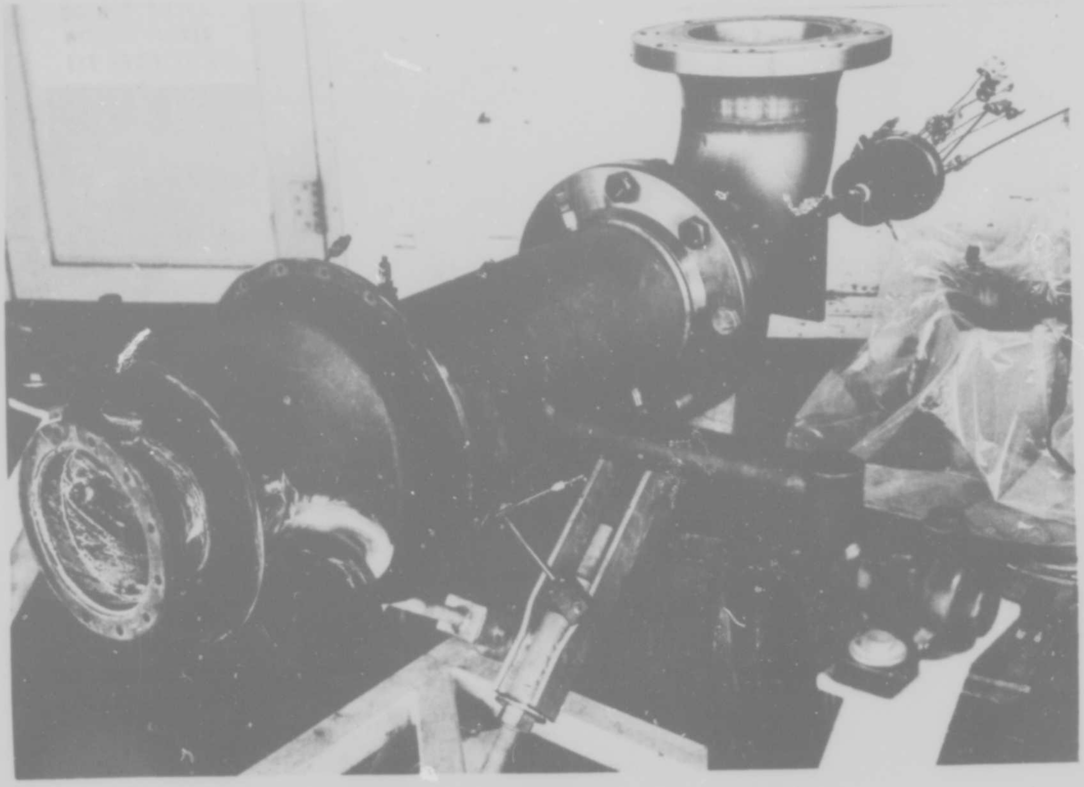
5.2 Verification Tests. Prior to the incorporation of this combustor in the GTP30 APU, a series of tests were conducted to verify the structural and functional integrity of the combustor under simulated engine operating conditions. These tests were conducted on the GTP30 combustor test rig shown schematically in Figure 37. The assembled test rig is shown in Figure 38. This test rig was fully instrumented, including the capability for measuring turbine inlet (combustor discharge) temperatures with the rotatable thermocouple rake shown in Figure 39.

Combustor metal temperatures were determined with use of Thermindex paint. For purposes of this test, a painted combustor was operated and cooled down under closely controlled conditions to eliminate thermal soak-back effects. The color changes of the Thermindex paint were then analyzed, and isotherms were plotted directly on the combustor, as shown in Figures 40 and 41. The temperature profiles shown in these figures were obtained on the Shelldyne-H combustor by operating the combustor with Grade JP-4 fuel and then with Shelldyne-H fuel. After the JP-4 fuel run, the combustor was examined and the location of any hot spots noted. The combustor was then reinstalled and operated on Shelldyne-H fuel. There were no differences either in the number, location, or size of the observed hot spots. This indicates that the combustor metal temperatures experienced with Shelldyne-H fuel were not hotter than those experienced with Grade JP-4 fuel.



MODEL GTP30 COMBUSTOR TEST
RIG SCHEMATIC

FIGURE 37



ASSEMBLED MODEL GTP30 COMBUSTOR TEST RIG

FIGURE 38

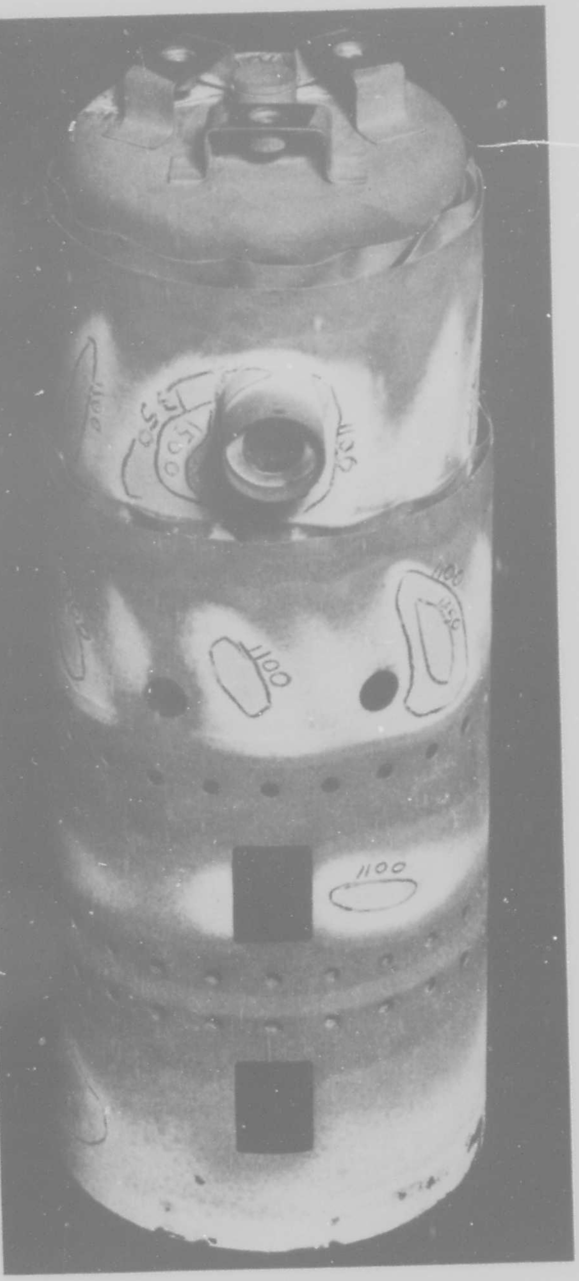
Three hot spots were observed on the combustor--one on the dome (1700°F), one just below the primary pipe (1500°F) as shown in Figure 41, and a third one (1500°F) just below the igniter chamber, as shown in Figure 42. The temperatures at these hot spots were not excessive and were considered to be acceptable for purposes of planned engine tests.

During the Thermindex paint test, the turbine inlet (combustor discharge) temperatures were surveyed to ensure that the combustor was not streaking or producing local hot spots that would have a detrimental effect on the turbine. The data, as shown in Figure 43, indicated that the combustor discharge temperature profiles were well within acceptable limits for operation with the GTP30 APU. This combustor was therefore removed from the combustion rig and incorporated in the endurance test engine.

5.3 Performance Testing. Performance testing of the Shelldyne-H combustor consisted of steady-state combustion performance evaluation, lean-limit blowout tests, and rich-limit blowout tests. The combustor used for performance-evaluation testing was identical with the combustor that had been used during verification testing. Another combustor was modified in an attempt to reduce the dome hot spot. The modification consisted of angling the holes 2 degrees toward the dome. The effect of this modification was to reduce the dome hot-spot temperature by approximately 250°F, as shown in Figure 44. Therefore, it was concluded that the hot spots noted could be eliminated with very minor developmental changes.

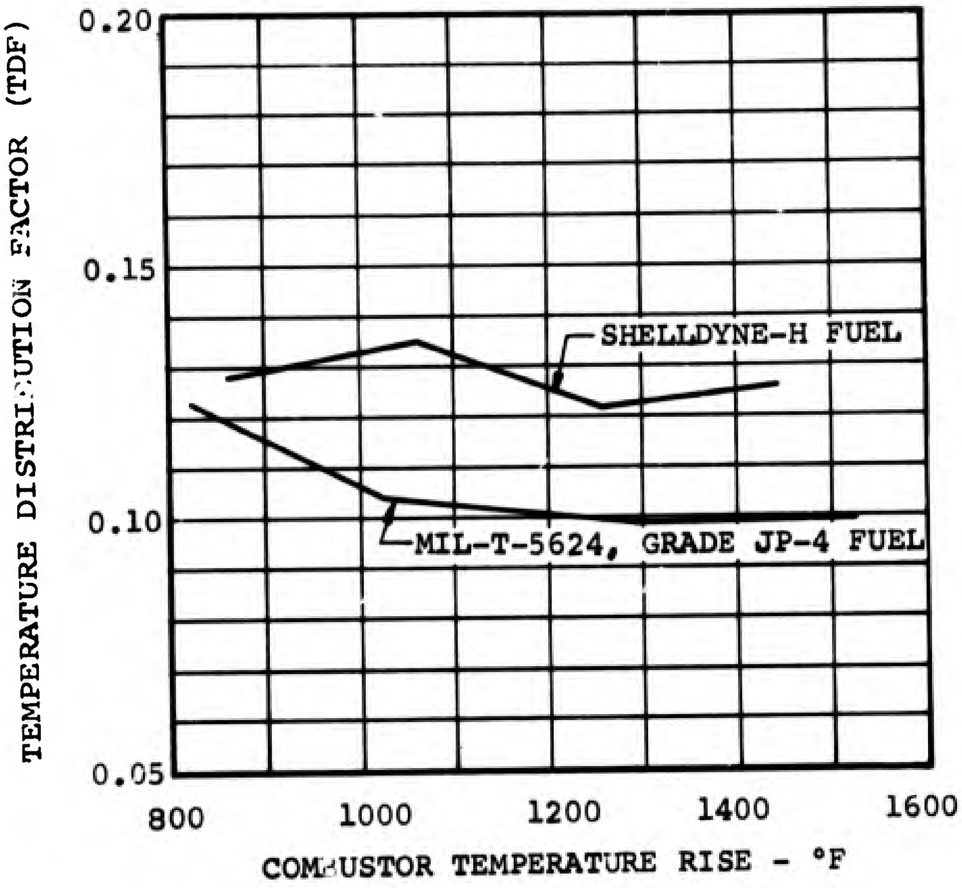
The fuel delivery system used for combustion testing is shown in Figure 45. The tests were conducted by setting and establishing the fuel-flow conditions with Grade JP-4 fuel and taking data. The system was then switched, by reversing the normally open and normally closed solenoid valves, to Shelldyne-H fuel. By judicious initial adjustment of these two metering valves, the combustor temperatures would remain the same, and very little time was spent operating with Shelldyne-H fuel to stabilize the test conditions. This system and test sequencing provided minimum Shelldyne-H fuel consumption and rapid test execution. After completion of a given test point with Shelldyne-H fuel, the two solenoid valves were again reversed and the next test point established on Grade JP-4 fuel by adjusting the main control valve. This procedure was then repeated for each test condition.

All data from these tests was recorded with a digital data-acquisition system. Data cards were then entered directly into the computer for reduction. A typical computer presentation of the output data is shown in Figure 46. The circumferential TDF profile for the data of Figure 46 is shown in Figure 46a for the axial positions of 10, 30, 50, 70, and



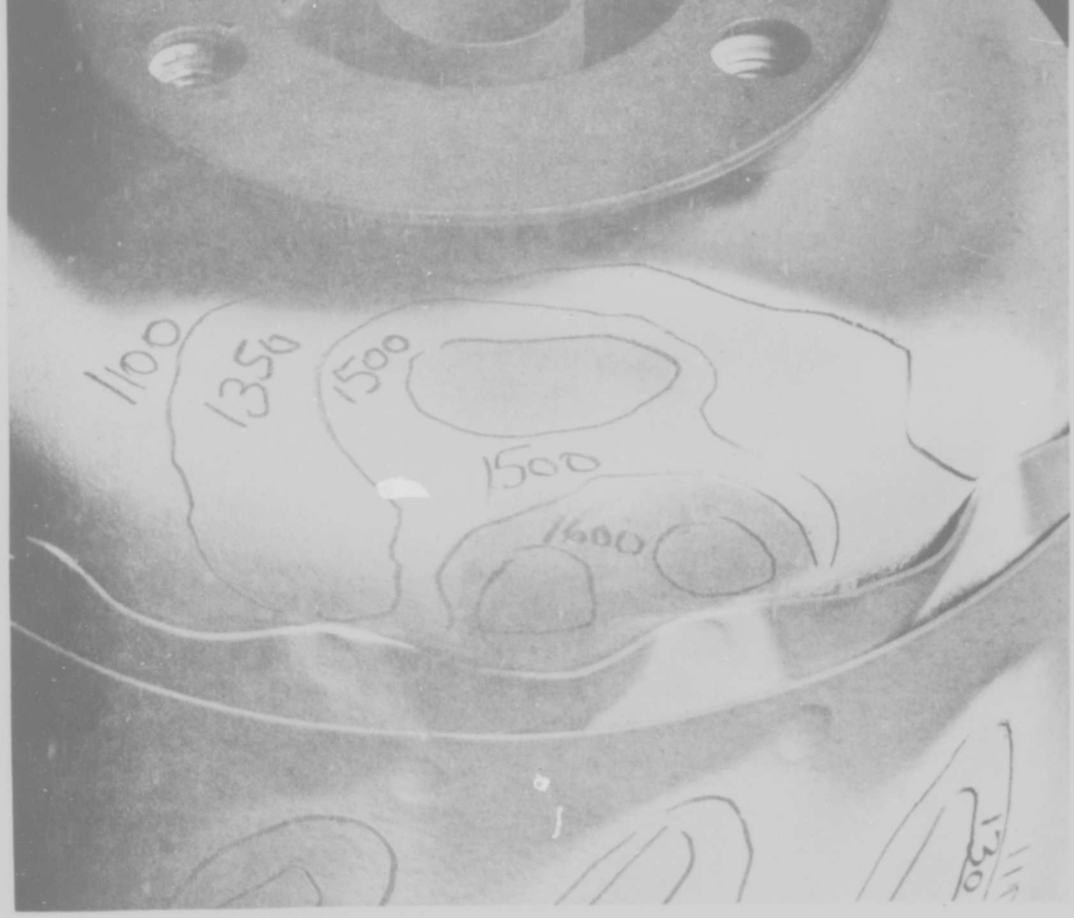
SHELLDYNE-H COMBUSTOR ISOTHERMS

FIGURE 42



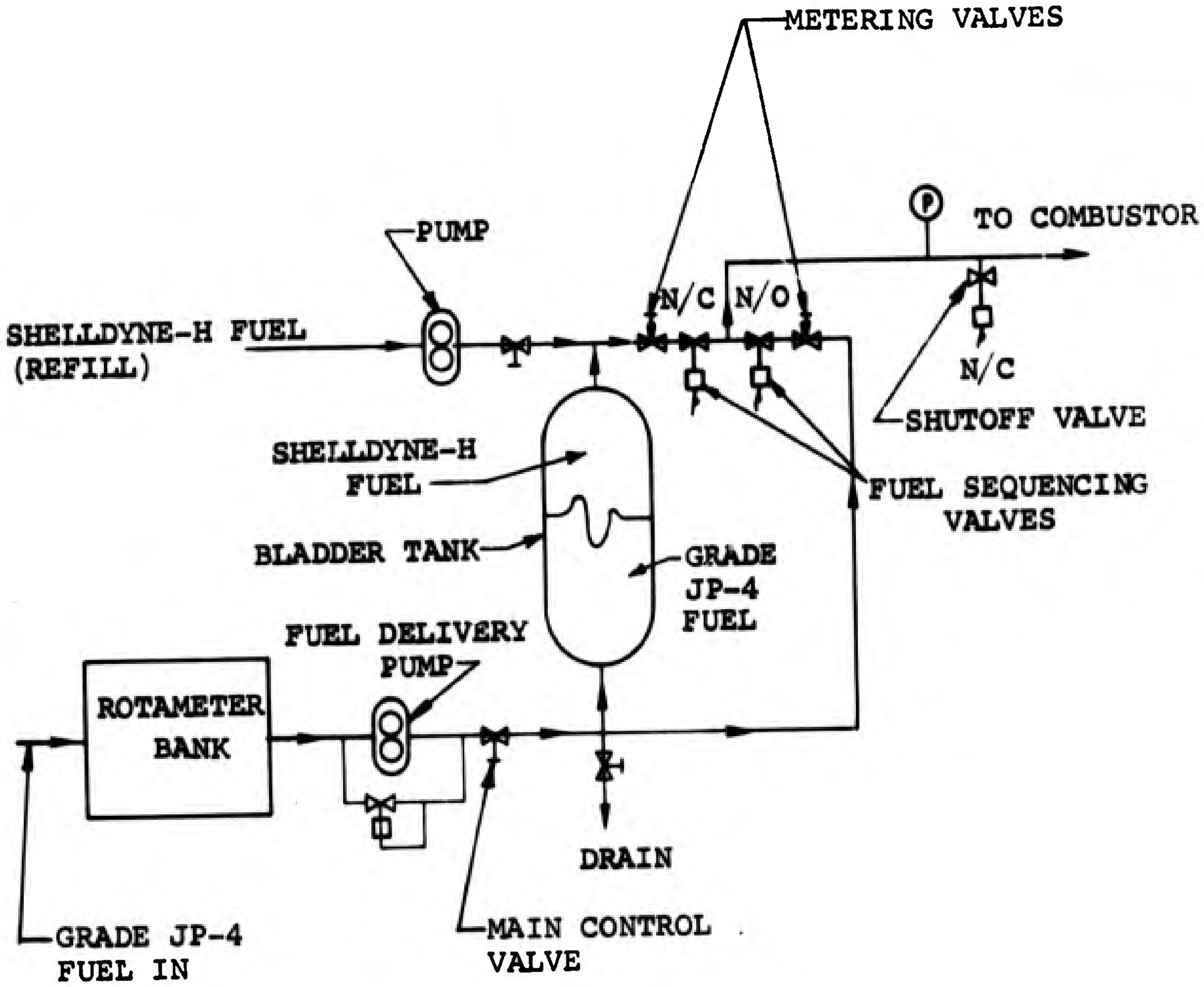
SHELLDYNE-H COMBUSTOR
TEMPERATURE DISTRIBUTION FACTOR

FIGURE 43



SHELLDYNE-H MODIFIED COMBUSTOR ISOTHERMS

FIGURE 44



N/C = NORMALLY CLOSED

N/O = NORMALLY OPEN

COMBUSTION TEST
FUEL DELIVERY SYSTEM

FIGURE 45

90 percent of the turbine inlet nozzle span. The minimum, average, and maximum observed TDF's for these data are shown in Figure 46b.

5.3.1 Steady-State Performance. Combustion efficiency of the Shelldyne-H combustor operating with Grade JP-4 fuel is presented in Figure 47. The dashed line in this figure reflects the typical performance characteristics shown for comparative purposes of fully developed JP-4 fuel combustors. This data reflects that the combustor as tested was, in fact, not fully developed, and also the degree of improvement that could potentially result with further development. Combustor performance with Shelldyne-H fuel is presented in Figure 48. During the test program it was discovered that under some operating conditions Grade JP-4 fuel leakage into the Shelldyne-H fuel supply occurred. This was the result of a faulty valve and occurred spasmodically. Several test points were rerun to check the data considered questionable.

The data represented by plain circles in Figure 48 may or may not represent a run with contaminated Shelldyne-H fuel. The flagged circles represent data obtained from reruns with pure Shelldyne-H fuel. Correlation of the data revealed an undesirable amount of scatter, but the reasons for the data scatter were not apparent. Consequently, attempts to correlate the data, based on other combustor performance parameter groups, were undertaken, but the results were negative, as shown in Figures 49 and 50.

A direct comparison of the combustor performance with Grade JP-4* and Shelldyne-H fuels is presented in Figure 51. This data indicates that the combustor efficiency with Shelldyne-H fuel is less than with JP-4 fuel. However, it is impossible to quantify the relationship between the two fuels that would exist for a fully developed combustor.

The pattern factor or temperature distribution factor (TDF) obtained with the combustor operating on Grade JP-4 and Shelldyne-H fuels is shown in Figures 52 and 53, respectively. A direct comparison between the TDF's obtained with the two fuels is given in Figure 54. This data indicates that the TDF's are practically identical. The significance of this result is that the calculated turbine inlet temperature allowable with either fuel is the same. If, for instance, the TDF for Shelldyne-H fuel had been significantly higher, then the maximum allowable calculated turbine inlet temperature would have to be lower to satisfy the same turbine inlet temperature limits.

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*MIL-T-5624, Grade JP-4, fuel characteristics vary between batches. A continuous check of the characteristics of the fuel used was made to affirm that the test results with Grade JP-4 fuel could be normalized. See Appendix II.

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COMBUSTOR PAP 214161 SN 2                                                                                              SCAN   1     PAGE

****************************************   ****************************************   ****************************************
       ITEM             UNIT                        ITEM              UNIT                        ITEM              UNIT
****************************************   ****************************************   ****************************************
BAROMETER               IN HG A    28.87   ORIFICE FUEL TEMP.     DEG F        0.0   COMBUSTOR AREA          IN2         12.6
ORIFICE ID                --           6   FUEL 1 SG                --       0.780   EFFECTIVE FLOW AREA     IN2        4.144
ORIFICE DIAMETER          IN       1.750   FUEL 2 SG                --     *******   TURBINE INLET PRESS.    PSIA        15.5
DUCT DIAMETER             IN       3.068   FUEL 1 FLOW RATE       LB/HR       39.0   MEASURED TEMP. RISE     DEG F     1509.6
ORIFICE INLET TEMP.     DEG F      330.0   FUEL 1 COR FLOW RATE   LB/HR       40.2   IDEAL TEMP. RISE        DEG F     1612.2
ORIFICE INLET PRESS.     PSIG      190.0   FUEL 2 FLOW RATE       LB/HR       40.2   COMBUSTOR EFFICIENCY     --         0.94
ORIFICE DELTA P         IN H2O      13.8   FUEL AIR RATIO           --      0.024    VELOCITY                FT/SEC      90.6
AIR FLOW                LB/SEC      0.46   COMBUSTOR INLET TEMP   DEG F      266.0   WA/(P3)2                 --       0.3855
AIR FLOW                LB/HR     1645.2   COMBUSTOR INLET TEMP   DEG R      725.7   WA/(VOL)(P3)2            --       4.7018
FUEL 1                    --          94   COMBUSTOR INLET PRES IN HG G       3.40   WA/(P3)2(T3)1/2          --       0.0143
ROTOMETER                 --       00096   COMBUSTOR INLET PRES   PSIA        16.0   WA/(VOL)(P3)2(T3)1/2     --       0.1745
FUEL 2                    --         SDM   COMBUSTOR INLET PRES    ATS         1.1   V/(P3)(T3)               --       0.1146
FUEL 1 TEMPERATURE      DEG F       90.0   COMBUSTOR INLET PRES    ATS2        1.2   T4/T3                    --        3.000
FUEL 2 TEMPERATURE      DEG F       90.0   COMBUSTOR VOLUME        FT3      0.0820   T.C. CORRECT. FACTOR     --       1.0000


          ******************************************************************************************************
          CIRC                      RADIAL POSITION                         MAXIMUM    MINIMUM    AVERAGE DELTA P, IN H2O
          POS.     9.00      7.00      5.00      3.00      1.00        T4         T4         T4      POS.  5.00
          ******************************************************************************************************
             0   1622.27   1580.00   1653.18   1757.33   1650.45    1757.33    1580.00    1652.65          9.40
            15   1706.00   1643.64   1699.33   1781.63   1740.89    1781.63    1643.64    1714.30          9.00
            30   1620.00   1541.25   1643.64   1691.33   1667.73    1691.33    1541.25    1632.79          8.80
            45   1589.09   1521.06   1607.27   1733.33   1627.27    1733.33    1521.06    1615.61          8.30
            60   1454.68   1418.67   1508.22   1647.27   1625.45    1647.27    1418.67    1530.86         10.20
            75   1631.67   1597.27   1655.00   1724.89   1630.00    1724.89    1597.27    1647.77          9.80
            90   1745.33   1731.11   1742.22   1750.67   1697.56    1750.67    1697.56    1733.38         10.80
           105   1842.85   1863.64   1841.91   1819.55   1820.00    1863.64    1819.55    1837.59         12.00
           120   1746.67   1725.33   1740.00   1836.82   1928.10    1928.10    1725.33    1799.38         40.10
           135   1774.44   1802.73   1759.11   1776.22   1881.02    1881.02    1759.11    1798.86         16.10
           150   1804.09   1810.45   1783.02   1775.79   1768.50    1810.45    1768.50    1788.37         23.50
           165   1821.36   1805.91   1813.64   1795.00   1822.27    1822.27    1795.00    1811.64         22.30
           180   1837.73   1777.11   1749.50   1776.00   1825.45    1837.73    1749.50    1797.56         19.10
           195   1860.00   1866.36   1850.48   1845.71   1849.05    1866.36    1845.71    1854.32         17.90
           210   1855.71   1896.34   1897.80   1891.95   1941.82    1941.82    1855.71    1896.73         14.10
           225   1849.09   1893.90   1887.27   1868.64   1920.00    1920.00    1868.64    1891.78         13.40
           240   1773.56   1755.11   1762.50   1815.00   1784.42    1815.00    1755.11    1778.12         11.50
           255   1867.73   1870.45   1899.76   1901.18   1930.45    1930.45    1867.73    1893.91         10.70
           270   1789.53   1846.36   1904.42   1859.52   1912.86    1912.86    1789.53    1870.54         10.30
           285   1807.27   1877.73   1870.98   1866.82   1890.00    1890.98    1807.27    1866.56         10.00
           300   1713.00   1725.78   1741.33   1837.27   1754.67    1837.27    1713.00    1754.41         10.00
           315   1774.44   1852.84   1832.27   1890.00   1863.64    1890.00    1774.44    1842.64          9.50
           330   1712.00   1813.18   1820.91   1798.64   1856.67    1856.67    1712.00    1800.28          9.45
           345   1759.11   1792.27   1799.09   1851.90   1825.00    1851.90    1759.11    1805.48          9.20
           360   1622.27   1580.00   1653.18   1757.33   1650.45    1757.33    1580.00    1652.65          9.40
          ******************************************************************************************************
           MAX   1849.09   1896.34   1904.42   1901.18   1941.82                                     40.10
           MIN   1454.68   1418.67   1508.22   1647.27   1625.45                                      8.30
           AVG   1749.90   1752.02   1771.79   1803.94   1800.59                                     13.07
          ******************************************************************************************************
          MAXIMUM T4 1941.82
          MINIMUM T4 1418.67
          AVERAGE T4 1775.69

COMBUSTOR PAP 214161 SN 2                                                                                              SCAN   1     PAGE   2

                                              TEMPERATURE DISTRIBUTION FACTOR

               **************************************************************************************************
               CIRC                    RADIAL POSITION                              MAXIMUM    MINIMUM    AVERAGE
               POS.     9.00      7.00      5.00      3.00      1.00       TDF        TDF        TDF
               **************************************************************************************************
                  0   -0.1016   -0.1296   -0.0811   -0.0121   -0.0829    -0.0121    -0.1296    -0.0815
                 15   -0.0461   -0.0874   -0.0506    0.0040   -0.0230     0.0040    -0.0874    -0.0406
                 30   -0.1031   -0.1553   -0.0874   -0.0558   -0.0715    -0.0558    -0.1553    -0.0946
                 45   -0.1236   -0.1686   -0.1115   -0.0280   -0.0983    -0.0280    -0.1686    -0.1060
                 60   -0.2126   -0.2365   -0.1771   -0.0859   -0.0995    -0.0859    -0.2365    -0.1621
                 75   -0.0954   -0.1182   -0.0759   -0.0336   -0.0965    -0.0336    -0.1182    -0.0847
                 90   -0.0201   -0.0295   -0.0221   -0.0165   -0.0517    -0.0165    -0.0517    -0.0280
                105    0.0445    0.0583    0.0439    0.0291    0.0294     0.0583     0.0291     0.0410
                120   -0.0152   -0.0333   -0.0104    0.0405    0.1010     0.1010    -0.0333     0.0157
                135   -0.0108    0.0179   -0.0110    0.0004    0.0703     0.0703    -0.0110     0.0154
                150    0.0188    0.0231    0.0049    0.0001   -0.0047     0.0231    -0.0047     0.0084
                165    0.0309    0.0200    0.0252    0.0128    0.0309     0.0309     0.0128     0.0238
                180    0.0411    0.0010   -0.0041    0.0016    0.0330     0.0411    -0.0041     0.0145
                195    0.0559    0.0601    0.0496    0.0464    0.0488     0.0601     0.0464     0.0521
                210    0.0530    0.0799    0.0809    0.0770    0.1101     0.1101     0.0530     0.0802
                225    0.0751    0.0783    0.0739    0.0616    0.0956     0.0956     0.0616     0.0769
                240   -0.0014   -0.0136   -0.0087    0.0261    0.0058     0.0261    -0.0136     0.0016
                255    0.0610    0.0628    0.0922    0.0631    0.1025     0.1025     0.0610     0.0783
                270    0.0092    0.0733    0.0853    0.0556    0.0909     0.0909     0.0092     0.0629
                285    0.0209    0.0676    0.0764    0.0604    0.0757     0.0764     0.0209     0.0602
                300   -0.0415   -0.0330   -0.0227    0.0408   -0.0139     0.0408    -0.0415    -0.0141
                315   -0.0008    0.0511    0.0375    0.0757    0.0583     0.0757    -0.0008     0.0444
                330   -0.0422    0.0249    0.0300    0.0152    0.0537     0.0537    -0.0422     0.0163
                345   -0.0110    0.0110    0.0155    0.0505    0.0327     0.0505    -0.0110     0.0195
                360   -0.1016   -0.1296   -0.0811   -0.0121   -0.0829    -0.0121    -0.1296    -0.0815
               **************************************************************************************************
                MAX    0.0751    0.0799    0.0853    0.0831    0.1101
                MIN   -0.2126   -0.2365   -0.1771   -0.0858   -0.0995
                AVG   -0.0171   -0.0156   -0.0026    0.0187    0.0169
               **************************************************************************************************
               MAXIMUM TDF  0.1101
               MINIMUM TDF -0.2365
```

COMPUTER PRESENTATION DATA

FIGURE 46

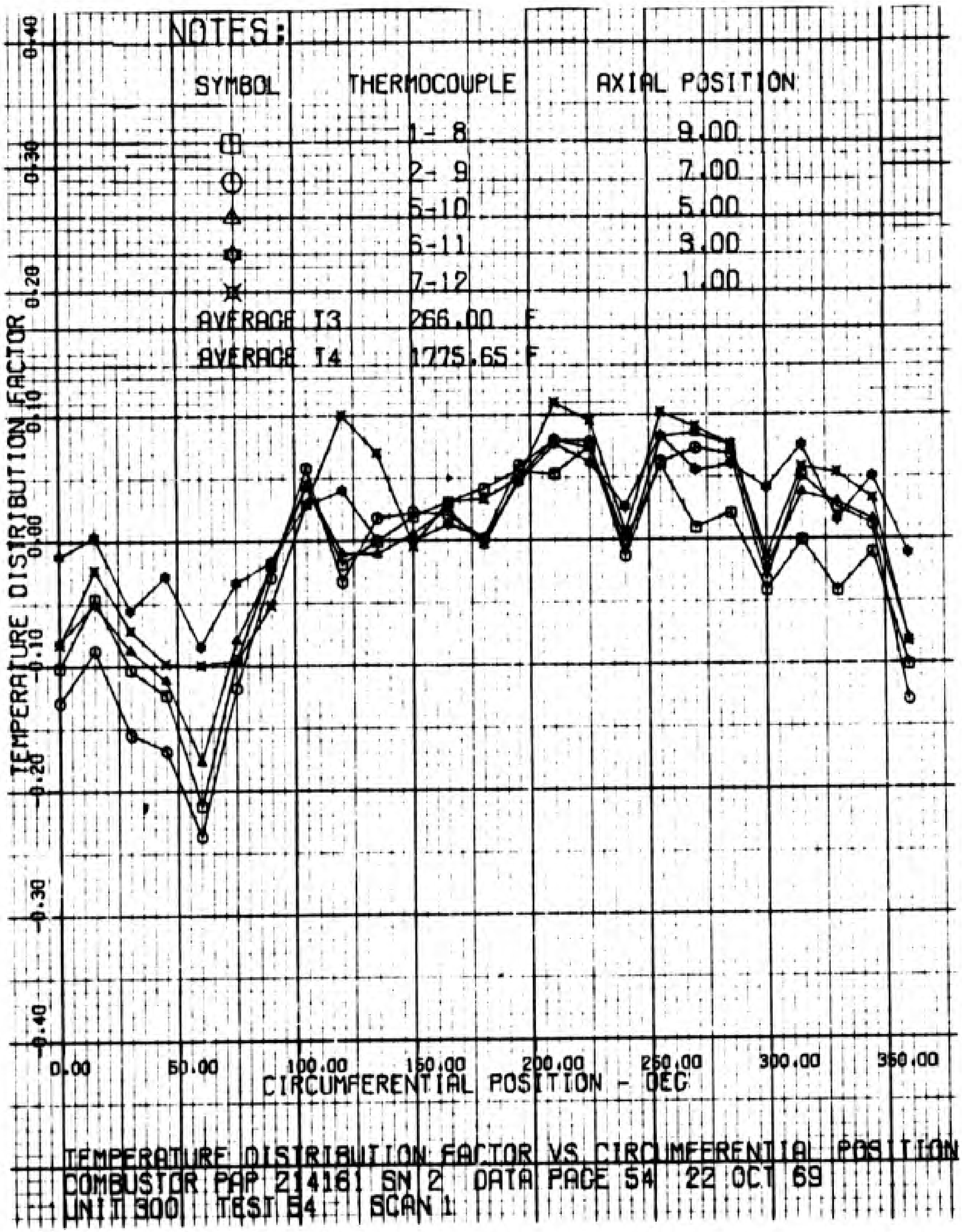

NOTES;
SYMBOL
THERMOCOUPLE
AXIAL POSITION
1- 8
9.00
2- 9
7.00
5-10
5.00
6-11
3.00
7-12
1.00
AVERAGE T3
266.00 F
AVERAGE T4
1775.65 F
TEMPERATURE DISTRIBUTION FACTOR
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
CIRCUMFERENTIAL POSITION - DEG
TEMPERATURE DISTRIBUTION FACTOR VS CIRCUMFERENTIAL POSITION
COMBUSTOR PAP 214161 SN 2 DATA PAGE 54 22 OCT 69
UNIT 300 TEST 54 SCAN 1

FIGURE 46a

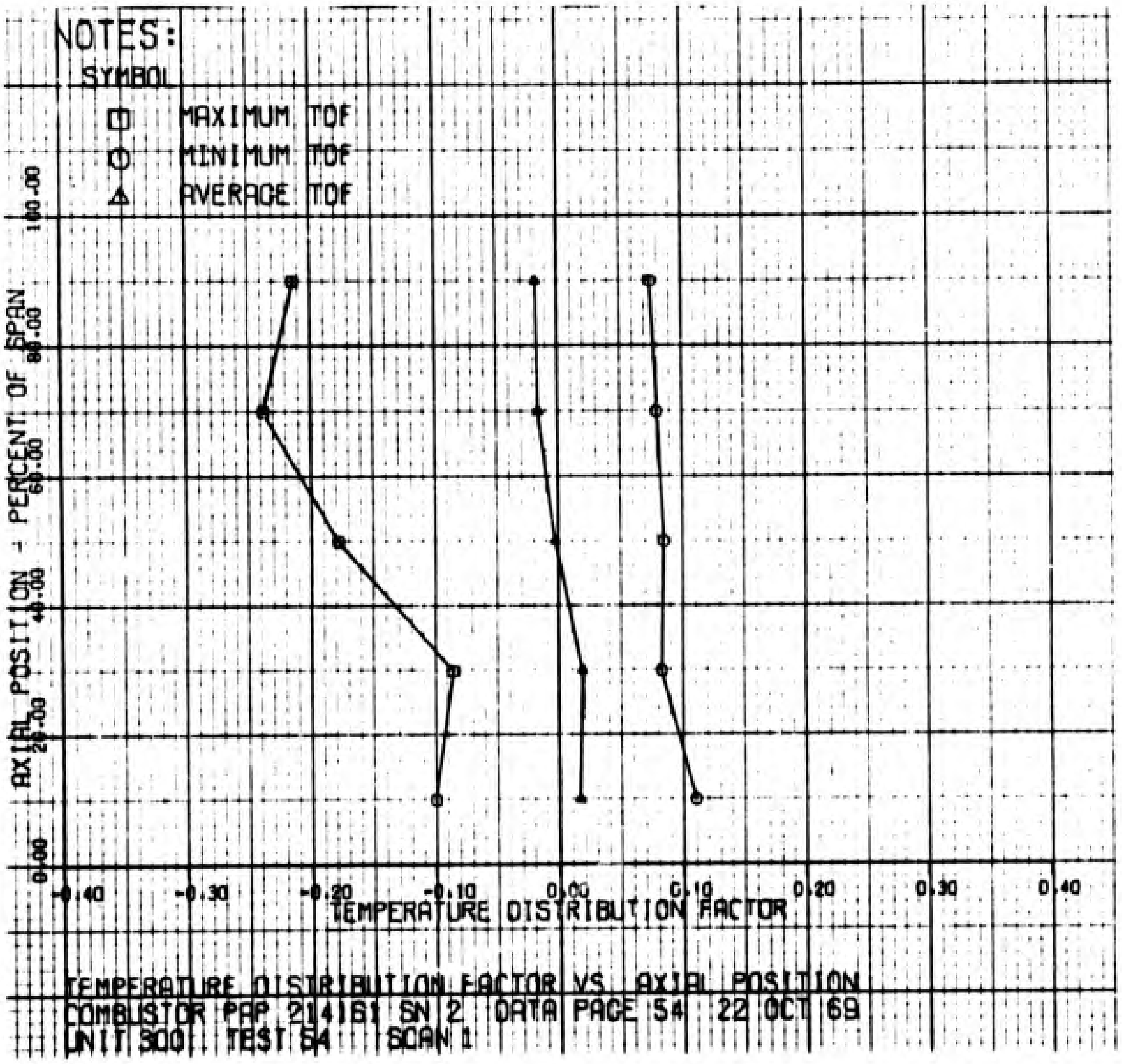
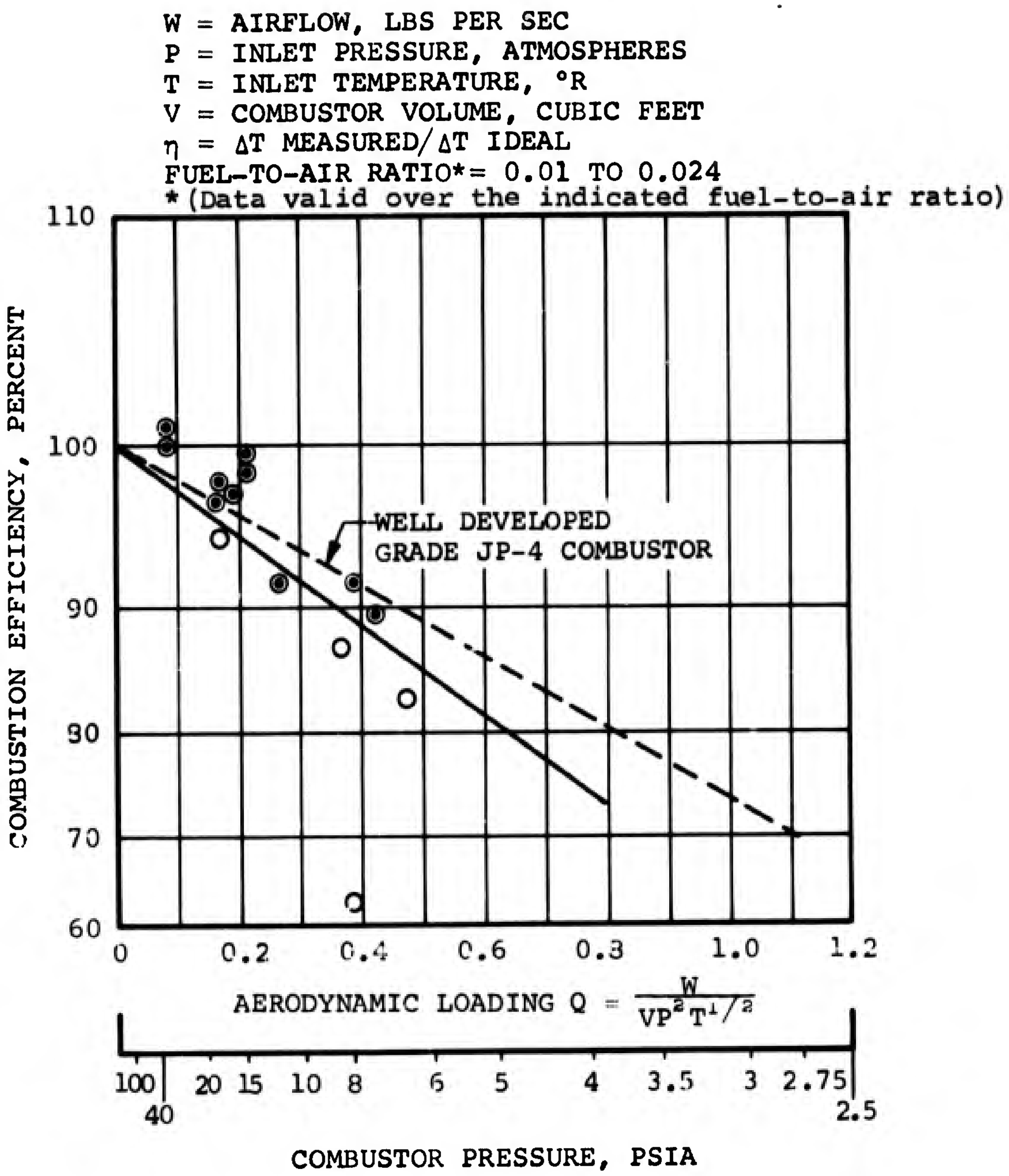
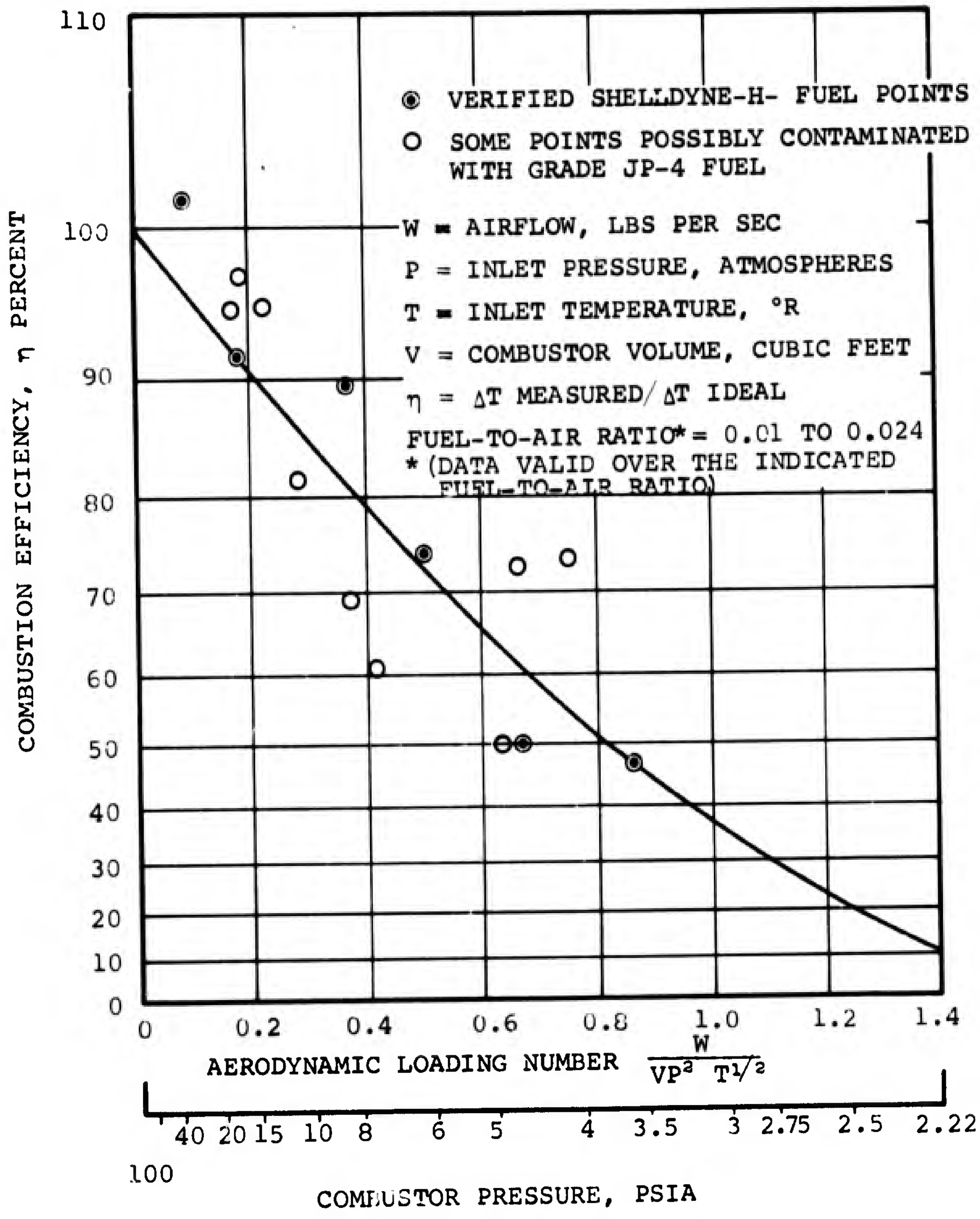

NOTES:
SYMBOL
MAXIMUM TDF
MINIMUM TDF
AVERAGE TDF
AXIAL POSITION - PERCENT OF SPAN
0.00
20.00
40.00
60.00
80.00
100.00
-0.40
-0.30
-0.20
-0.10
0.00
0.10
0.20
0.30
0.40
TEMPERATURE DISTRIBUTION FACTOR
TEMPERATURE DISTRIBUTION FACTOR VS AXIAL POSITION
COMBUSTOR PAP 214161 SN 2 DATA PAGE 54 22 OCT 69
UNIT 300 TEST 54 SCAN 1

FIGURE 46b



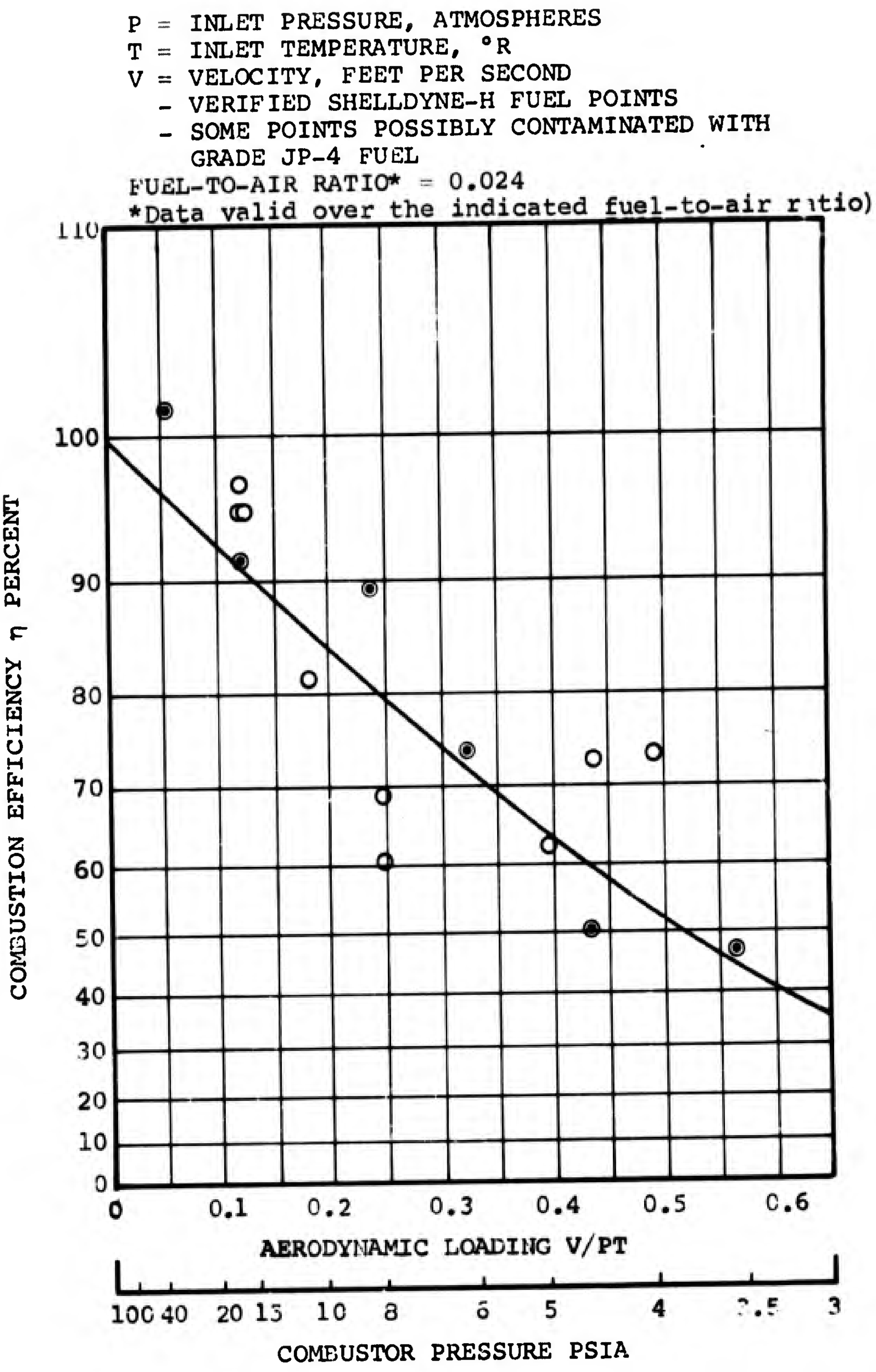
SHELLDYNE-H COMBUSTOR PERFORMANCE
WITH MIL-T-5624, GRADE JP-4 FUEL

FIGURE 47



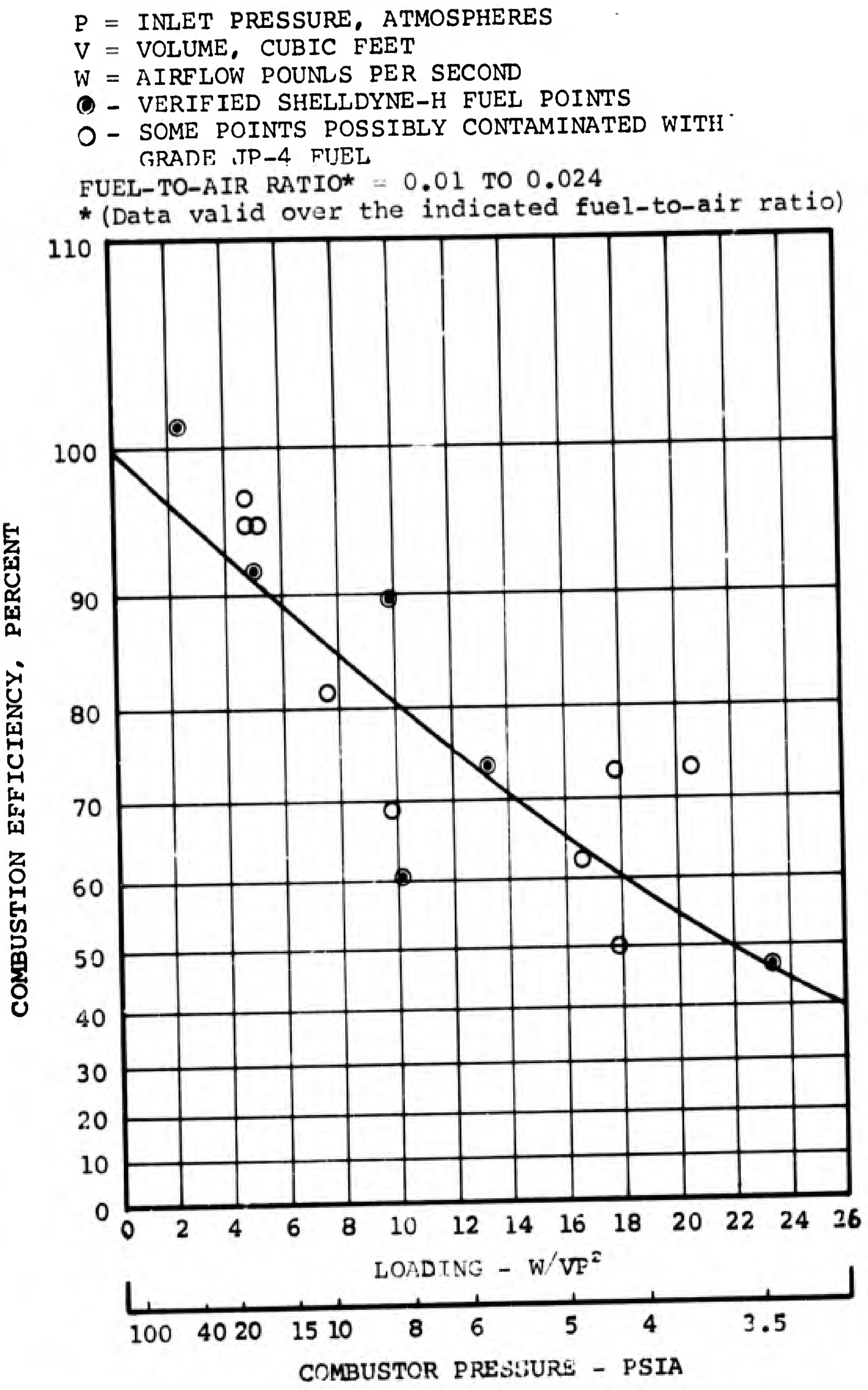
SHELLDYNE-H COMBUSTOR PERFORMANCE

FIGURE 48

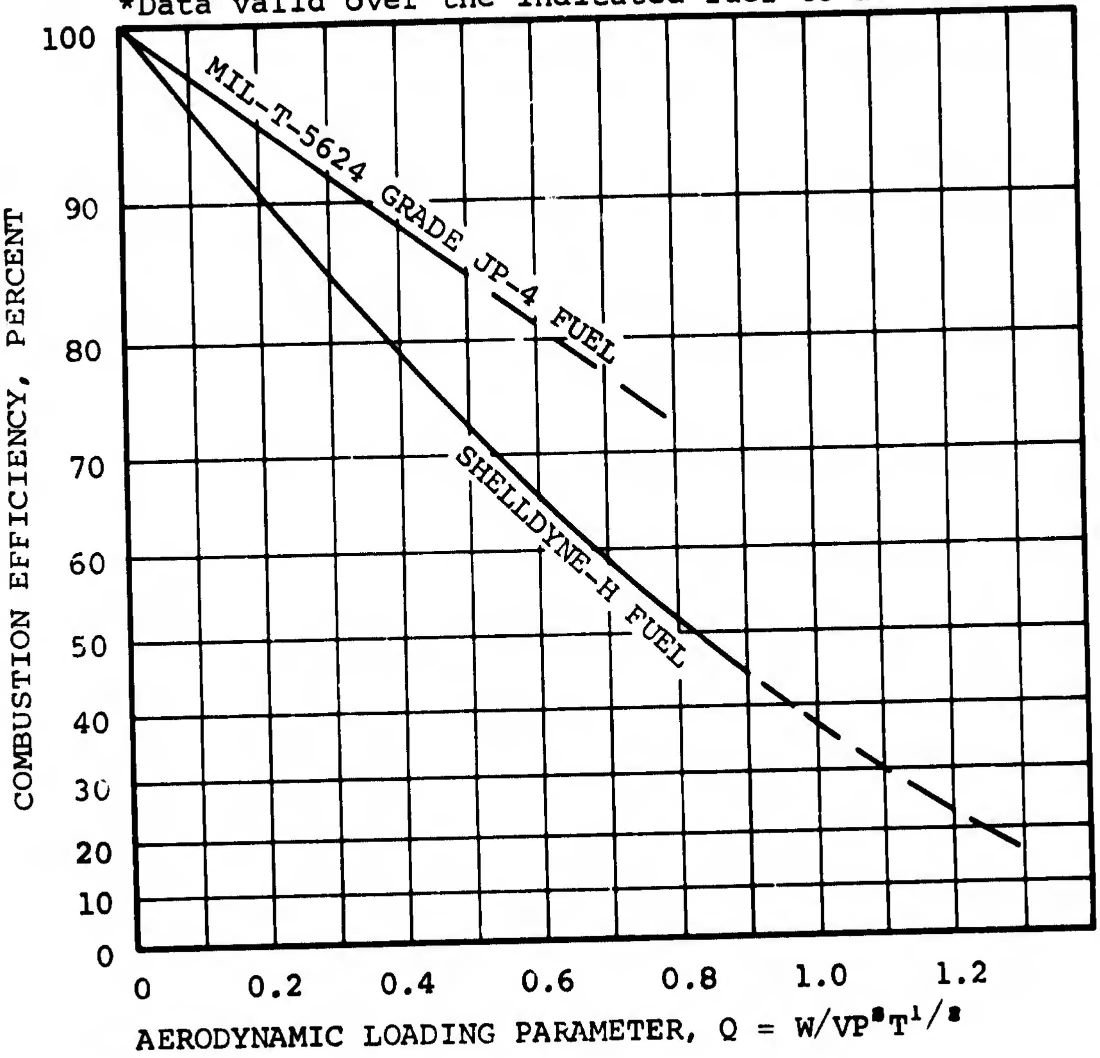


SHELLDYNE-H COMBUSTOR PERFORMANCE
WITH SHELLDYNE-H FUEL
(ALTERNATE CORRELATION)

FIGURE 49



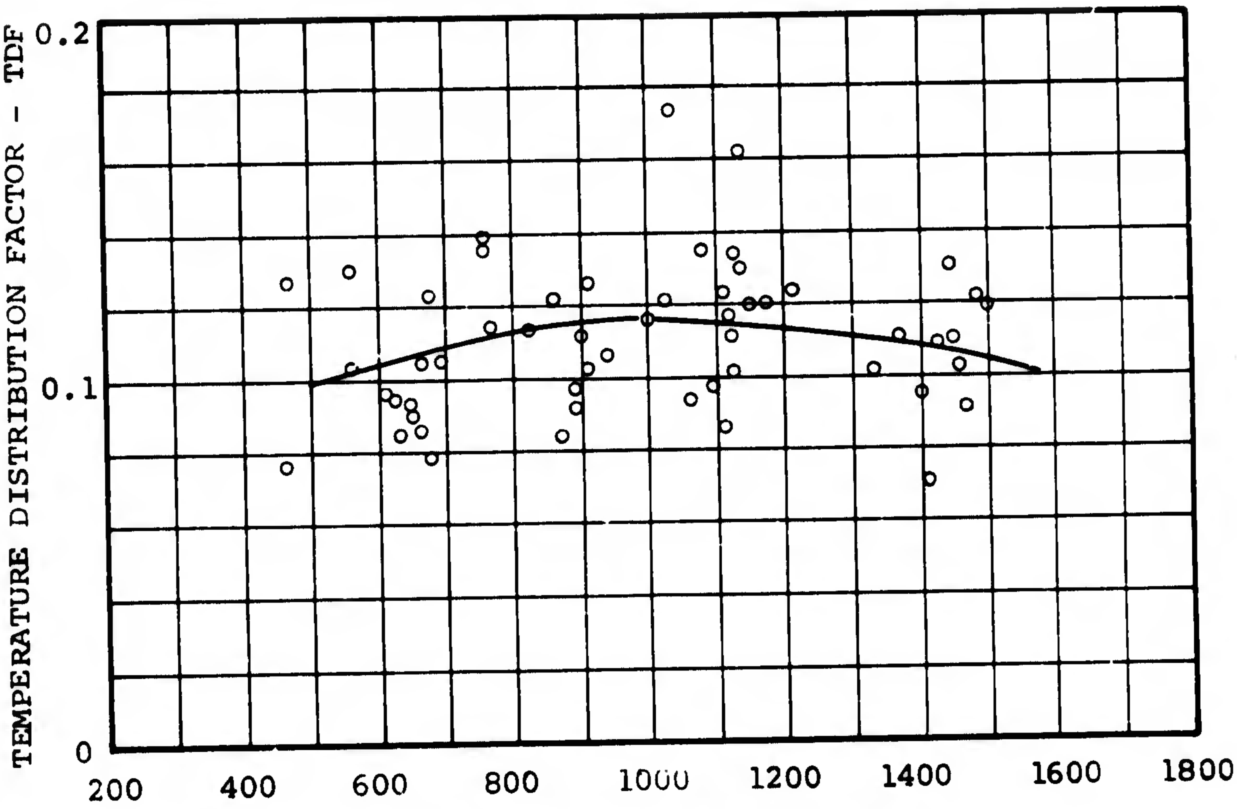
SHELLDYNE-H COMBUSTOR PERFORMANCE
WITH SHELLDYNE-H FUEL
(ALTERNATE CORRELATION)
FIGURE 50



P = INLET PRESSURE, ATMOSPHERES
T = INLET TEMPERATURE, °F
V = VOLUME PER CUBIC FOOT
W = AIRFLOW, POUNDS PER SECOND
FUEL-TO-AIR RATIO*= 0.01 TO 0.024
*Data valid over the indicated fuel-to-air ratio

SHELLDYNE-H COMBUSTOR
PERFORMANCE COMPARISON

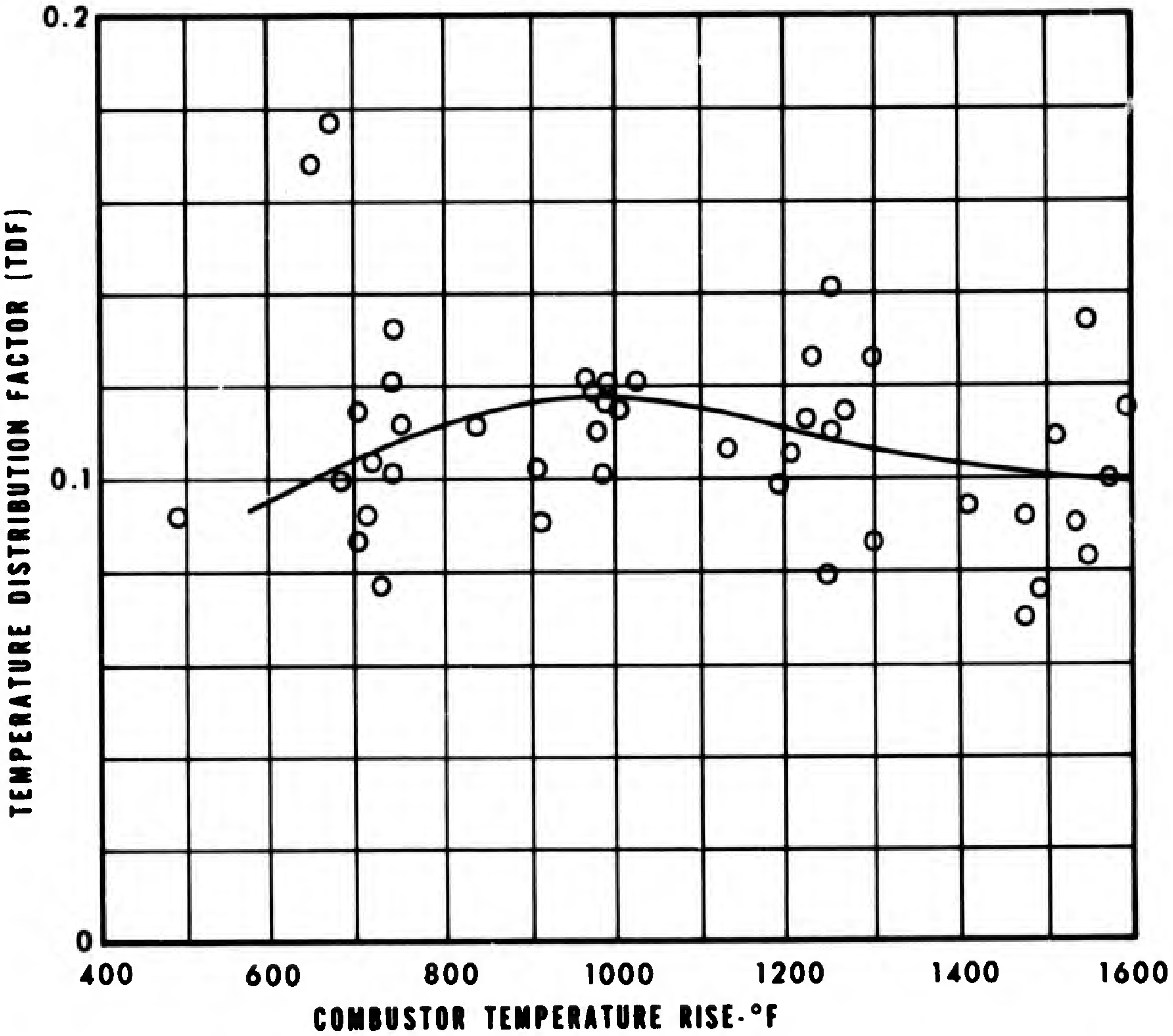
FIGURE 51



COMBUSTOR TEMPERATURE RISE - °F

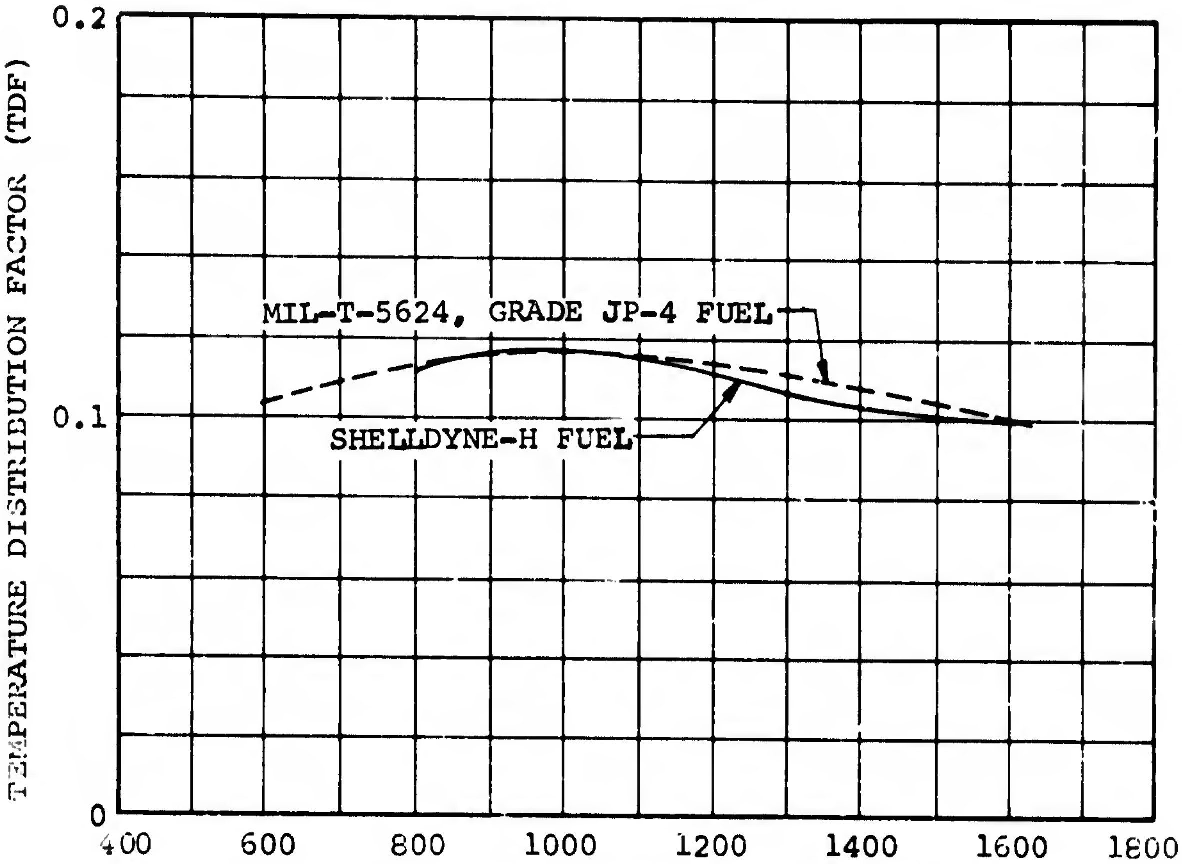
COMBUSTOR DISTRIBUTION FACTOR
SHELLDYNE-H COMBUSTOR
USING MIL-T-5624, GRADE JP-4 FUEL

FIGURE 52



COMBUSTOR DISTRIBUTION FACTOR
SHELLDYNE-H COMBUSTOR
USING SHELLDYNE-H FUEL

FIGURE 53



TEMPERATURE DISTRIBUTION
FACTOR COMPARISON

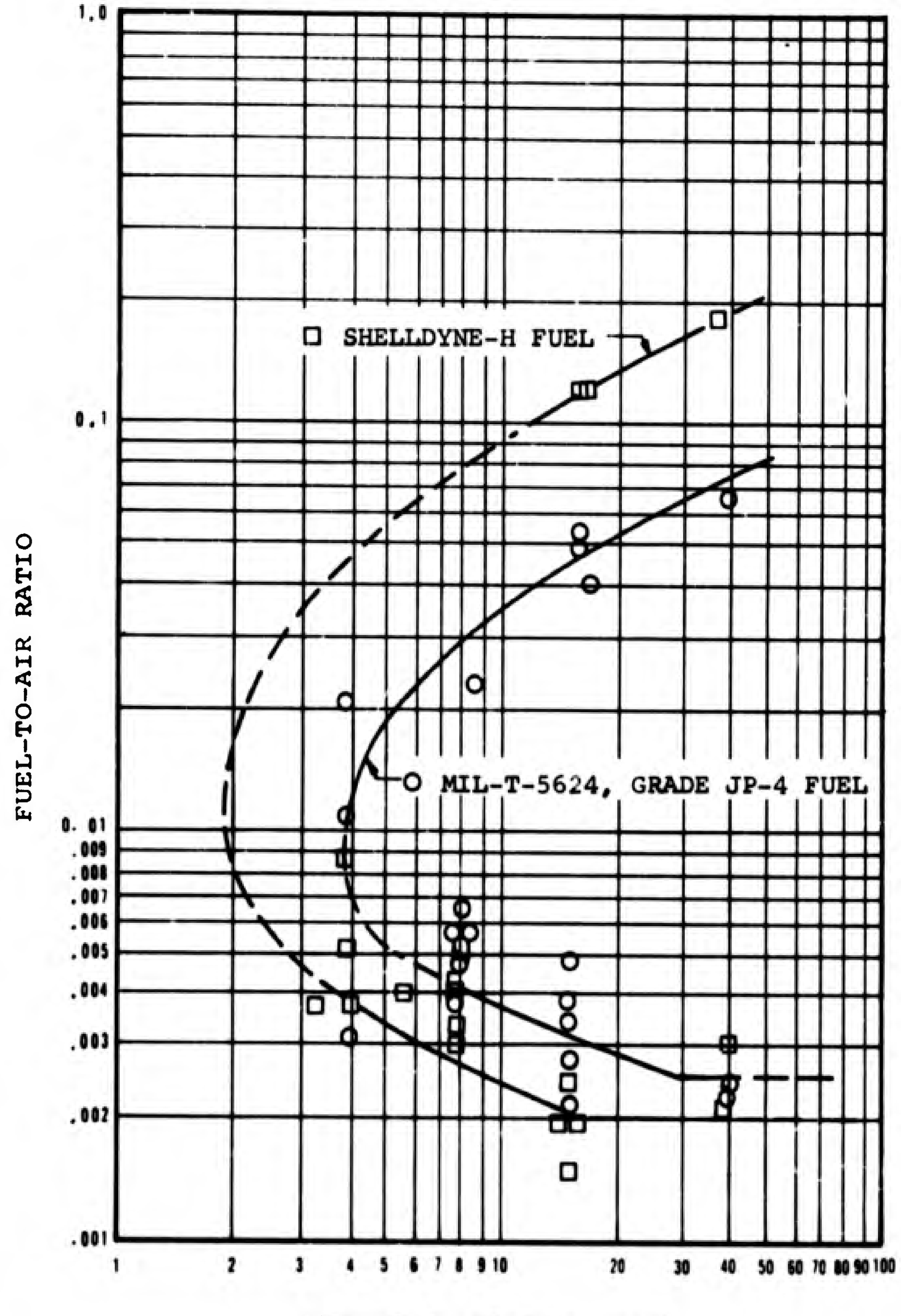
FIGURE 54

5.3.2 Stability Limits. The combustion stability limits for both Grade JP-4 fuel and Shelldyne-H fuel were determined with the Shelldyne-H combustor. The stability limits for Shelldyne-H fuel are broader than for JP-4 fuel as shown in Figure 55. This data indicates that Shelldyne-H continues to burn at half the minimum combustor absolute pressure required by Grade JP-4 fuel.

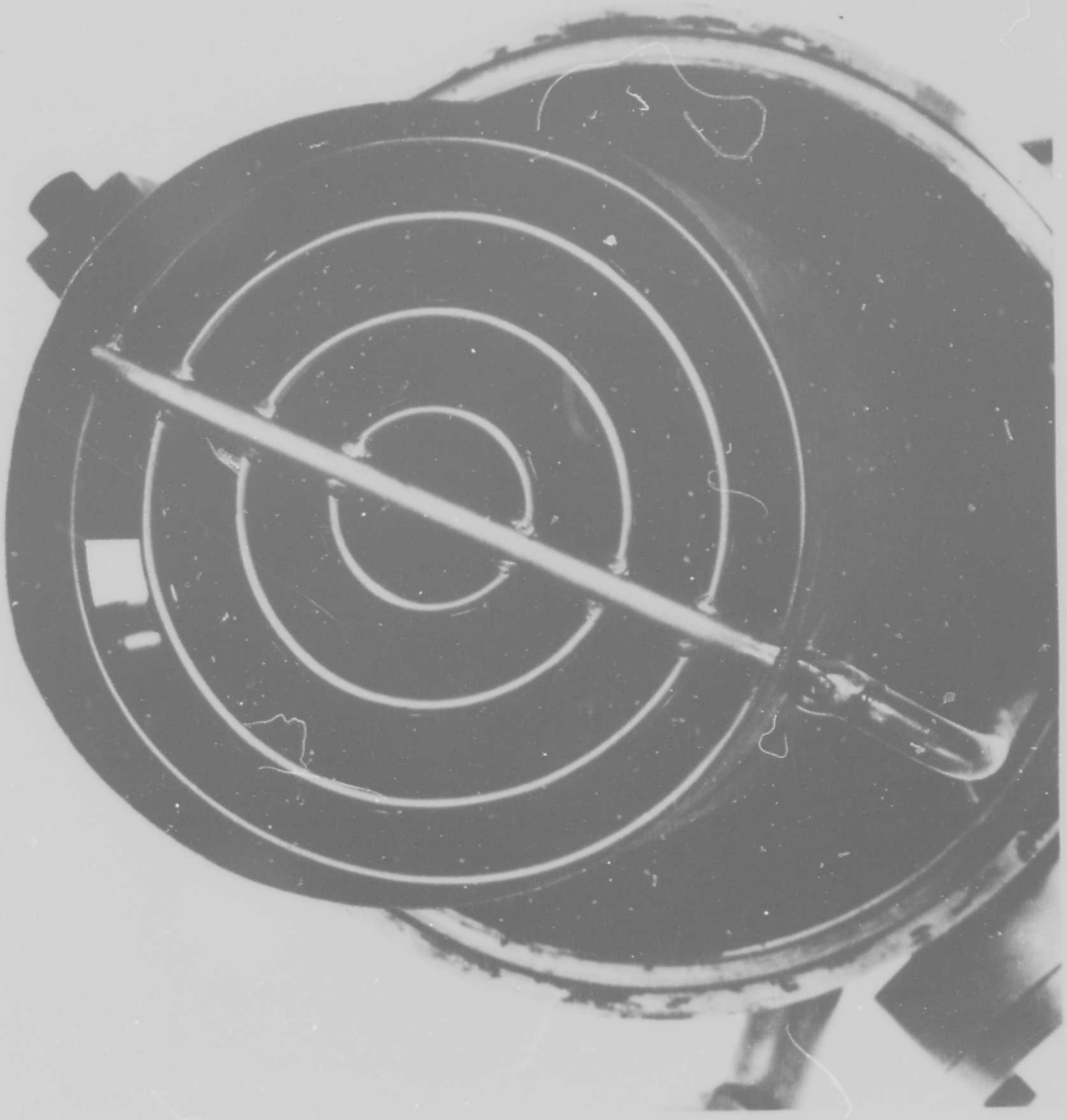
The test rig was modified to provide a rich-blowout-limit testing capability. These modifications consisted of installing a water-injection manifold in the combustor discharge, as shown in Figure 56. During rich-blowout testing, water was sprayed into the combustor exhaust to prevent overtemperature of the combustor test rig. The water spray was directed downstream and was arranged in such a manner as to preclude the possibility of water being carried back into the combustor by recirculation. The measured exhaust temperature was then corrected for temperature depression, from water and airflow rate data. The broader combustion stability of Shelldyne-H fuel, as shown in the above figure, indicates that an engine operating with Shelldyne-H fuel would be more tolerant to operating perturbations than one operating with Grade JP-4 fuel.

5.4 Ignition Tests. Ignition testing was performed to determine the comparative ignition characteristics of Shelldyne-H and JP-4 fuels at reduced temperatures and pressures. The tests were conducted by supplying the combustor with air and fuel thermally conditioned to simulate the conditions experienced in the GTP30 APU during a start. The air was conditioned by blow-down turbines capable of providing air at temperatures down to minus 60°F. The fuel system shown schematically in Figure 57, was used to thermally condition both the fuel and the fuel delivery lines. The Shelldyne-H fuel storage tank was filled and immersed in a trichloroethylene bath. The bath, tank, and Shelldyne-H fuel were then chilled with dry ice, and the desired test temperature was maintained by bubbling CO_2 through the bath. The line connecting the Shelldyne-H fuel tank through the normally closed solenoid valve to the combustor could then be prechilled up to the valve by recirculating cold Shelldyne-H fuel from the tank through the line and back to the tank.

The Shelldyne-H fuel tank served two purposes--first, to store a relatively large quantity of cold Shelldyne-H fuel, and second, to act as a heat exchanger. Controlled quantities of fuel were delivered to the combustor by pressurizing the storage tank with a metered quantity of warm Shelldyne-H fuel and opening the solenoid valve. Warm Shelldyne-H fuel stratified in the upper portion of the tank, thereby expelling cold fuel from the bottom of the tank. Because the tank volume was

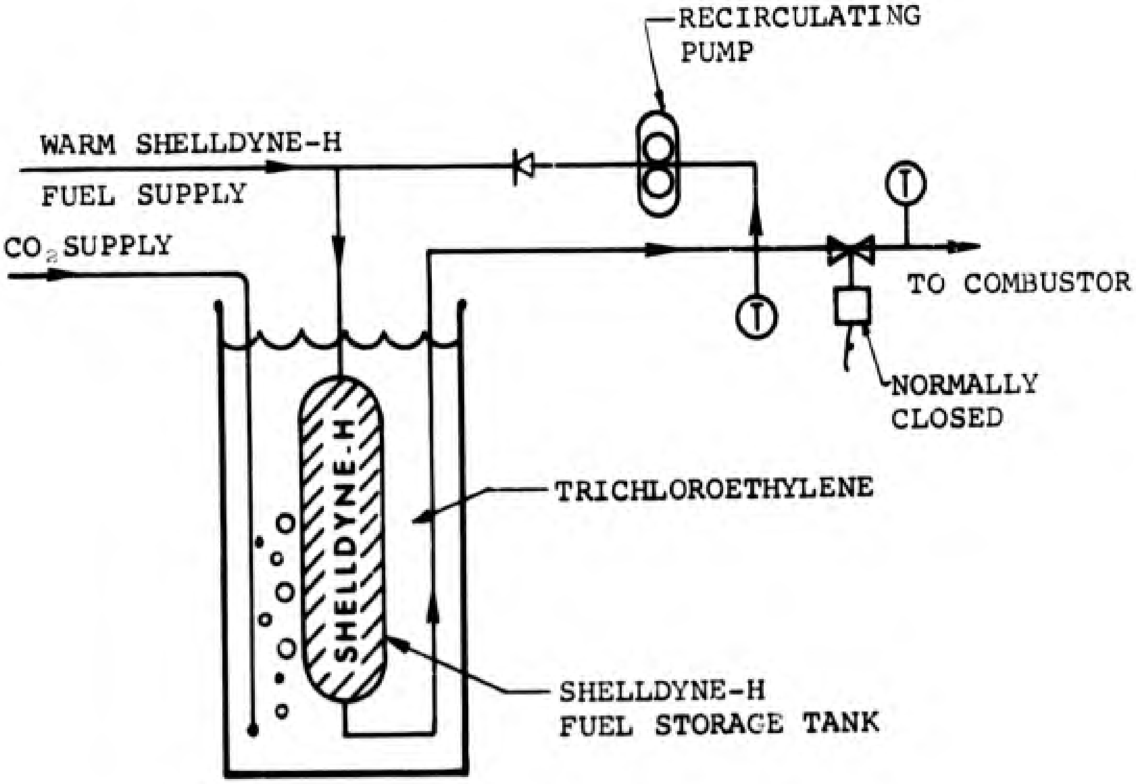


COMBUSTION STABILITY CHARACTERISTICS OF
MIL-T-5624, GRADE JP-4 FUEL AND SHELLDYNE-H FUEL
FIGURE 55



WATER-INJECTION MANIFOLD
IN COMBUSTOR EXHAUST

FIGURE 56



IGNITION TEST

FUEL CONDITIONING AND DELIVERY SYSTEM

FIGURE 57

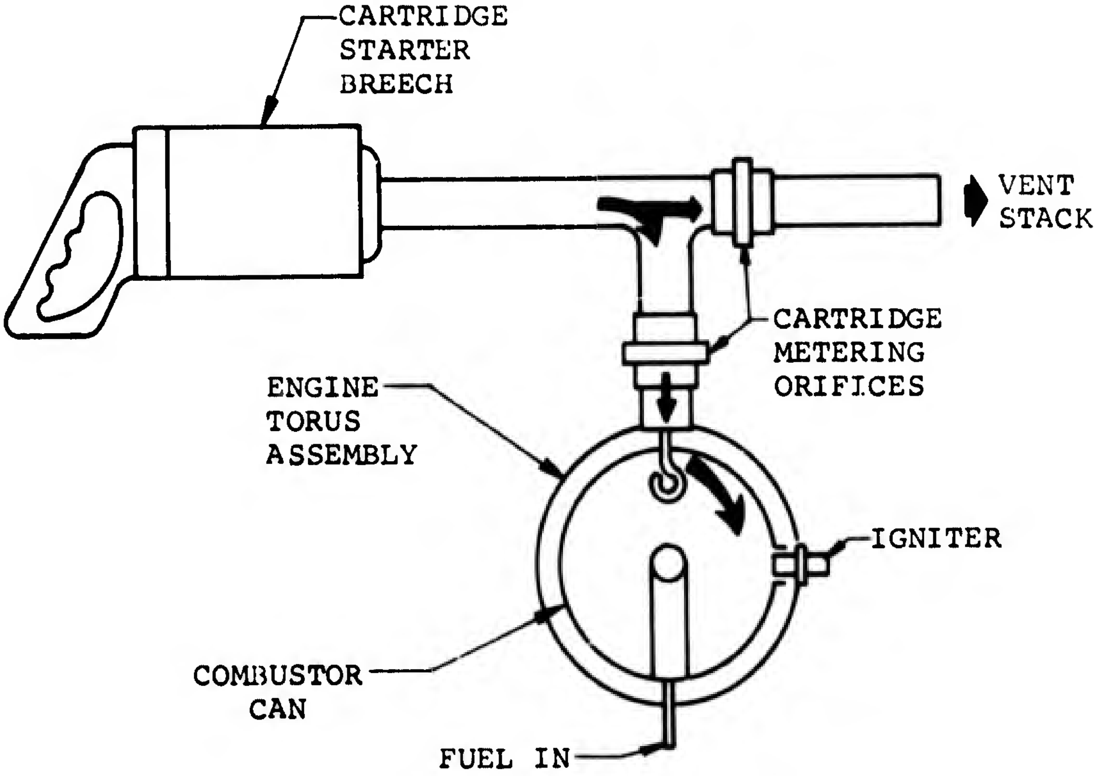
large compared to the amount of fuel required for an ignition test, the tank was never emptied of cold fuel. Warm fuel remained in the tank long enough to become chilled to the average bulk temperature.

An alternate ignition system, consisting of a cartridge starter, breech, and manifolding as shown in Figure 58, was also fabricated and tested. The purpose of this system was to simulate an engine configuration in which a cartridge starter grain is used to motor the engine for starting. A small amount of the starter gases was introduced directly into the combustor. These gases are both hot (1500°F to 2000°F) and hydrogen-rich. Consequently, it was anticipated that the effects of both direct heating and secondary combustion would aid in ignition. The amount of cartridge gas injected into the combustor was controlled by the two metering orifices. A series of orifice plates were fabricated, which, when used in paired combinations, would provide various quantities of gas to the combustor.

Several injector-tube configurations were preliminarily screened. A single configuration, shown in Figure 59, was used for ignition tests in the GTP30 combustion test rig. The injector tube consisted of a length of stainless steel tubing looped so that the discharge flow would impinge on the tube. A palladium coating was applied to the outside of the tubing to act as a catalytic ignition source between the hydrogen in the main decomposition gases and the air flowing through the combustor.

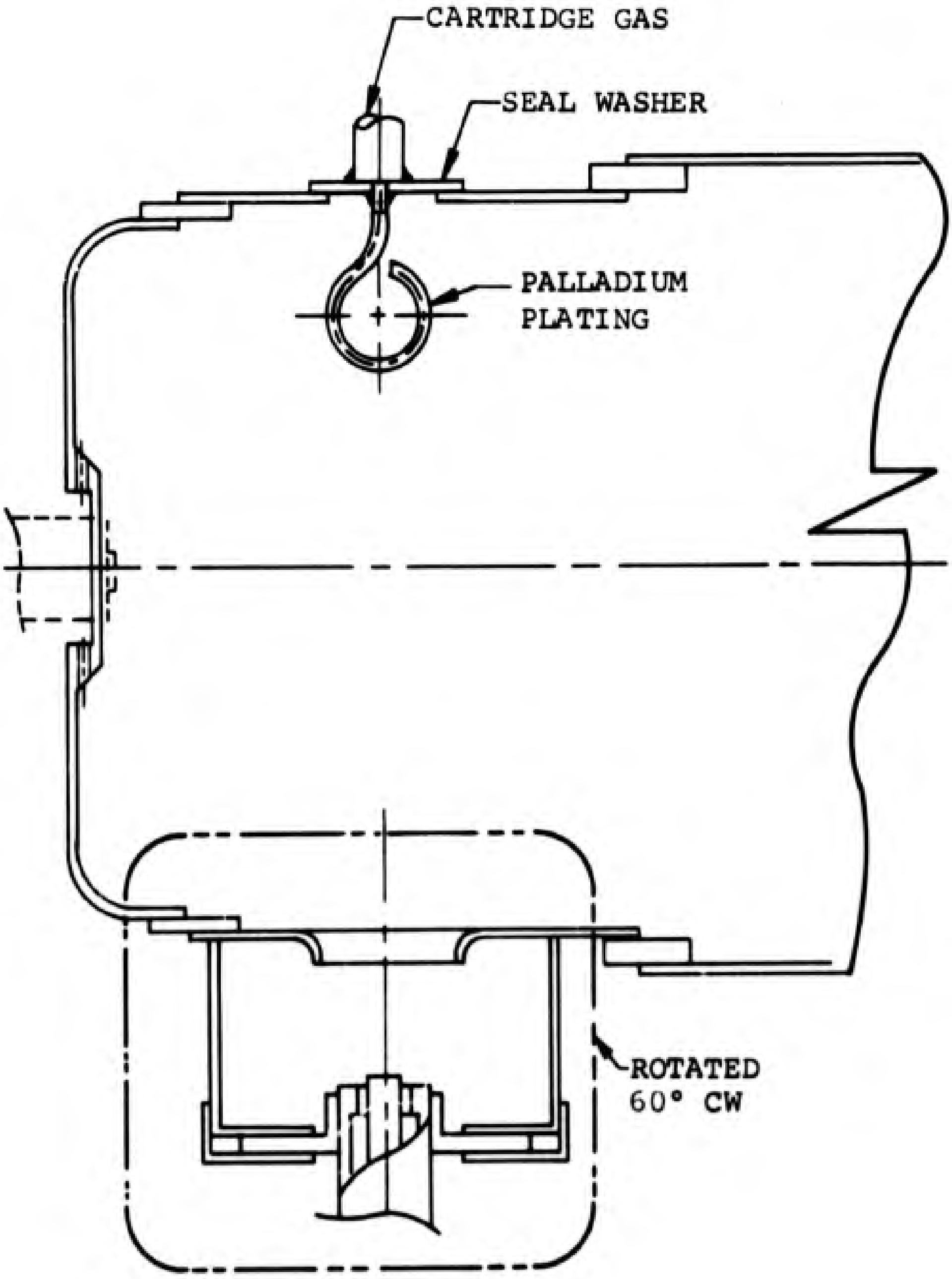
Ignition testing was initiated with a preliminary test, which was performed by operating the combustor under prevailing ambient conditions with Shelldyne-H fuel at normal start-air and fuel-flow rates. The combustor inlet air and fuel temperatures were then gradually reduced to minus 20°, at which point the flame extinguished. This test indicated that the minimum ignition temperature for Shelldyne-H fuel under GTP30 start conditions would be higher than minus 20°F. The viscosity of Shelldyne-H fuel at minus 20°F is 550 centistokes. It is interesting to note that the maximum fuel viscosity normally considered for use by the aviation industry is 12 centistokes. Central power generating stations generally do not attempt to burn fuel at viscosities greater than 500 centistokes.

Several tests were run with fuel delivery temperatures that were both above and below the combustor inlet air temperature. These tests indicated that even though the fuel may be preheated, the fuel temperature entering the combustor



CARTRIDGE STARTER IGNITION SYSTEM

FIGURE 58



CARTRIDGE GAS INJECTOR TUBE

FIGURE 59

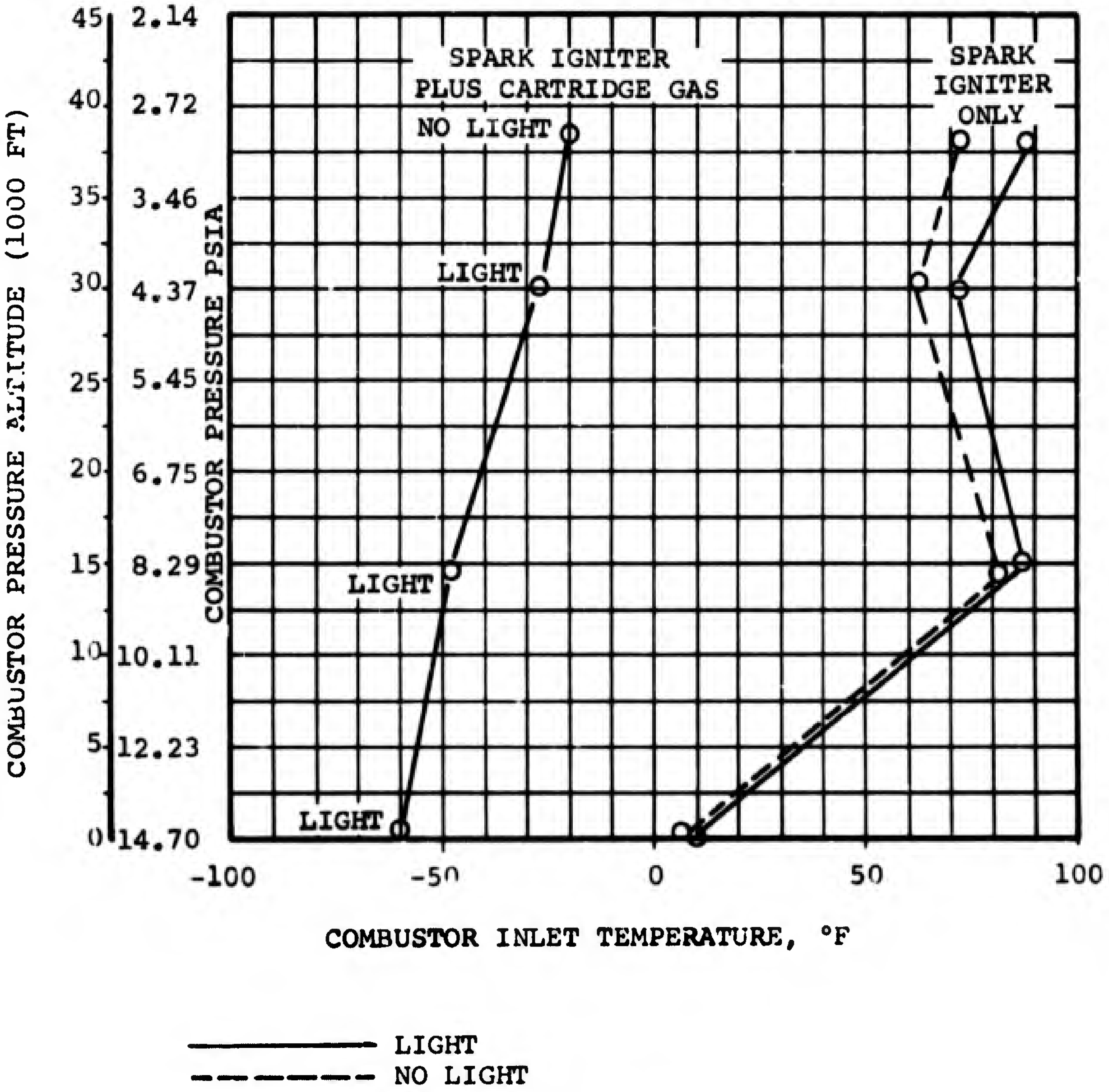
is essentially the same as the combustor component temperature. The reason for this is that the thermal mass of the combustor, associated lines and fittings, and combustor airflow is large compared to the thermal mass of the fuel used during an ignition cycle. Consequently, the combustor inlet air temperature will control the fuel temperature and related ignition characteristics.

The ignition characteristics obtained with the Shelldyne-H combustor operating on Grade JP-4 fuel are presented in Figure 60. This data is for two ignition configurations: first, using only the spark igniter, and second, using cartridge gas injection plus the spark igniter. The ignition temperature depression with cartridge gas injection is significant (70°F). Therefore, the direct introduction of heat and hydrogen in the combustor does aid low-temperature ignition, as would be expected. Attempts to obtain autoignition, by using only cartridge gases as the ignition source, were unsuccessful. However, it is believed that autoignition could be accomplished with proper design of the gas-injector tube. The design, as shown previously in Figure 58, forced the gases to impinge on the palladium-coated section only, one or two diameters from the tube end. Consequently, the local velocities were only slightly subsonic, as the tube itself was choked. Therefore, very little, if any, air (oxygen) could mix with the cartridge gases prior to impingement on the palladium. If any reaction was catalyzed, the local velocities were higher than the ensuing flame speed, and ignition was not effected.

The minimum ignition temperature with this combustor, with the use of a conventional spark igniter, was 8°F. This indicated that significant improvements in ignition characteristics of the combustor are attainable with additional development. Practically all combustors in production today can be started at minus 65°F, with use of Grade JP-4 fuel.

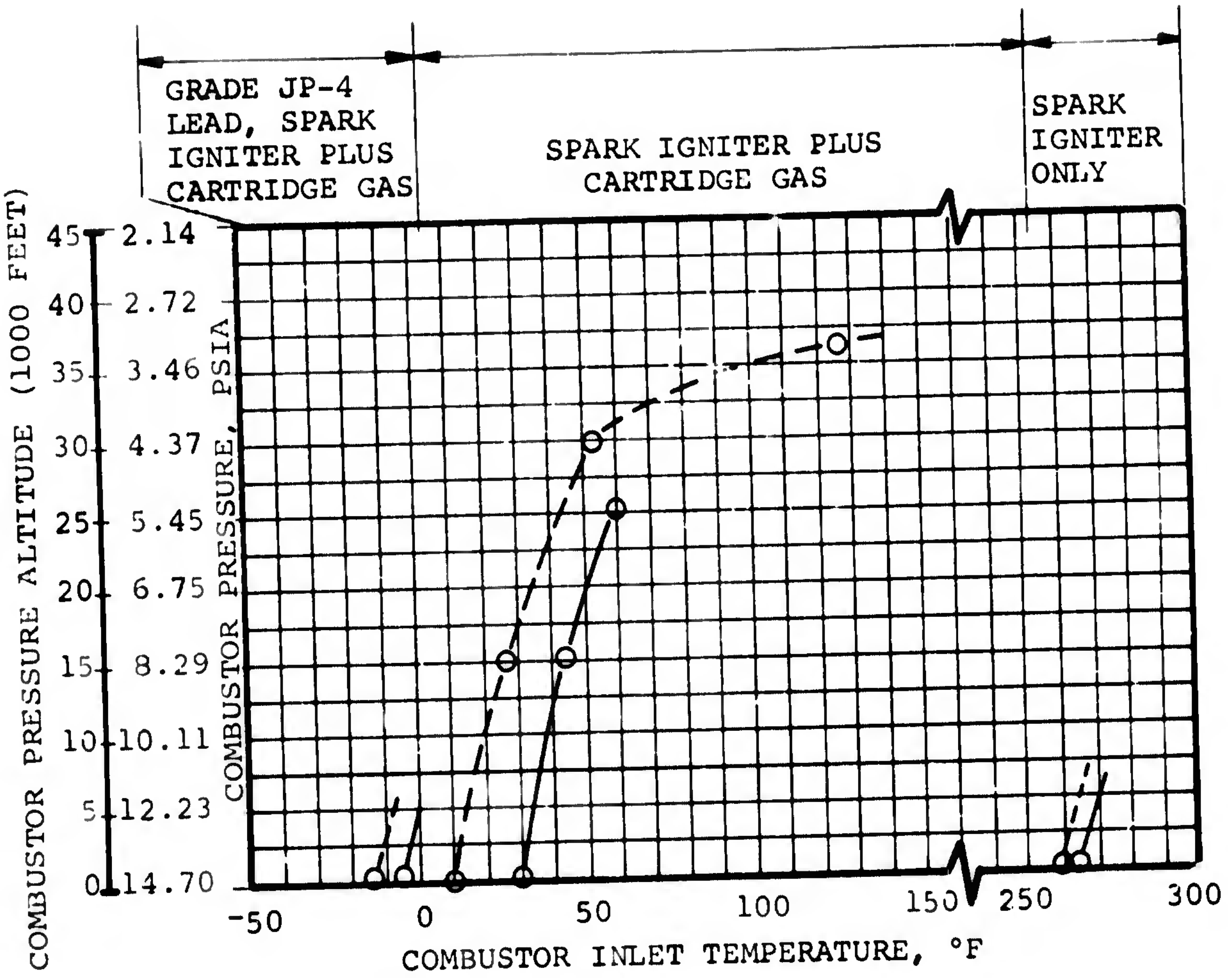
The ignition characteristics obtained with Shelldyne-H fuel are presented in Figure 61. Direct ignition of Shelldyne-H fuel with a conventional spark igniter, required a combustor inlet air temperature of 265°F, as shown. With cartridge gas injection, plus the spark igniter, the minimum ignition temperature was reduced to 30°F.

A third ignition configuration with Shelldyne-H fuel was attempted. In this configuration a small amount of Grade JP-4 fuel (2.5 cubic centimeters) was put in the fuel line to act as a "lead" of Grade JP-4 fuel. The results, as shown in Figure 61, indicated that the ignition temperature could



IGNITION CHARACTERISTICS OF
MIL-T-5624, GRADE JP-4 FUEL
WITH SHELLDYNE-H COMBUSTOR

FIGURE 60



NOTES:

- – – – – – NO LIGHT
- ———— LIGHT

SHELLDYNE-H FUEL IGNITION
CHARACTERISTICS WITH
SHELLDYNE-H COMBUSTOR

FIGURE 61

be further reduced to minus 5°F, which is only 15°F above the minimum steady-state combustion temperature determined with Shelldyne-H fuel initially.

> NOTE: This data is for simulated-start airflow and fuel-flow conditions. Consequently, the results in no way reflect on the steady-state design-point combustion characteristics with use of either Grade JP-4 or Shelldyne-H fuel at reduced temperatures. Furthermore, it should be remembered that the pressure and temperature parameters reflected in Figures 60 and 61 are measured at the combustor inlet. Therefore, the effects of engine compressor pressure ratio and engine inlet ram must be taken into account to relate the data to prevailing flight conditions.

A direct comparison of the results in Figures 60 and 61 reveals that Shelldyne-H fuel is more difficult to ignite than Grade JP-4 fuel. However, techniques have been demonstrated for circumventing this deficiency until such time as direct ignition techniques can be developed.

SECTION VI

ENGINE ENDURANCE TESTING

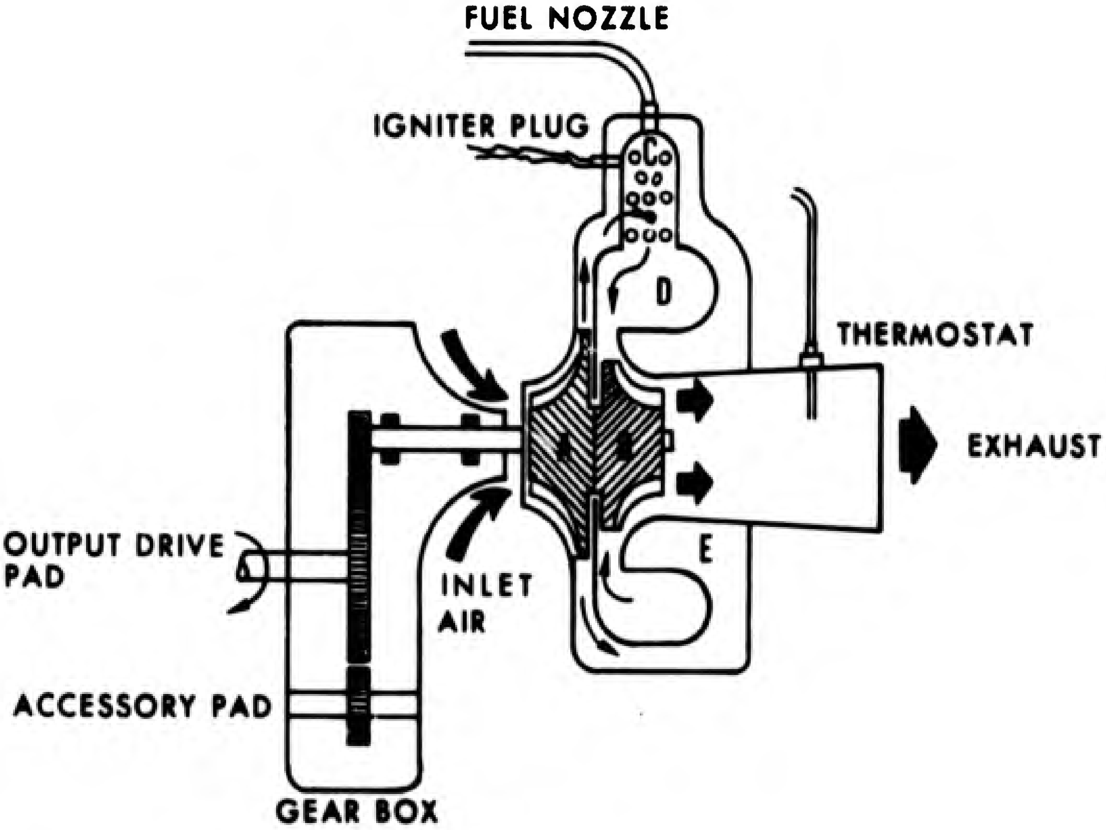
1. OBJECTIVES. The overall effects of prolonged operation of current turbomachinery with Shelldyne-H fuel were to be evaluated. An endurance test program consisting of a cyclic loading sequence with multiple engine starts was to be accomplished. The engine chosen for this test was the AiResearch Model GTP30-67 Auxiliary Power Unit (APU).

2. SUMMARY AND RESULTS. Over 60 hours of operation and 54 successful starts were accomplished during this test without encountering serious technological problems. Post-endurance teardown inspection of all engine parts revealed no detrimental effects as a result of operation with Shelldyne-H fuel that could preclude its selection as a jet engine or gas turbine fuel.

3. ENGINE DESCRIPTION AND BUILDUP DOCUMENTATION. The Model GTP30-67 APU utilized as the test engine in the evaluation of Shelldyne-H fuel is a small, single-shaft turbine engine designed primarily for use as an on-board aircraft APU. The engine, although not a current production model, was selected for its inherent low-fuel-consumption characteristics and the immediate availability of component parts.

Figure 62 schematically depicts the basic components of the Model GTP30 Engine. The high-speed rotating group consists of a single-stage centrifugal compressor and a single-stage radial-inflow turbine, both mounted on a single shaft that is supported at one end by a pair of positively lubricated ball bearings. The nominal operating speed for this rotating assembly is 52,800 rpm. A single reduction gearbox is used to reduce this speed to 8000 rpm at the output drive pad. Auxiliary drive pads are included to drive accessories such as the fuel-control unit.

The airflow discharged from the 2.5:1-pressure-ratio compressor is expanded through a diffuser into a plenum that also houses the single-can combustor. High-temperature gases leaving the combustor are distributed uniformly to the turbine inlet nozzles by a scroll-shaped torus. After passing through the turbine, the exhaust gases are discharged through a thermostat-equipped tail pipe to atmosphere.



A. IMPELLER
B. TURBINE
C. COMBUSTOR
D. TORUS
E. PLENUM

MODEL GTP30 ENGINE, SCHEMATIC

FIGURE 62

Figure 63 shows the various component parts of the rotating group, including turbine wheel and shaft, compressor impeller, compressor/turbine seal plate bearings, bearing carrier, seals, and spacers. Figure 64 shows the assembled rotating group prior to installation in the endurance test engine.

The buildup of the endurance engine was accomplished according to standard production procedures, with nominal clearances and tolerances used throughout the assembly. All power section and fuel-handling components employed in the buildup were new parts. The gearbox, however, had been previously used in-house in a small, portable power cart. Figures 65 and 66 show the assembled Shelldyne-H endurance engine, including accessory equipment such as the fuel control, fuel solenoid, and ignition system.

Additional pretest photographs of the turbine hot-end components are presented in a later section of this report for comparison with photographs taken at the conclusion of the test.

3.1 Conduct of the Endurance Test. Figure 67 shows the Shelldyne-H endurance engine installed in the test cell prior to commencement of the 50-hour test. The engine was equipped with a water brake dynamometer and calibrated force ring for accurate load determination. In addition, the engine was fully instrumented for all temperature and pressure measurements pertinent to the evaluation of its performance with Shelldyne-H fuel. Fuel was supplied to the unit by pumping it from the as-received barrels into the test-cell fuel-handling system and thence to the engine. Fuel flow rates were measured with a turbine flowmeter, calibrated for Shelldyne-H fuel. The flowmeter was installed in the fuel supply line between the supply pump and the test cell fuel system.

As discussed in the combustion section of this report, ignition of Shelldyne-H fuel could not be accomplished by use of conventional methods. Therefore, all starts during the course of the endurance tests were made by injecting a small quantity of MIL-T-52624, Grade JP-4, fuel into the fuel line between the fuel solenoid and the GTP30 combustor. prior to start initiation. The amount of Grade JP-4 used was minimized to ensure that the engine was accelerating to governed speed on Shelldyne-H fuel.

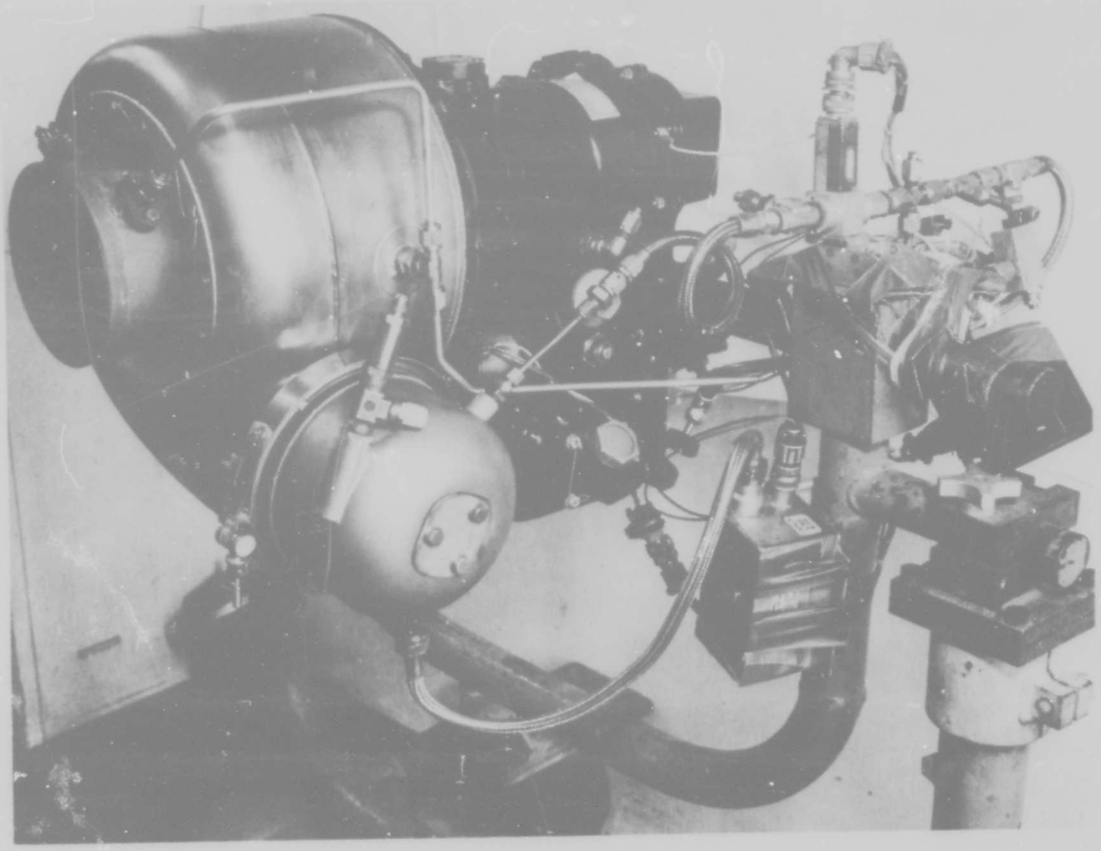
During the initial check-out runs some difficulty was encountered in achieving a fuel governor setting that would provide stable control at all load conditions. Several governor spring rates from 30 to 60 pounds per inch were

MODEL GTP30 ENGINE
ROTATING ASSEMBLY COMPONENT PARTS

FIGURE 63

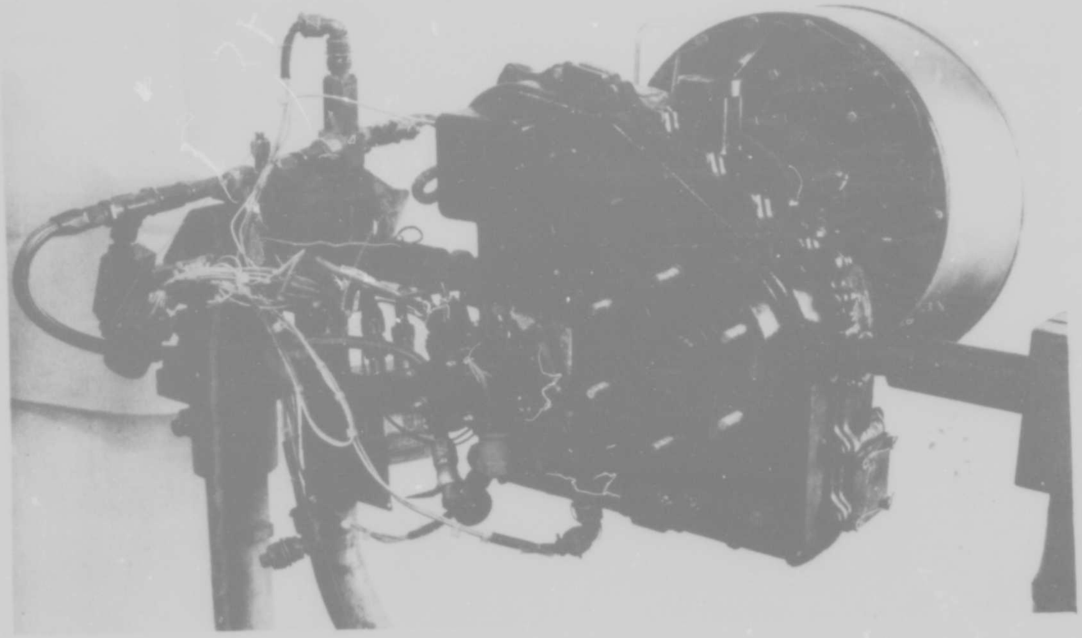
MP-25232

MODEL GTP30 ENGINE
ASSEMBLED ROTATING GROUP
FIGURE 64



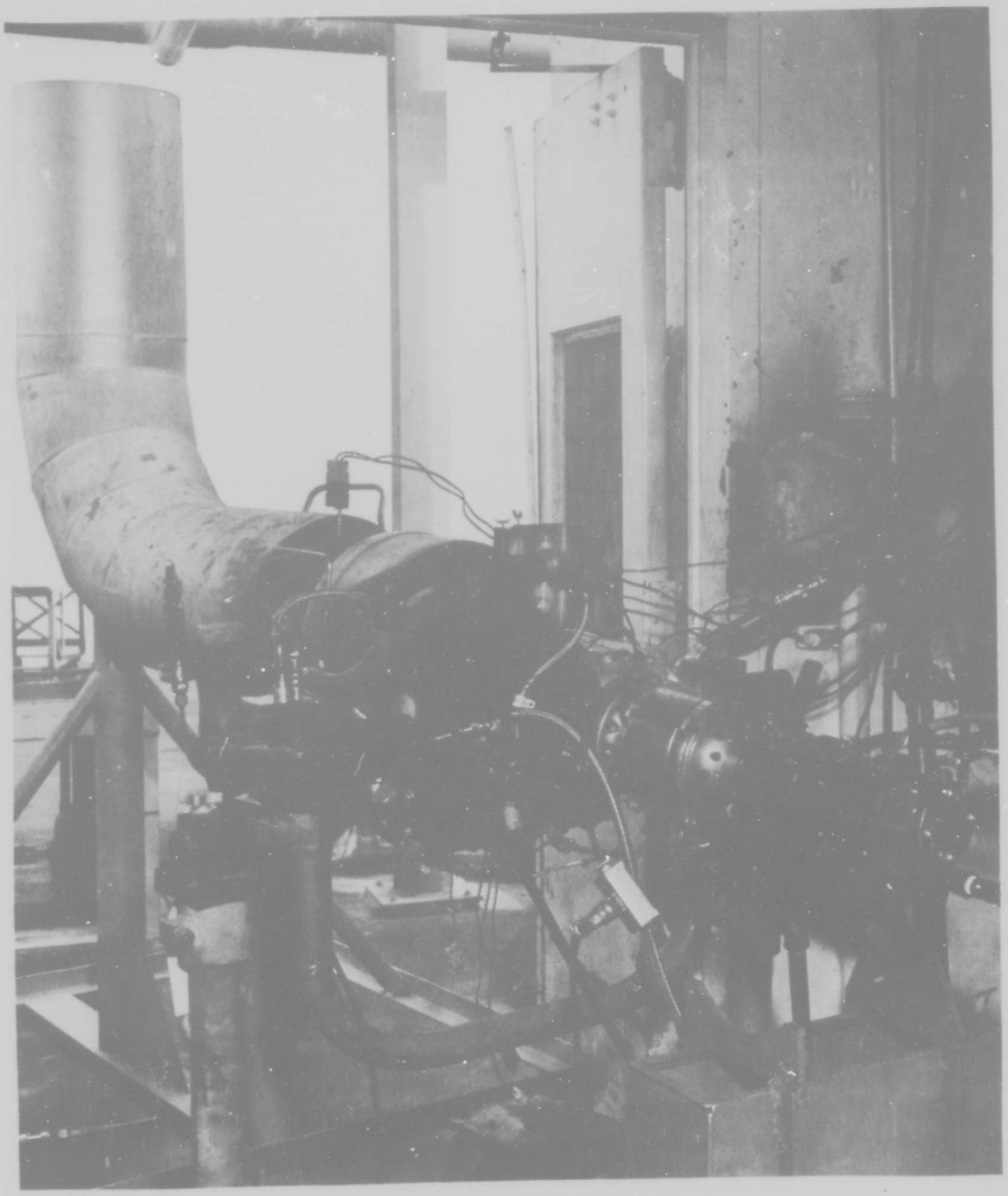
MODEL GTP30
SHELLDYNE-H ENDURANCE ENGINE

FIGURE 65



MODEL GTP30
SHELLDYNE-H ENDURANCE ENGINE

FIGURE 66



SHELLDYNE-H ENDURANCE ENGINE TEST SETUP

FIGURE 67

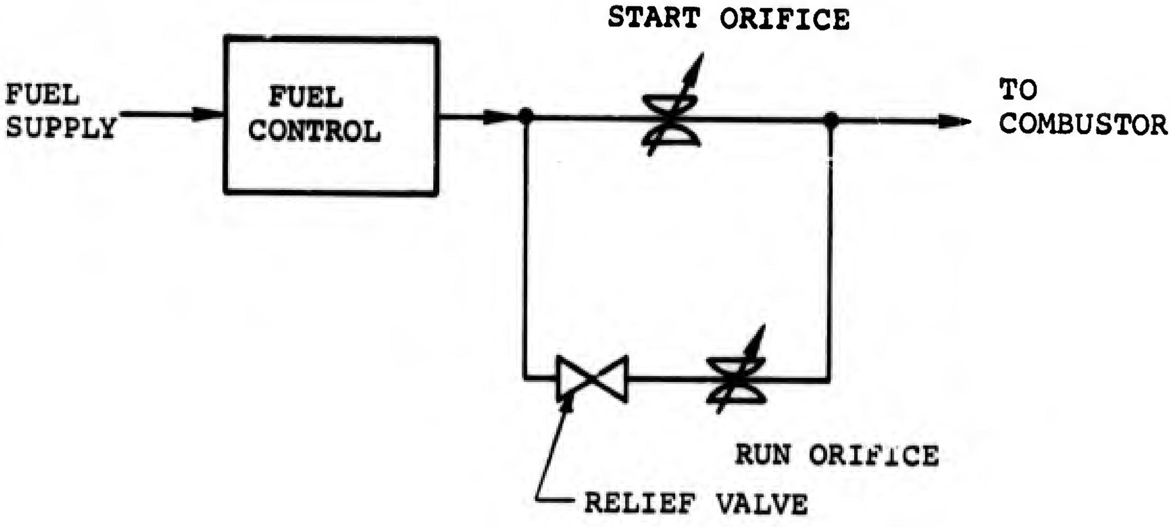
MP-25238

installed without success. It was determined from these preliminary tests that the problem arose from the use of a single downstream restriction between the fuel control and the combustor, as described in Section V of this report. If this orifice were adjusted for good engine starting, then too much fuel pressure would be required at full load conditions and the engine speed would decrease or "droop" excessively. The final solution involved the installation of two orifices and a relief valve in the fuel line. The first, or start, orifice allowed for proper adjustment of the fuel rates during a start. The second, or run, orifice permitted the maximum fuel rates to be obtained with reasonable control pressures. The relief valve was used to admit fuel to the second orifice during the latter portion of the start schedule. This system, which is shown schematically in Figure 68, was utilized during the entire endurance test in conjunction with a 54-pound-per-inch governor spring.

The endurance test was conducted around the clock from September 9 through September 12, 1969, with brief shut-downs for all shift changes and lunch breaks. Additional shutdowns were made for various test-cell equipment adjustments and fuel barrel changes.

The loading schedule for the test consisted of ten of the following time/load cycles:

Segment	Description
(a)	5 minutes at maximum output plus 5 minutes at no load (idle) plus 20 minutes at normal output.
(b)	5 minutes at maximum output plus 5 minutes at no load plus 20 minutes at 75% normal output.
(c)	5 minutes at maximum output plus 5 minutes at no load plus 20 minutes at normal output.
(d)	5 minutes at maximum output plus 5 minutes at no load plus 20 minutes at 50% normal output.
(e)	5 minutes at maximum output plus 5 minutes at no load plus 20 minutes at normal output.
(f)	5 minutes at maximum output plus 5 minutes at no load plus 20 minutes at 25% normal output.
(g)	2 hours consisting of 8 cycles at 10 minutes at no load (idle) and 5 minutes at maximum output.



FUEL SYSTEM SCHEMATIC
SHELLDYNE-H ENDURANCE ENGINE TEST

FIGURE 68

One hundred percent normal output was established for the Model GTP30-67 Engine as 48 horsepower at 52,800 rpm turbine speed for the average ambient temperatures encountered. Maximum output was established as that power available at 1325°F turbine discharge temperature. If for some reason, such as extremely high ambient temperature, a condition of compressor surge was encountered, maximum output was considered to be the highest surge-free discharge temperature that could be obtained up to 1325°F.

3.2 Endurance Test Performance Results. Figures 69 through 77 contain a tabulation of all data recorded during the endurance test, as well as those calculated and corrected data pertinent to performance evaluation. (Figures 69 through 77 are a reduced reproduction of the computer printout.) The following is a definition of the column headings used for the endurance test data:

TEST NO.	(Example 01A1) 01-the first of 10 cycles, A-the first segment of A through G segments described in the preceding section of this report, 1-the first subsegment of segment A.
SPEED	Output shaft speed in rpm. 8000 = 52,800 rpm turbine speed.
TURB. DISCH TEMP	Average of eight turbine exhaust-gas temperature measurements in degrees F.
TORQ.	Measured output torque in inch-pounds.
FUEL FLOW	Fuel flow rate in pounds per hour.
FUEL SUP. PRESS PSIG	Fuel supply pressure at the fuel-control inlet, psig.
FUEL NOZ. PRESS	Fuel nozzle pressure at the fuel control outlet, psig.
AMB. TEMP	Average of eight inlet air temperature measurements in degrees F.
COMP PRESS	Compressor discharge pressure, psig.
FUEL TEMP	Fuel temperature at fuel-control inlet in degrees F.
BAR. PRESS	Test-cell barometric pressure in inches of mercury absolute.
VIBR.	Engine vibration peak-to-peak displacement in mils.
HP	Calculated output horsepower.
HP CORR	Output horsepower corrected to sea-level standard day conditions.
DISCH TEMP CORR	Turbine exhaust-gas temperature corrected to standard-day conditions, in degrees F.
FUEL FLOW CORR	Fuel flow rate corrected to sea-level standard-day conditions, pounds per hour.
SFC	Specific fuel consumption in pounds per horsepower-hour and Btu per horsepower-hour.

ENDURANCE ENGINE TEST DATA

FUEL USED SHELLDYNE-H   LOWER HEATING VALUE 17800. BTU/LB

COMBUSTOR TYPE --- SHELLDYNE VAPORIZER ---

TEST NO.	SPEED RPM	TURB. DISCH TEMP F	TORQ. IN-LB	FUEL FLOW PPH	SHELLDYNE-H FUEL SUP. PRESS PSIG	SHELLDYNE-H FUEL NOZ. PRESS PSIG	AMB. TEMP F	COMP PRESS PSIG	FUEL TEMP F	BAR. PRESS IN-LB	VIBR. MILS	HP HP	HP CORR HP	DISCH TEMP CORR F	FUEL FLOW CORR LB-HR	SFC LB/ HP-HR	SFC BTU/ HP-HR
01A1	7960.0	1325.0	397.5	80.00	18.00	146.0	97.0	19.0	90.0	28.65	0.100	50.2	50.6	1234.5	80.6	1.59	28364.3
01A2	8090.0	588.0	0.0	36.90	23.00	103.0	99.0	17.0	90.0	28.65	0.130	0.0	0.0	545.9	36.7	N/A	N/A
01A3	7950.0	1290.0	380.0	77.30	18.00	143.0	101.0	18.0	94.0	28.65	0.110	47.9	48.1	1193.3	77.6	1.61	28705.2
01B1	7940.0	1327.0	392.5	80.00	17.00	146.0	102.0	19.0	97.0	28.65	0.110	49.4	49.6	1225.4	80.2	1.61	28798.0
01B2	8090.0	593.0	0.0	36.50	23.00	104.0	102.0	17.0	97.0	28.65	0.130	0.0	0.0	544.8	36.6	N/A	N/A
01B3	7980.0	1097.0	287.5	66.30	18.00	132.0	105.0	18.0	98.0	28.65	0.120	36.4	36.4	998.4	66.3	1.82	32419.4
01C1	7940.0	1325.0	385.0	80.00	18.00	143.0	106.0	18.0	100.0	28.65	0.110	48.5	48.5	1214.9	80.0	1.64	29359.0
01C2	8080.0	590.0	0.0	36.60	23.00	102.0	103.0	16.9	101.0	28.65	0.120	0.0	0.0	543.6	36.6	N/A	N/A
01C3	7940.0	1320.0	380.0	80.00	18.00	143.0	109.0	18.0	101.0	28.65	0.110	47.8	47.9	1212.4	80.0	1.67	29745.3
01D1	7930.0	1325.0	382.5	80.00	18.00	143.0	105.0	18.0	102.0	28.65	0.100	48.1	48.1	1217.0	80.0	1.66	29588.1
01D2	8080.0	593.0	0.0	36.60	23.00	101.0	104.0	17.0	102.0	28.65	0.120	0.0	0.0	545.6	36.6	N/A	N/A
01D3	8010.0	900.0	190.0	55.00	20.00	119.0	104.0	18.0	103.0	28.65	0.100	24.1	24.1	828.1	55.0	2.27	40542.4
01E1	7930.0	1325.0	377.5	80.00	18.00	142.0	106.0	18.0	104.0	28.65	0.110	47.4	47.4	1214.9	80.0	1.68	29980.0
01E2	8090.0	593.0	0.0	36.60	23.00	100.0	105.0	17.5	104.0	28.65	0.140	0.0	0.0	544.6	36.6	N/A	N/A
01E3	7940.0	1309.0	372.5	79.80	17.50	140.0	108.0	18.0	105.0	28.65	0.110	46.9	46.8	1192.3	79.6	1.70	30268.3
01F1	7950.0	1323.0	385.0	80.00	18.00	145.0	104.0	19.0	98.0	28.68	0.130	48.5	48.5	1217.3	80.0	1.64	29322.1
01F2	8080.0	597.0	0.0	36.30	23.00	104.0	103.0	17.0	99.0	28.68	0.130	0.0	0.0	550.3	36.3	N/A	N/A
01F3	8040.0	738.0	95.0	44.50	21.00	110.0	105.0	17.0	100.0	28.68	0.120	12.1	12.1	677.8	44.4	3.67	65360.1
01G1	8280.0	609.0	0.0	36.40	23.00	104.0	104.0	17.0	104.0	28.68	0.120	0.0	0.0	556.7	36.4	N/A	N/A
01G2	7950.0	1325.0	390.0	80.00	18.00	143.0	169.0	19.0	102.0	28.68	0.120	49.1	46.7	1100.1	76.0	1.62	28946.1
01G3	8100.0	595.0	0.0	36.40	25.00	103.0	105.0	17.0	102.0	28.68	0.120	0.0	0.0	546.5	36.3	N/A	N/A
01G4	7950.0	1310.0	375.0	80.00	21.00	140.0	110.0	19.0	103.0	28.68	0.120	47.3	47.0	1192.7	79.6	1.69	30104.0
01G5	8100.0	600.0	0.0	36.50	25.00	103.0	109.0	17.0	104.0	28.68	0.140	0.0	0.0	551.1	36.4	N/A	N/A
01G6	7950.0	1323.0	377.5	81.50	21.00	140.0	108.0	18.0	105.0	28.68	0.130	47.6	47.4	1208.8	81.2	1.71	30465.3
01G7	8090.0	5970.0	0.0	36.50	25.00	102.0	107.0	17.0	105.0	28.68	0.120	0.0	0.0	5464.3	36.4	N/A	N/A
01G8	7950.0	1318.0	377.5	82.30	21.00	141.0	110.0	18.0	105.0	28.68	0.120	47.6	47.4	1200.0	81.9	1.74	30764.4
01G9	8090.0	600.0	0.0	36.50	25.00	103.0	108.0	17.0	106.0	28.68	0.130	0.0	0.0	548.2	36.3	N/A	N/A
01G10	7950.0	1318.0	377.5	82.20	21.00	140.0	110.0	18.0	106.0	28.68	0.120	47.6	47.4	1200.0	81.8	1.72	30727.0
01G11	8090.0	600.0	0.0	36.50	25.00	103.0	109.0	17.0	107.0	28.68	0.130	0.0	0.0	547.2	36.3	N/A	N/A
01G12	7940.0	1323.0	372.5	82.00	21.00	140.0	118.0	18.0	107.0	28.68	0.110	46.9	46.3	1187.8	81.0	1.74	31102.8
01G13	8080.0	603.0	0.0	36.50	25.00	104.0	112.0	17.0	108.0	28.68	0.130	0.0	0.0	547.0	36.2	N/A	N/A
01G14	7940.0	1323.0	372.5	82.30	21.00	140.0	117.0	18.0	108.0	28.68	0.110	46.9	46.4	1189.9	81.4	1.75	31216.6
01G15	8090.0	605.0	0.0	36.30	25.00	102.0	113.0	17.0	109.0	28.68	0.130	0.0	0.0	547.9	36.0	N/A	N/A
01G16	7940.0	1310.0	365.0	81.50	20.00	140.0	119.0	18.0	109.0	28.68	0.110	45.9	45.5	1182.3	80.7	1.77	31548.3
02A1	7940.0	1325.0	385.0	81.00	13.00	140.0	112.0	19.0	106.0	28.54	0.120	48.5	48.4	1202.1	80.8	1.67	29726.0
02A2	8090.0	610.0	0.0	35.00	19.00	95.0	112.0	18.0	107.0	28.54	0.140	0.0	0.0	553.4	34.9	N/A	N/A
02A3	7950.0	1320.0	375.0	80.00	14.00	135.0	120.0	19.0	109.0	28.54	0.110	47.3	46.9	1181.1	79.3	1.69	30104.0
02B1	7940.0	1325.0	390.0	81.00	13.00	140.0	110.0	19.0	108.0	28.54	0.110	49.1	49.1	1206.3	81.0	1.64	29344.9
02B2	8050.0	600.0	0.0	42.00	19.00	105.0	108.0	18.0	103.0	28.54	0.170	0.0	0.0	548.2	42.0	N/A	N/A
02B3	7980.0	1085.0	285.0	65.00	15.00	130.0	110.0	18.0	106.0	28.54	0.120	36.0	36.0	987.8	65.0	1.80	32062.5

FIGURE 69

ENDURANCE ENGINE TEST DATA

FUEL USED SHELLDYNE-H   LOWER HEATING VALUE 17800. BTU/LB

COMBUSTOR TYPE --- SHELLDYNE VAPORIZER ---

TEST NO.	SPEED RPM	TURB. DISCH TEMP F	TORQ. IN-LB	FUEL FLOW PPH	FUEL SUP. PRESS PSIG	SHELLDYNE-H FUEL NOZ. PRESS PSIG	AMB. TEMP F	COMP PRESS PSIG	FUEL TEMP F	BAR. PRESS IN-LB	VIBR. MILS	HP HP	HP CORR HP	DISCH TEMP CORR F	FUEL FLOW CORR LB-HR	SFC LB/ HP-HR	SFC BTU/ HP-HR
02C1	7930.0	1325.0	380.0	80.00	13.00	145.0	112.0	19.0	107.0	28.54	0.100	47.8	47.7	1202.1	79.8	1.67	29782.8
02C2	8090.0	605.0	0.0	44.00	18.50	130.0	109.0	17.0	108.0	28.54	0.170	0.0	0.0	551.8	44.0	N/A	N/A
02C3	7930.0	1315.0	380.0	80.00	13.50	145.0	110.0	19.0	108.0	28.54	0.110	47.8	47.8	1197.2	80.0	1.67	29782.8
02D1	7930.0	1325.0	385.0	80.50	13.50	145.0	112.0	19.0	108.0	28.54	0.110	48.4	48.3	1202.1	80.3	1.66	29579.7
02D2	8090.0	605.0	0.0	44.00	18.50	100.0	109.0	18.0	107.0	28.54	0.160	0.0	0.0	551.8	44.0	N/A	N/A
02D3	8000.0	895.0	290.0	55.00	15.50	130.0	108.0	18.5	106.0	28.54	0.160	36.8	36.8	817.7	55.1	1.49	26595.4
02E1	7920.0	1325.0	390.0	80.50	12.50	145.0	106.0	19.0	106.0	28.54	0.120	49.0	49.1	1214.9	80.8	1.64	29237.4
02E2	8070.0	600.0	0.0	44.00	18.50	105.0	105.0	18.5	107.0	28.54	0.150	0.0	0.0	551.1	44.2	N/A	N/A
02E3	7930.0	1300.0	380.0	80.30	13.00	140.0	108.0	19.0	106.0	28.54	0.110	47.8	47.9	1187.7	80.4	1.67	29894.5
02F1	7920.0	1325.0	387.5	80.50	12.50	145.0	108.0	19.0	106.0	28.54	0.110	48.6	48.7	1210.6	80.6	1.65	29428.0
02F2	8090.0	605.0	0.0	44.00	18.00	100.0	106.0	18.5	105.0	28.54	0.170	0.0	0.0	554.7	44.1	N/A	N/A
02F3	8030.0	725.0	95.0	51.00	14.00	110.0	104.0	18.5	106.0	28.54	0.150	12.1	12.1	667.1	51.2	4.21	75000.4
02G1	8110.0	590.0	0.0	38.00	18.00	100.0	98.0	17.5	100.0	28.54	0.170	0.0	0.0	548.7	38.4	N/A	N/A
02G2	7920.0	1323.0	385.0	80.00	13.50	145.0	103.0	19.5	102.0	28.54	0.110	48.3	48.6	1219.5	80.5	1.65	29433.1
02G3	8115.0	600.0	0.0	38.50	18.50	100.0	98.0	18.5	102.0	28.54	0.150	0.0	0.0	558.0	38.9	N/A	N/A
02G4	7930.0	1325.0	392.5	80.00	14.00	148.0	103.0	19.0	102.0	28.54	0.110	49.3	49.7	1221.3	80.5	1.61	28834.3
02G5	8090.0	595.0	0.0	38.50	18.50	105.0	99.0	18.0	102.0	28.54	0.140	0.0	0.0	552.4	38.8	N/A	N/A
02G6	7910.0	1320.0	390.0	80.00	14.00	140.0	102.0	19.5	101.0	28.54	0.110	48.9	49.3	1218.9	80.5	1.63	29092.5
02G7	8060.0	595.0	0.0	38.50	19.00	105.0	101.0	18.5	101.0	28.54	0.150	0.0	0.0	550.4	38.8	N/A	N/A
02G8	7910.0	1325.0	385.0	80.00	14.00	140.0	101.0	19.5	101.0	28.54	0.110	48.3	48.7	1225.7	80.6	1.65	29470.3
02G9	8070.0	595.0	0.0	38.50	19.50	105.0	100.0	18.5	100.0	28.54	0.150	0.0	0.0	551.4	38.8	N/A	N/A
02G10	7920.0	1320.0	385.0	80.00	14.00	145.0	102.0	19.5	100.0	28.54	0.110	48.3	48.7	1218.9	80.5	1.65	29433.1
02G11	8050.0	590.0	0.0	35.50	19.50	105.0	102.0	19.0	100.0	28.54	0.150	0.0	0.0	544.8	35.7	N/A	N/A
02G12	7920.0	1315.0	385.0	78.50	14.00	145.0	96.0	19.5	99.0	28.54	0.110	48.3	49.0	1227.4	79.5	1.62	28881.3
02G13	8070.0	590.0	0.0	35.50	19.50	100.0	96.0	19.0	99.0	28.54	0.150	0.0	0.0	550.7	35.9	N/A	N/A
02G14	7920.0	1320.0	385.0	77.50	14.00	145.0	97.0	19.0	99.0	28.54	0.110	48.3	48.9	1229.8	78.4	1.60	28513.3
02G15	8040.0	590.0	0.0	35.50	19.50	100.0	97.0	19.0	98.0	28.54	0.150	0.0	0.0	549.7	35.9	N/A	N/A
02G16	7920.0	1320.0	390.0	77.50	14.00	145.0	98.0	19.5	98.0	28.54	0.110	49.0	49.5	1227.6	78.3	1.58	28147.8
03A1	7920.0	1320.0	387.5	77.50	14.00	145.0	98.0	19.5	98.0	28.60	0.110	48.6	49.1	1227.6	78.1	1.59	28329.4
03A2	8050.0	590.0	0.0	35.00	19.50	105.0	97.0	19.5	98.0	28.60	0.130	0.0	0.0	549.7	35.3	N/A	N/A
03A3	7930.0	1290.0	377.5	77.20	14.50	143.0	98.0	20.0	98.0	28.60	0.110	47.4	47.9	1199.7	77.8	1.62	28930.7
03B1	7910.0	1315.0	390.0	77.40	14.50	145.0	98.0	20.0	98.0	28.60	0.110	48.9	49.3	1223.0	78.0	1.58	28147.0
03B2	8050.0	595.0	0.0	35.20	19.50	100.0	96.0	19.5	98.0	28.60	0.140	0.0	0.0	555.3	35.5	N/A	N/A
03B3	7950.0	1075.0	285.0	63.70	15.50	135.0	95.0	20.0	98.0	28.60	0.110	35.9	36.3	1005.2	64.4	1.77	31539.9
03C1	7910.0	1315.0	390.0	77.40	14.00	142.0	96.0	20.0	98.0	28.60	0.110	48.9	49.4	1227.4	78.2	1.58	28147.0
03C2	8060.0	590.0	0.0	35.20	18.50	100.0	96.0	19.0	98.0	28.60	0.150	0.0	0.0	550.7	35.5	N/A	N/A
03C3	7920.0	1290.0	380.0	77.00	10.50	145.0	96.0	20.0	95.0	28.60	0.110	47.7	48.2	1204.1	77.8	1.61	28702.1
03D1	7920.0	1325.0	392.5	77.50	10.50	150.0	96.0	20.0	96.0	28.60	0.120	49.3	49.8	1236.7	78.3	1.57	27968.5
03D2	8060.0	595.0	0.0	35.00	18.00	100.0	96.0	19.0	96.0	28.60	0.140	0.0	0.0	555.3	35.3	N/A	N/A
03D3	7790.0	880.0	185.0	49.00	16.00	120.0	96.0	19.5	96.0	28.60	0.110	22.8	23.1	821.4	49.5	2.14	38143.4

FIGURE 70

ENDURANCE ENGINE TEST DATA

FUEL USED SHELLDYNE-H   LOWER HEATING VALUE 17800. BTU/LB

COMBUSTOR TYPE --- SHELLDYNE VAPORIZER ---

						SHELLDYNE-H											
TEST NO.	SPEFD RPM	TURB. DISCH TEMP F	TORQ. IN-LB	FUEL FLOW PPH	FUEL SUP. PRESS PSIG	FUEL NOZ. PRESS PSIG	AMB. TEMP F	COMP PRESS PSIG	FUEL TEMP F	BAR. PRESS IN-LB	VIBR. MILS	HP HP	HP CORR HP	DISCH TEMP CORR F	FUEL FLOW CORR LB-HR	SFC LB/ HP-HR	SFC BTU/ HP-HR
03E1	7910.0	1322.0	387.5	77.50	12.50	150.0	98.0	20.0	96.0	28.60	0.110	48.6	49.0	1229.5	78.1	1.59	28365.2
03E2	8070.0	590.0	0.0	35.00	18.50	110.0	93.0	19.0	96.0	28.60	0.140	0.0	0.0	553.7	35.4	N/A	N/A
03E3	7920.0	1295.0	380.0	77.00	12.50	145.0	96.0	20.0	96.0	28.60	0.110	47.7	48.2	1208.7	77.8	1.61	28702.4
03F1	7920.0	1300.0	372.5	77.30	13.00	148.0	100.0	18.0	94.0	28.60	0.120	46.8	47.1	1204.7	77.8	1.65	29394.1
03F2	8040.0	585.0	0.0	37.00	14.50	100.0	94.0	19.0	92.0	28.60	0.140	0.0	0.0	548.0	37.4	N/A	N/A
03F3	8010.0	715.0	95.0	44.00	13.50	110.0	95.0	19.0	90.0	28.60	0.130	12.0	12.2	668.5	44.5	3.64	64867.8
03G1	8050.0	590.0	0.0	39.50	23.00	103.0	98.0	18.0	95.0	28.60	0.140	0.0	0.0	548.7	39.8	N/A	N/A
03G2	7930.0	1215.0	337.5	71.30	14.00	140.0	100.0	18.0	95.0	28.60	0.110	42.4	42.7	1125.9	71.8	1.67	29888.5
03G3	8060.0	593.0	0.0	39.50	23.00	101.0	100.0	17.0	96.0	28.60	0.150	0.0	0.0	549.5	39.7	N/A	N/A
03G4	7920.0	1323.0	352.5	78.80	15.00	138.0	109.0	18.0	100.0	28.67	0.120	44.2	44.1	1206.6	78.5	1.77	31684.8
03G5	8080.0	615.0	0.0	35.00	20.00	100.0	109.0	17.5	102.0	28.67	0.140	0.0	0.0	560.9	34.8	N/A	N/A
03G6	7930.0	1325.0	357.5	78.90	15.00	143.0	110.0	18.5	102.0	28.67	0.120	44.9	44.7	1206.3	78.5	1.75	31222.0
03G7	8070.0	615.0	0.0	35.00	20.00	100.0	109.0	17.5	104.0	28.67	0.140	0.0	0.0	560.9	34.8	N/A	N/A
03G8	7920.0	1325.0	350.0	78.80	15.00	143.0	113.0	18.0	105.0	28.67	0.120	43.9	43.6	1200.0	78.2	1.79	31890.8
03G9	8080.0	617.0	0.0	35.00	20.00	100.0	110.0	17.5	105.0	28.67	0.140	0.0	0.0	561.7	34.8	N/A	N/A
03G10	7910.0	1325.0	350.0	78.50	15.50	142.0	111.0	18.5	105.0	28.67	0.120	43.9	43.7	1204.2	78.1	1.78	31809.5
03G11	8070.0	620.0	0.0	35.00	20.00	100.0	111.0	17.5	106.0	28.67	0.150	0.0	0.0	563.5	34.8	N/A	N/A
03G12	7920.0	1325.0	350.0	78.50	15.50	141.0	111.0	18.5	105.0	28.67	0.130	43.9	43.7	1204.2	78.1	1.78	31769.4
03G13	8070.0	618.0	0.0	35.00	20.00	100.0	109.0	18.0	105.0	28.67	0.150	0.0	0.0	563.6	34.8	N/A	N/A
03G14	7910.0	1325.0	352.5	78.50	15.50	144.0	111.0	18.5	106.0	28.67	0.130	44.2	44.0	1204.2	78.1	1.77	31583.9
03G15	8080.0	616.0	0.0	35.00	20.00	100.0	110.0	17.5	106.0	28.61	0.150	0.0	0.0	560.8	34.9	N/A	N/A
03G16	7920.0	1325.0	350.0	78.50	15.50	146.0	112.0	19.0	106.0	28.61	0.120	43.9	43.8	1202.1	78.1	1.78	31769.4
04A1	7920.0	1325.0	347.5	77.50	15.50	142.0	112.0	18.7	106.0	28.61	0.120	43.6	43.4	1202.1	77.2	1.77	31590.3
04A2	8070.0	619.0	0.0	35.50	20.00	100.0	110.0	18.0	106.0	28.61	0.150	0.0	0.0	563.5	35.4	N/A	N/A
04A3	7091.0	1325.0	347.5	77.70	15.50	143.0	111.0	18.7	107.0	28.61	0.120	39.0	38.9	1204.2	77.4	1.98	35374.8
04B1	7092.0	1325.0	347.5	77.50	15.50	143.0	114.0	19.0	107.0	28.61	0.120	39.1	38.8	1197.9	77.0	1.98	35278.5
04B2	8090.0	630.0	0.0	35.00	20.00	100.0	113.0	18.0	107.0	28.61	0.160	0.0	0.0	570.5	34.8	N/A	N/A
04B3	7940.0	1055.0	285.0	68.50	16.30	132.0	110.0	18.5	107.0	28.61	0.130	35.9	35.8	960.5	68.3	1.90	33959.2
04C1	7910.0	1325.0	350.0	77.50	15.20	142.0	111.0	18.5	107.0	28.61	0.130	43.9	43.7	1204.2	77.2	1.76	31404.3
04C2	8070.0	620.0	0.0	35.50	20.00	100.0	108.0	18.0	107.0	28.61	0.150	0.0	0.0	566.4	35.4	N/A	N/A
04C3	7920.0	1325.0	352.5	77.50	15.50	144.0	110.0	18.5	107.0	28.61	0.120	44.2	44.2	1206.3	77.3	1.74	31142.2
04D1	7920.0	1325.0	355.0	77.50	15.00	145.0	110.0	18.5	107.0	28.61	0.120	44.6	44.5	1206.3	77.3	1.73	30922.9
04D2	8070.0	619.0	0.0	35.50	19.00	100.0	106.0	18.0	106.0	28.61	0.150	0.0	0.0	566.6	35.5	N/A	N/A
04D3	7970.0	935.0	190.0	55.00	16.00	120.0	107.0	18.5	106.0	28.61	0.150	24.0	24.0	855.8	55.0	2.28	40745.8
04E1	7910.0	1325.0	352.5	77.50	13.00	143.0	107.0	18.7	106.0	28.61	0.130	44.2	44.2	1212.7	77.5	1.75	31181.6
04E2	8060.0	615.0	0.0	35.50	16.50	100.0	105.0	17.5	106.0	28.61	0.140	0.0	0.0	564.9	35.5	N/A	N/A
04E3	7910.0	1310.0	350.0	76.00	13.00	142.0	108.0	18.5	105.0	28.61	0.130	43.9	43.9	1196.9	75.9	1.73	30796.5
04F1	7920.0	1325.0	357.5	77.50	12.50	146.0	106.0	18.5	105.0	28.61	0.130	44.9	44.9	1214.9	77.6	1.74	30706.7
04F2	8060.0	610.0	0.0	35.00	15.50	100.0	104.0	18.0	105.0	28.61	0.140	0.0	0.0	561.3	35.1	N/A	N/A
04F3	8020.0	715.0	95.0	44.50	15.00	110.0	103.0	18.0	105.0	28.61	0.130	12.0	12.1	659.0	44.6	3.68	65525.1

FIGURE 71

ENDURANCE ENGINE TEST DATA

FUEL USED SHELLDYNE-H   LOWER HEATING VALUE 17800. BTU/LB

COMBUSTOR TYPE --- SHELLDYNE VAPORIZER ---

						SHELLDYNE-H											
TEST NO.	SPEED RPM	TURB. DISCH TEMP F	TORQ. IN-LB	FUEL FLOW PPH	FUEL SUP. PRESS PSIG	FUEL NOZ. PRESS PSIG	AMB. TEMP F	COMP PRESS PSIG	FUEL TEMP F	BAR. PRESS IN-LB	VIBR. MILS	HP HP	HP CORR HP	DISCH TEMP CORR F	FUEL FLOW CORR LB-HR	SFC LB/HP-HR	SFC BTU/HP-HR
04G1	8050.0	607.0	0.0	33.50	18.50	109.0	100.0	18.0	97.0	28.61	0.160	0.0	0.0	562.5	33.7	N/A	N/A
04G2	7920.0	1325.0	360.0	77.50	14.50	146.0	102.0	19.0	99.0	28.61	0.130	45.2	45.4	1223.5	77.8	1.71	30493.4
04G3	8050.0	612.0	0.0	33.50	19.50	109.0	102.0	18.0	100.0	28.66	0.140	0.0	0.0	565.1	33.6	N/A	N/A
04G4	7910.0	1325.0	363.7	80.00	15.00	145.0	103.0	18.5	102.0	28.66	0.130	45.6	45.7	1221.3	80.1	1.75	31192.0
04G5	8040.0	610.0	0.0	33.50	19.50	107.0	101.0	18.0	102.0	28.66	0.140	0.0	0.0	564.3	33.6	N/A	N/A
04G6	7900.0	1325.0	365.0	80.00	15.00	146.0	101.0	18.5	102.0	28.66	0.120	45.7	45.9	1225.7	80.3	1.74	31124.5
04G7	8040.0	610.0	0.0	33.50	20.00	110.0	102.0	18.0	102.0	28.66	0.130	0.0	0.0	563.3	33.6	N/A	N/A
04G8	7091.0	1325.0	360.0	79.00	15.00	140.0	106.0	18.5	103.0	28.66	0.120	40.5	40.4	1214.9	78.9	1.95	34717.6
04G9	8080.0	610.0	0.0	33.50	20.00	100.0	103.0	18.2	102.0	28.66	0.140	0.0	0.0	562.3	33.5	N/A	N/A
04G10	7920.0	1325.0	362.5	79.00	15.00	142.0	105.0	18.5	103.0	28.66	0.120	45.5	45.5	1217.0	79.0	1.73	30869.3
04G11	8050.0	610.0	0.0	33.50	20.00	105.0	104.0	18.0	103.0	28.66	0.130	0.0	0.0	561.3	33.5	N/A	N/A
04G12	7910.0	1325.0	362.5	79.00	15.00	143.0	105.0	18.7	104.0	28.66	0.120	45.4	45.5	1217.0	79.0	1.73	30908.3
04G13	8070.0	612.0	0.0	33.50	20.00	100.0	103.0	18.2	103.0	28.66	0.140	0.0	0.0	564.1	33.5	N/A	N/A
04G14	7910.0	1325.0	360.0	77.50	15.00	146.0	104.0	18.5	104.0	28.66	0.120	45.1	45.2	1219.2	77.6	1.71	30532.0
04G15	8080.0	610.0	0.0	32.50	20.00	100.0	101.0	18.0	102.0	28.66	0.140	0.0	0.0	564.3	32.6	N/A	N/A
04G16	7910.0	1325.0	362.5	77.50	15.00	146.0	102.0	18.5	104.0	28.66	0.120	45.4	45.6	1223.5	77.7	1.70	30321.4
05A1	7910.0	1325.0	360.0	77.50	15.20	147.0	102.0	18.5	103.0	28.69	0.120	45.1	45.2	1223.5	77.6	1.71	30532.0
05A2	8080.0	614.0	0.0	33.50	20.00	100.0	102.0	18.2	102.0	28.69	0.140	0.0	0.0	566.9	33.5	N/A	N/A
05A3	7910.0	1325.0	362.5	77.50	15.20	146.0	104.0	18.5	103.0	28.69	0.120	45.4	45.5	1219.2	77.5	1.70	30322.4
05B1	7910.0	1325.0	365.0	77.50	12.50	147.0	104.0	18.5	103.0	28.69	0.120	45.8	45.8	1219.2	77.5	1.69	30113.7
05B2	8030.0	614.0	0.0	33.50	18.50	110.0	103.0	18.0	102.0	28.69	0.140	0.0	0.0	565.9	33.5	N/A	N/A
05B3	7950.0	1045.0	285.0	65.50	13.00	130.0	102.0	18.5	102.0	28.69	0.120	35.9	36.0	965.0	65.6	1.82	32431.1
05C1	7910.0	1322.0	370.0	77.20	11.50	150.0	95.0	19.0	91.0	28.71	0.120	46.4	46.7	1236.2	77.7	1.66	29591.8
05C2	8030.0	610.0	0.0	35.00	16.00	100.0	95.0	18.5	91.0	28.71	0.130	0.0	0.0	570.4	35.2	N/A	N/A
05C3	7910.0	1300.0	365.0	77.20	11.00	148.0	97.0	19.0	94.0	28.71	0.120	45.8	46.0	1211.2	77.6	1.68	29997.2
05D1	7900.0	1315.0	375.0	77.20	11.00	148.0	97.0	19.0	95.0	28.71	0.130	47.0	47.2	1225.2	77.6	1.64	29234.2
05D2	8030.0	590.0	0.0	31.50	19.00	110.0	95.0	18.5	93.0	28.71	0.140	0.0	0.0	551.7	31.7	N/A	N/A
05D3	7970.0	910.0	190.0	55.00	16.50	120.0	96.0	19.0	93.0	28.71	0.160	24.0	24.1	849.4	55.3	2.28	40745.8
05E1	7910.0	1315.0	370.0	77.20	13.50	145.0	97.0	19.0	95.0	28.71	0.150	46.4	46.7	1225.2	77.6	1.66	29591.8
05E2	8090.0	610.0	0.0	33.50	19.00	100.0	98.0	18.5	95.0	28.71	0.150	0.0	0.0	567.3	33.6	N/A	N/A
05E3	7920.0	1315.0	375.0	77.30	14.50	145.0	98.0	19.0	99.0	28.71	0.150	47.1	47.3	1223.0	77.6	1.64	29198.1
05F1	7910.0	1300.0	375.0	77.20	14.50	145.0	92.0	19.5	90.0	28.79	0.140	47.0	47.4	1222.2	77.7	1.64	29197.2
05F2	8060.0	595.0	0.0	33.50	19.00	102.0	96.0	18.5	92.0	28.71	0.130	0.0	0.0	557.3	33.7	N/A	N/A
05F3	8030.0	720.0	95.0	41.60	18.00	112.0	93.0	19.0	92.0	28.71	0.160	12.1	12.2	675.7	41.9	3.43	61176.8
05G1	8080.0	595.0	0.0	33.50	19.00	100.0	92.0	18.8	90.0	28.79	0.130	0.0	0.0	559.4	33.7	N/A	N/A
05G2	7920.0	1300.0	367.5	77.20	14.00	145.0	94.0	19.5	92.0	28.79	0.120	46.1	46.4	1217.8	77.6	1.67	29755.5
05G3	8060.0	590.0	0.0	35.00	19.00	100.0	92.0	18.8	93.0	28.79	0.140	0.0	0.0	554.7	35.2	N/A	N/A
05G4	7910.0	1305.0	370.0	77.20	14.00	145.0	93.0	19.5	92.0	28.79	0.120	46.4	46.7	1224.7	77.7	1.66	29591.8
05G5	8070.0	590.0	0.0	35.00	19.00	100.0	93.0	18.8	93.0	28.79	0.140	0.0	0.0	553.7	35.2	N/A	N/A
05G6	7910.0	1320.0	367.5	77.20	12.50	145.0	95.0	19.5	92.0	28.79	0.120	46.1	46.3	1234.3	77.5	1.67	29793.1

FIGURE 72

ENDURANCE ENGINE TEST DATA

FUEL USED SHELLDYNE-H   LOWER HEATING VALUE 17800. BTU/LB

COMBUSTOR TYPE --- SHELLDYNE VAPORIZER ---

TEST NO.	SPEED RPM	TURB. DISCH- TEMP F	TORQ. IN-LB	FUEL FLOW PPH	FUEL SUP. PRESS PSIG	SHELLDYNE-H FUEL NOZ. PRESS PSIG	AMB. TEMP F	COMP PRESS PSIG	FUEL TEMP F	BAR. PRESS IN-LB	VIBR. MILS	HP HP	HP CORR HP	DISCH TEMP CORR F	FUEL FLOW CORR LB-HR	SFC LB/ HP-HR	SFC BTU/ HP-HR
05G7	8070.0	590.0	0.0	35.00	19.00	100.0	93.0	19.0	93.0	28.79	0.130	0.0	0.0	553.7	35.2	N/A	N/A
05G8	7900.0	1322.0	380.0	77.50	14.50	148.0	95.0	19.0	93.0	28.79	0.140	47.6	47.8	1236.2	77.8	1.64	28961.6
05G9	8060.0	600.0	0.0	35.00	19.00	100.0	94.0	18.5	94.0	28.79	0.130	0.0	0.0	562.0	35.2	N/A	N/A
05G10	7910.0	1325.0	377.5	80.00	13.50	148.0	96.0	19.0	94.0	28.79	0.120	47.3	47.5	1236.7	80.3	1.68	30055.8
05G11	8040.0	598.0	0.0	34.20	19.50	108.0	95.0	18.0	94.0	28.79	0.130	0.0	0.0	559.1	34.3	N/A	N/A
05G12	7910.0	1325.0	372.5	78.20	13.50	148.0	97.0	18.5	95.0	28.79	0.130	46.7	46.8	1234.5	78.4	1.67	29773.9
05G13	8040.0	601.0	0.0	34.20	19.50	108.0	95.0	18.0	94.0	28.79	0.130	0.0	0.0	561.9	34.3	N/A	N/A
05G14	7910.0	1325.0	372.5	78.20	13.50	148.0	97.0	19.0	94.0	28.79	0.130	46.7	46.8	1234.5	78.4	1.67	29773.9
05G15	8040.0	603.0	0.0	34.20	19.50	108.0	96.0	18.0	94.0	28.79	0.130	0.0	0.0	562.8	34.3	N/A	N/A
05G16	7910.0	1325.0	372.5	78.40	13.50	148.0	97.0	19.0	95.0	28.79	0.130	46.7	46.6	1234.5	78.6	1.67	29850.1
06A1	7910.0	1325.0	372.5	82.50	18.00	148.0	98.0	19.0	93.0	28.73	0.130	46.7	46.9	1232.3	82.8	1.76	31411.1
06A2	8080.0	613.0	0.0	34.30	23.00	102.0	97.0	18.5	96.0	28.73	0.120	0.0	0.0	561.8	34.4	N/A	N/A
06A3	7920.0	1323.0	365.0	79.50	18.00	147.0	102.0	19.0	98.0	28.73	0.130	45.8	45.9	1221.7	79.5	1.73	30851.9
06B1	7920.0	1325.0	367.5	78.80	18.50	147.0	103.0	19.0	100.0	28.73	0.130	46.1	46.1	1221.3	78.7	1.70	30374.4
06B2	8100.	613.0	0.0	34.30	23.00	100.0	102.0	18.3	100.0	28.73	0.140	0.0	0.0	566.0	34.3	N/A	N/A
06B3	7960.0	1125.0	285.0	67.00	21.00	133.0	104.0	18.5	101.0	28.73	0.140	35.9	35.9	1044.3	66.9	1.86	33134.1
06C1	7910.0	1325.0	362.5	78.80	18.50	143.0	106.0	19.0	102.0	28.73	0.140	45.4	45.3	1214.9	78.5	1.73	30830.0
06C2	8050.0	613.0	0.0	34.30	23.00	100.0	104.0	18.3	102.0	28.73	0.150	0.0	0.0	564.0	34.2	N/A	N/A
06C3	7910.0	1325.0	360.0	78.00	20.00	140.0	107.0	18.5	103.0	28.73	0.140	45.1	45.0	1212.7	77.7	1.72	30729.0
06D1	7920.0	1325.0	362.5	78.00	20.50	140.0	107.0	18.4	104.0	28.73	0.130	45.5	45.3	1212.7	77.7	1.71	30478.5
06D2	8050.0	613.0	0.0	34.30	23.00	100.0	105.0	18.3	104.0	28.73	0.150	0.0	0.0	563.0	34.2	N/A	N/A
06D3	7980.0	943.0	192.5	56.50	23.00	125.0	105.0	18.4	104.0	28.73	0.140	24.3	24.3	866.1	56.3	2.31	41266.7
06E1	7910.0	1325.0	360.0	78.80	20.00	144.0	107.0	18.5	105.0	28.73	0.140	45.1	45.0	1212.7	78.5	1.74	31044.1
06E2	8090.0	615.0	0.0	35.00	25.00	100.0	106.0	18.0	105.0	28.73	0.150	0.0	0.0	563.9	34.9	N/A	N/A
06E3	7920.0	1325.0	370.0	81.00	19.50	146.0	106.0	18.5	100.0	28.73	0.120	46.4	46.3	1214.9	80.7	1.74	31039.2
06F1	7920.0	1323.0	362.5	81.00	19.50	146.0	106.0	18.5	100.0	28.73	0.130	45.5	45.4	1213.0	80.7	1.77	31650.8
06F2	8080.0	617.0	0.0	35.00	24.50	100.0	107.0	18.0	106.0	28.73	0.140	0.0	0.0	564.7	34.8	N/A	N/A
06F3	8030.0	763.0	95.0	45.30	22.00	109.0	109.0	18.0	104.0	28.73	0.140	12.1	12.0	695.9	45.0	3.74	66610.0
06G1	8030.0	617.0	0.0	35.70	23.00	104.0	107.0	17.8	105.0	28.73	0.140	0.0	0.0	564.7	35.5	N/A	N/A
06G2	7910.0	1325.0	367.5	80.30	17.50	143.0	107.0	18.5	102.0	28.73	0.120	46.1	45.9	1212.7	80.0	1.74	30989.5
06G3	8050.0	615.0	0.0	34.60	23.00	106.0	107.0	17.8	103.0	28.75	0.130	0.0	0.0	562.9	36.4	N/A	N/A
06G4	7900.0	1320.0	365.0	81.60	20.00	146.0	108.0	18.5	104.0	28.75	0.130	45.7	45.5	1206.0	81.1	1.78	31747.0
06G5	8050.0	613.0	0.0	36.70	23.00	105.0	108.0	17.8	105.0	28.75	0.140	0.0	0.0	560.0	36.5	N/A	N/A
06G6	7910.0	1323.0	365.0	81.20	20.00	144.0	108.0	18.5	105.0	28.75	0.130	45.8	45.5	1208.8	80.7	1.77	31551.4
06G7	8040.0	610.0	0.0	36.50	23.00	106.0	106.0	17.7	106.0	28.75	0.150	0.0	0.0	559.3	36.3	N/A	N/A
06G8	7900.0	1321.0	365.0	81.10	20.00	143.0	109.0	18.2	106.0	28.75	0.140	45.7	45.4	1204.8	80.6	1.77	31552.5
06G9	8060.0	612.0	0.0	36.50	23.00	105.0	107.0	17.5	106.0	28.75	0.150	0.0	0.0	560.1	36.3	N/A	N/A
06G10	7910.0	1320.0	367.5	81.30	20.00	144.0	108.0	18.0	105.0	28.75	0.140	46.1	45.8	1206.0	80.8	1.76	31375.4
06G11	8050.0	608.0	0.0	36.00	23.00	105.0	108.0	17.5	106.0	28.75	0.140	0.0	0.0	555.5	35.8	N/A	N/A
06G12	7920.0	1320.0	367.5	81.00	19.00	143.0	109.0	18.0	106.0	28.75	0.140	46.1	45.8	1203.9	80.5	1.75	31220.1

FIGURE 73

ENDURANCE ENGINE TEST DATA

FUEL USED SHELLDYNE-H   LOWER HEATING VALUE 17800. BTU/LB

COMBUSTOR TYPE --- SHELLDYNE VAPORIZER ---

TEST NO.	SPEED RPM	TURB. DISCH TEMP F	TORQ. IN-LB	FUEL FLOW PPH	FUEL SUP. PRESS PSIG	SHELLDYNE-H FUEL NOZ. PRESS PSIG	AMB. TEMP F	COMP PRESS PSIG	FUEL TEMP F	BAR. PRESS IN-LB	VIBR. MILS	HP HP	HP CORR HP	DISCH TEMP CORR F	FUEL FLOW CORR LB-HR	SFC LB/ HP-HR	SFC BTU/ HP-HR
06G13	8050.0	610.0	0.0	36.00	22.00	109.0	107.0	17.5	106.0	28.75	0.140	0.0	0.0	558.3	35.8	N/A	N/A
06G14	7920.0	1323.0	367.5	80.00	17.50	142.0	108.0	18.0	106.0	28.75	0.130	46.1	45.9	1208.8	79.5	1.73	30834.7
06G15	8050.0	610.0	0.0	35.00	22.00	105.0	106.0	17.5	106.0	28.75	0.140	0.0	0.0	559.3	34.8	N/A	N/A
06G16	7910.0	1330.0	372.5	81.70	17.00	144.0	107.0	18.5	106.0	28.75	0.130	46.7	46.5	1217.3	81.3	1.74	31106.3
07A1	7920.0	1325.0	370.0	77.50	17.50	146.0	108.0	17.1	104.0	28.71	0.130	46.4	46.3	1210.6	77.2	1.66	29669.3
07A2	8050.0	610.0	0.0	30.50	22.50	110.0	105.0	16.5	104.0	28.71	0.140	0.0	0.0	560.3	30.4	N/A	N/A
07A3	7920.0	1325.0	365.0	76.00	18.00	145.0	108.0	17.5	106.0	28.71	0.130	45.8	45.6	1210.6	75.7	1.65	29493.6
07B1	7920.0	1325.0	370.0	76.00	17.00	144.0	110.0	17.5	109.0	28.71	0.130	46.4	46.2	1206.3	75.5	1.63	29095.0
07B2	8050.0	612.0	0.0	30.50	22.00	110.0	107.0	16.5	106.0	28.71	0.130	0.0	0.0	560.1	30.4	N/A	N/A
07B3	7950.0	1120.0	285.0	62.50	20.50	130.0	108.0	16.9	105.0	28.71	0.130	35.9	35.8	1023.3	62.2	1.73	30945.7
07C1	7920.0	1325.0	367.5	75.50	16.00	143.0	107.0	17.1	105.0	28.71	0.130	46.1	45.0	1212.7	75.2	1.63	29100.4
07C2	8040.0	610.0	0.0	29.50	16.00	110.0	105.0	16.0	104.0	28.71	0.130	0.0	0.0	560.3	29.4	N/A	N/A
07C3	7920.0	1325.0	367.5	74.50	17.00	140.0	107.0	17.0	105.0	28.71	0.130	46.1	46.0	1212.7	74.2	1.61	28714.6
07D1	7910.0	1325.0	367.5	74.50	18.50	148.0	107.0	17.0	103.0	28.71	0.130	46.1	45.9	1212.7	74.2	1.61	28751.1
07D2	8050.0	608.0	0.0	30.00	23.50	110.0	105.0	16.0	103.0	28.71	0.140	0.0	0.0	558.4	29.9	N/A	N/A
07D3	7980.0	935.0	190.0	49.00	20.00	125.0	105.0	17.0	104.0	28.71	0.140	24.0	24.0	858.8	48.9	2.03	36255.3
07E1	7910.0	1325.0	372.5	77.00	17.50	141.0	106.0	17.5	105.0	28.71	0.140	46.7	46.6	1214.9	76.8	1.64	29217.0
07E2	8050.0	605.0	0.0	30.50	22.50	109.0	104.0	16.5	105.0	28.71	0.140	0.0	0.0	556.7	30.4	N/A	N/A
07E3	7910.0	1325.0	367.5	76.50	17.50	145.0	107.0	17.5	105.0	28.71	0.140	46.1	45.9	1212.7	76.2	1.65	29523.0
07F1	7900.0	1325.0	370.0	76.00	17.50	145.0	107.0	17.3	105.0	28.71	0.130	46.3	46.2	1212.7	75.7	1.63	29166.7
07F2	8060.0	608.0	0.0	30.00	22.50	110.0	104.0	16.5	104.0	28.71	0.130	0.0	0.0	559.4	29.9	N/A	N/A
07F3	8010.0	740.0	95.0	40.50	21.00	119.0	103.0	16.8	104.0	28.71	0.150	12.0	12.0	682.1	40.5	3.35	59707.9
07G1	8040.0	600.0	0.0	30.00	22.50	109.0	102.0	16.5	104.0	28.73	0.140	0.0	0.0	554.0	30.0	N/A	N/A
07G2	7910.0	1325.0	370.0	76.00	17.50	147.0	105.0	17.5	104.0	28.73	0.130	46.4	46.3	1217.0	75.8	1.63	29131.6
07G3	8050.0	600.0	0.0	30.00	22.00	109.0	104.0	16.5	104.0	28.73	0.140	0.0	0.0	552.1	29.9	N/A	N/A
07G4	7900.0	1325.0	370.0	76.00	17.00	147.0	104.0	17.2	104.0	28.73	0.130	46.3	46.3	1219.2	75.9	1.63	29166.7
07G5	8040.0	598.0	0.0	29.00	22.50	110.0	98.0	17.0	100.0	28.73	0.140	0.0	0.0	546.8	29.1	N/A	N/A
07G6	7910.0	1325.0	395.0	76.50	16.50	150.0	92.0	18.5	98.0	28.81	0.140	49.5	49.9	1245.7	77.0	1.54	27467.6
07G7	8040.0	575.0	0.0	28.00	22.50	110.0	90.0	17.0	98.0	28.81	0.140	0.0	0.0	542.5	28.2	N/A	N/A
07G8	7900.0	1325.0	400.0	76.50	16.50	150.0	93.0	18.0	97.0	28.81	0.110	50.1	50.4	1243.4	76.9	1.52	27158.5
07G9	8050.0	580.0	0.0	28.00	22.50	110.0	92.0	17.2	95.0	28.81	0.130	0.0	0.0	545.3	28.1	N/A	N/A
07G10	7910.0	1325.0	397.5	76.50	16.50	150.0	94.0	18.0	96.0	28.81	0.120	49.8	50.1	1241.2	76.8	1.53	27294.8
07G11	8050.0	575.0	0.0	28.50	22.50	110.0	91.0	17.0	96.0	28.81	0.130	0.0	0.0	541.5	28.7	N/A	N/A
07G12	7900.0	1325.0	402.5	76.50	16.50	150.0	94.0	18.0	95.0	28.81	0.120	50.4	50.7	1241.2	76.8	1.51	26989.9
07G13	8040.0	575.0	0.0	28.50	22.50	110.0	92.0	17.0	96.0	28.81	0.130	0.0	0.0	540.6	28.6	N/A	N/A
07G14	7900.0	1325.0	400.0	77.00	16.50	150.0	91.0	18.0	96.0	28.81	0.120	50.1	50.5	1248.0	77.6	1.53	27336.1
07G15	8040.0	570.0	0.0	27.50	22.00	110.0	88.0	17.0	94.0	28.81	0.150	0.0	0.0	539.8	27.7	N/A	N/A
07G16	7900.0	1325.0	402.5	77.50	16.50	150.0	92.0	18.0	94.0	28.81	0.120	50.4	50.8	1245.7	78.0	1.53	27342.7
08A1	7910.0	1325.0	400.0	77.50	16.50	150.0	92.0	18.0	92.0	28.84	0.120	50.2	50.5	1245.7	77.9	1.54	27478.6
08A2	8050.0	575.0	0.0	26.50	22.00	110.0	90.0	17.0	93.0	28.84	0.130	0.0	0.0	542.5	26.7	N/A	N/A

FIGURE 74

ENDURANCE ENGINE TEST DATA

FUEL USED SHELLDYNE-H   LOWER HEATING VALUE 17800. BTU/LB

COMBUSTOR TYPE --- SHELLDYNE VAPORIZER ---

TEST NO.	SPEED RPM	TURB. DISCH TEMP F	TORQ. IN-LB	FUEL FLOW PPH	FUEL SUP. PRESS PSIG	SHELLDYNE-H FUEL NOZ. PRESS PSIG	AMB. TEMP F	COMP PRESS PSIG	FUEL TEMP F	BAR. PRESS IN-LB	VIBR. MILS	HP HP	HP CORR HP	DISCH TEMP CORR F	FUEL FLOW CORR LB-HR	SFC LB/ HP-HR	SFC BTU/ HP-HR
08A3	7920.0	1285.0	380.0	71.30	17.50	145.0	90.0	17.8	93.0	28.84	0.120	47.7	48.1	1212.5	71.8	1.49	26577.4
08B1	7910.0	1325.0	405.0	76.50	15.00	449.0	91.0	18.2	92.0	28.84	0.130	50.8	51.1	1248.0	77.0	1.50	26789.3
08B2	8085.0	575.0	0.0	26.50	22.00	110.0	92.0	17.0	93.0	28.84	0.130	0.0	0.0	540.6	26.6	N/A	N/A
08C1	7910.0	1325.0	400.0	76.50	16.50	150.0	92.0	18.0	93.0	28.84	0.140	50.2	50.5	1245.7	76.9	1.52	27124.4
08C2	8040.0	575.0	0.0	26.50	23.00	110.0	90.0	17.0	91.0	28.84	0.140	0.0	0.0	542.5	26.7	N/A	N/A
08C3	7930.0	1270.0	380.0	70.00	17.00	152.0	88.0	18.5	87.0	28.84	0.120	47.8	48.2	1202.7	70.6	1.46	26059.9
08D1	7920.0	1278.0	381.5	70.00	17.00	152.0	89.0	18.5	87.0	28.84	0.120	47.9	48.3	1208.1	70.6	1.46	25990.3
08D2	8080.0	573.0	0.0	26.30	22.50	104.0	96.0	18.0	88.0	28.84	0.130	0.0	0.0	534.8	26.3	N/A	N/A
08D3	7990.0	978.0	190.0	47.50	20.50	125.0	87.0	18.0	90.0	28.84	0.140	24.0	24.3	833.0	48.0	1.97	35101.5
08E1	7910.0	1313.0	395.0	71.40	17.00	153.0	89.0	18.7	90.0	28.84	0.120	49.5	50.0	1241.2	72.0	1.44	25630.4
08E2	8090.0	573.0	0.0	26.40	22.50	105.0	87.0	18.0	90.0	28.84	0.130	0.0	0.0	543.6	26.6	N/A	N/A
08E3	7920.0	1285.0	380.0	71.40	17.00	150.0	89.0	18.5	90.0	28.84	0.130	47.7	48.1	1214.7	72.0	1.49	26614.7
08F1	7920.0	1305.0	387.5	71.40	17.00	150.0	90.0	18.6	90.0	28.84	0.130	48.6	49.0	1231.4	71.9	1.46	26099.6
08F2	8080.0	577.0	0.0	26.50	22.50	104.0	89.0	18.0	90.0	28.84	0.150	0.0	0.0	545.4	26.7	N/A	N/A
08F3	8080.0	717.0	95.0	38.30	21.00	115.0	89.0	17.8	91.0	28.84	0.150	12.1	12.2	677.7	38.6	3.14	55975.3
08G1	8080.0	679.0	0.0	25.30	22.50	103.0	89.0	17.2	93.0	28.84	0.140	0.0	0.0	641.8	28.5	N/A	N/A
08G2	7900.0	1300.0	382.5	71.50	16.50	148.0	92.0	18.0	93.0	28.84	0.140	47.9	48.2	1222.2	71.9	1.49	26544.8
08G3	8090.0	579.0	0.0	28.30	22.50	103.0	90.0	17.0	93.0	28.84	0.140	0.0	0.0	546.3	28.5	N/A	N/A
08G4	7900.0	1300.0	385.0	72.70	17.00	150.0	93.0	18.0	94.0	28.84	0.140	48.2	48.5	1220.0	73.0	1.50	26815.4
08G5	8080.0	585.0	0.0	28.30	22.50	102.0	91.0	17.8	94.0	28.84	0.140	0.0	0.0	551.0	28.4	N/A	N/A
08G6	7910.0	1303.0	380.0	72.70	17.00	150.0	94.0	18.0	94.0	28.84	0.130	47.6	47.8	1220.6	72.9	1.52	27133.3
08G7	8080.0	583.0	0.0	28.30	22.50	102.0	92.0	17.8	94.0	28.84	0.150	0.0	0.0	548.1	28.4	N/A	N/A
08G8	7910.0	1300.0	377.5	72.90	17.00	150.0	94.0	18.0	94.0	28.84	0.140	47.3	47.5	1217.8	73.2	1.53	27306.4
08G9	8080.0	593.0	0.0	28.50	22.50	102.0	93.0	17.8	94.0	28.84	0.150	0.0	0.0	547.1	28.6	N/A	N/A
08G10	7900.0	1300.0	375.0	72.90	17.00	149.0	94.0	17.9	94.0	28.84	0.140	47.0	47.1	1217.8	73.2	1.55	27605.9
08G11	8070.0	585.0	0.0	28.80	23.00	104.0	93.0	17.7	94.0	28.84	0.140	0.0	0.0	549.0	28.9	N/A	N/A
08G13	8080.0	590.0	0.0	28.80	21.50	103.0	95.0	17.8	94.0	28.87	0.140	0.0	0.0	551.7	28.8	N/A	N/A
08G14	7900.0	1323.0	382.5	74.20	16.50	149.0	97.0	18.0	92.0	28.87	0.130	47.9	47.9	1232.6	74.2	1.54	27547.2
08G15	8050.0	593.0	0.0	28.80	22.50	108.0	96.0	17.5	94.0	28.87	0.140	0.0	0.0	553.5	28.8	N/A	N/A
08G16	7900.0	1283.0	362.5	72.80	16.50	150.0	97.0	18.1	94.0	28.87	0.130	45.4	45.4	1195.4	72.8	1.60	28518.6
09A1	7900.0	1285.0	365.0	72.90	16.50	148.0	97.0	18.1	94.0	28.87	0.140	45.7	45.7	1197.2	72.9	1.59	28362.2
09A2	8080.0	593.0	0.0	28.30	22.00	100.0	96.0	17.5	94.0	28.87	0.150	0.0	0.0	553.5	28.3	N/A	N/A
09A3	7900.0	1293.0	365.0	73.00	16.50	148.0	98.0	18.1	96.0	28.87	0.140	45.7	45.7	1202.5	72.9	1.59	28401.1
09B1	7900.0	1300.0	367.5	73.00	16.50	148.0	99.0	18.0	96.0	28.87	0.130	46.0	45.9	1206.9	72.8	1.58	28207.9
09B2	8080.0	594.0	0.0	28.30	22.50	100.0	96.0	17.3	96.0	28.87	0.140	0.0	0.0	554.4	28.3	N/A	N/A
09B3	7940.0	1092.0	285.0	62.50	18.00	135.0	98.0	18.0	94.0	28.87	0.150	35.9	35.8	1015.6	62.4	1.74	30984.7
09C1	7920.0	1300.0	372.5	73.00	16.50	148.0	99.0	18.0	96.0	28.87	0.140	46.8	46.7	1206.9	72.8	1.55	27759.6
09C2	8080.0	600.0	0.0	28.20	23.00	102.0	97.0	17.2	95.0	28.87	0.130	0.0	0.0	559.0	28.2	N/A	N/A
09C3	7920.0	1310.0	372.5	73.00	16.50	147.0	99.0	18.1	95.0	28.87	0.140	46.8	46.7	1216.2	72.8	1.55	27759.0
09D1	7910.0	1308.0	372.5	73.00	16.50	178.0	100.0	18.1	95.0	28.87	0.150	46.7	46.6	1212.1	72.8	1.56	27794.1

FIGURE 75

ENDURANCE ENGINE TEST DATA

FUEL USED SHELLDYNE-H   LOWER HEATING VALUE 17800. BTU/LB

COMBUSTOR TYPE --- SHELLDYNE VAPORIZER ---

TEST NO.	SPEED RPM	TURB. DISCH TEMP F	TORQ. IN-LB	FUEL FLOW PPH	FUEL SUP. PRESS PSIG	SHELLDYNE-H FUEL NOZ. PRESS PSIG	AMB. TEMP F	COMP PRESS PSIG	FUEL TEMP F	BAR. PRESS IN-LB	VIBR. MILS	HP HP	HP CORR HP	DISCH TEMP CORR F	FUEL FLOW CORR LB-HR	SFC LB/ HP-HR	SFC BTU/ HP-HR
09D2	8080.0	600.0	0.0	28.20	23.00	102.0	99.0	17.1	95.0	28.87	0.130	0.0	0.0	561.0	28.2	N/A	N/A
09D3	7980.0	908.0	192.5	50.50	20.00	125.0	99.0	17.5	97.0	28.87	0.130	24.3	24.3	842.9	50.4	2.07	36879.9
09E1	7910.0	1290.0	375.0	73.00	17.50	149.0	99.0	18.0	97.0	28.87	0.130	47.0	46.9	1197.6	72.9	1.55	27608.6
09E2	8070.0	600.0	0.0	28.30	23.00	103.0	98.0	17.5	98.0	28.87	0.130	0.0	0.0	558.0	28.2	N/A	N/A
09E3	7900.0	1325.0	380.0	74.00	17.50	149.0	99.0	18.0	98.0	28.87	0.130	47.6	47.5	1230.1	73.8	1.55	27653.7
09F1	7900.0	1325.0	380.0	73.50	17.30	149.0	101.0	18.0	98.0	28.87	0.130	47.6	47.4	1225.7	73.2	1.54	27466.8
09F2	8050.0	595.0	0.0	28.50	22.50	100.0	98.0	17.2	98.0	28.72	0.140	0.0	0.0	553.3	28.6	N/A	N/A
09F3	8010.0	725.0	95.0	38.30	21.50	120.0	98.0	17.8	98.0	28.72	0.140	12.0	12.1	674.3	38.4	3.17	56464.5
09G1	8070.0	593.0	0.0	29.50	22.50	102.0	96.0	17.5	98.0	28.72	0.000	0.0	0.0	553.5	29.6	N/A	N/A
09G2	7090.0	1325.0	382.5	77.50	17.00	149.0	100.0	18.3	98.0	28.72	0.000	43.0	43.1	1227.9	77.7	1.80	32059.5
09G3	8070.0	594.0	0.0	29.00	22.00	100.0	97.0	17.5	99.0	28.72	0.130	0.0	0.0	553.4	29.1	N/A	N/A
09G4	7900.0	1325.0	385.0	77.50	17.20	148.0	100.0	18.2	99.0	28.72	0.130	48.2	48.3	1227.9	77.7	1.60	28585.5
09G5	8050.0	590.0	0.0	29.30	22.50	105.0	98.0	17.5	95.0	28.72	0.140	0.0	0.0	548.7	29.4	N/A	N/A
09G6	7900.0	1315.0	382.5	77.20	17.00	148.0	100.0	18.5	99.0	28.72	0.130	47.9	48.0	1218.6	77.4	1.61	28661.0
09G7	8050.0	593.0	0.0	29.00	22.50	105.0	97.0	17.6	99.0	28.72	0.140	0.0	0.0	552.5	29.1	N/A	N/A
09G8	7900.0	1325.0	385.0	77.70	17.00	148.0	98.0	18.8	98.0	28.72	0.130	48.2	48.4	1232.3	78.0	1.61	28659.3
09G9	8040.0	580.0	0.0	29.50	22.50	110.0	95.0	17.5	92.0	28.72	0.140	0.0	0.0	542.3	29.7	N/A	N/A
09G10	7920.0	1310.0	382.5	77.50	17.00	149.0	96.0	18.0	94.0	28.72	0.130	48.0	48.3	1222.7	78.0	1.61	28699.7
09G11	8050.0	590.0	0.0	29.50	22.50	110.0	95.0	17.5	96.0	28.72	0.140	0.0	0.0	551.7	29.7	N/A	N/A
09G12	7910.0	1300.0	377.5	77.00	17.00	144.0	95.0	18.0	96.0	28.72	0.150	47.3	47.7	1219.6	77.9	1.62	28928.7
09G13	8050.0	585.0	0.0	30.00	22.00	110.0	94.0	17.5	98.0	28.72	0.140	0.0	0.0	548.0	30.2	N/A	N/A
09G14	7900.0	1310.0	385.0	77.50	16.50	148.0	95.0	18.5	97.0	28.72	0.140	48.2	48.6	1224.9	78.0	1.60	28585.5
09G15	8050.0	580.0	0.0	29.50	22.50	110.0	95.0	17.5	96.0	28.72	0.140	0.0	0.0	542.3	29.7	N/A	N/A
09G16	7900.0	1305.0	385.0	76.80	16.20	149.0	96.0	18.5	97.0	28.72	0.140	48.2	48.5	1218.1	77.2	1.59	28327.3
10A1	7910.0	1305.0	380.0	74.00	16.20	149.0	96.0	18.5	97.0	28.72	0.140	47.6	48.0	1218.1	74.4	1.55	27618.7
10A2	8050.0	590.0	0.0	28.50	22.00	110.0	96.0	17.5	97.0	28.72	0.140	0.0	0.0	550.7	28.6	N/A	N/A
10A3	7920.0	1300.0	380.0	74.50	16.20	147.0	96.0	18.5	96.0	28.72	0.140	47.7	48.0	1213.4	74.9	1.56	27770.2
10B1	7910.0	1300.0	380.0	74.00	16.00	147.0	96.0	18.5	96.0	28.72	0.140	47.6	48.0	1213.4	74.4	1.55	27618.7
10B2	8050.0	589.0	0.0	28.00	22.00	110.0	94.0	17.5	96.0	28.72	0.140	0.0	0.0	551.7	28.2	N/A	N/A
10B3	7950.0	1090.0	285.0	62.50	18.50	135.0	95.0	18.0	96.0	28.72	0.140	35.9	36.2	1019.2	62.9	1.73	30845.7
10C1	7900.0	1310.0	385.0	76.00	16.50	150.0	96.0	18.3	96.0	28.72	0.140	48.2	48.5	1222.7	76.4	1.57	28032.3
10C2	8050.0	575.0	0.0	28.00	21.50	110.0	92.0	17.5	90.0	28.72	0.140	0.0	0.0	540.6	28.2	N/A	N/A
10C3	7910.0	1290.0	380.0	75.50	15.50	149.0	93.0	18.5	92.0	28.72	0.130	47.6	48.1	1210.6	76.1	1.58	28176.6
10D1	7910.0	1305.0	380.0	74.50	15.00	150.0	96.0	18.5	94.0	28.72	0.150	47.6	48.0	1218.1	74.9	1.56	27805.4
10D2	8040.0	587.0	0.0	28.00	19.00	110.0	94.0	17.5	94.0	28.70	0.140	0.0	0.0	549.8	28.2	N/A	N/A
10D3	7970.0	900.0	190.0	49.50	16.50	125.0	94.0	18.0	94.0	28.70	0.160	24.0	24.2	843.1	49.9	2.06	36671.2
10E1	7900.0	1295.0	387.5	77.50	14.00	150.0	92.0	18.5	89.0	28.70	0.150	48.5	49.0	1217.5	78.3	1.59	28401.1
10E2	8060.0	590.0	0.0	28.00	22.50	110.0	92.0	17.5	91.0	28.70	0.140	0.0	0.0	554.7	28.3	N/A	N/A
10E3	7920.0	1300.0	380.0	74.50	18.50	150.0	95.0	18.5	93.0	28.72	0.130	47.7	48.1	1215.6	75.0	1.56	27770.2
10F1	7890.0	1310.0	390.0	76.00	18.00	152.0	96.0	18.5	94.0	28.72	0.130	48.8	49.1	1222.7	76.4	1.55	27707.9

FIGURE 76

ENDURANCE ENGINE TEST DATA

FUEL USED <u>SHELLDYNE-H</u>   LOWER HEATING VALUE 17800. BTU/LB

COMBUSTOR TYPE --- SHELLDYNE VAPORIZER ---

TEST NO.	SPEED	TURB. DISCH TEMP	TORQ.	FUEL FLOW	SHELLDYNE-H FUEL SUP. PRESS	FUEL NOZ. PRESS	AMB. TEMP	COMP PRESS	FUEL TEMP	BAR. PRESS	VIBR.	HP	HP CORR	DISCH TEMP CORR	FUEL FLOW CORR	SFC	SFC
	RPM	F	IN-LB	PPH	PSIG	PSIG	F	PSIG	F	IN-LB	MILS	HP	HP	F	LB-HR	LB/ HP-HR	BTU/ HP-HR
10F2	8040.0	592.0	0.0	29.50	22.00	110.0	93.0	17.0	94.0	28.72	0.130	0.0	0.0	546.1	29.7	N/A	N/A
10F3	8010.0	690.0	95.0	40.00	21.00	118.0	92.0	17.8	94.0	28.72	0.160	12.0	12.1	648.7	40.4	3.31	58970.7
10G1	8030.0	560.0	0.0	30.00	8.00	110.0	79.0	18.0	78.0	28.80	0.130	0.0	0.0	539.2	30.5	N/A	N/A
10G2	7910.0	1290.0	395.0	77.60	2.00	150.0	82.0	19.5	78.0	28.80	0.140	49.5	50.3	1235.2	78.8	1.56	27862.5
10G3	8090.0	560.0	0.0	30.00	17.50	110.0	80.0	18.8	78.0	28.80	0.130	0.0	0.0	538.2	30.5	N/A	N/A
10G4	7910.0	1315.0	410.0	77.80	11.50	155.0	82.0	18.2	78.0	28.80	0.130	51.4	52.3	1259.1	79.0	1.51	26912.0
10G5	8090.0	560.0	0.0	31.00	17.50	110.0	80.0	19.0	78.0	28.80	0.130	0.0	0.0	538.2	31.5	N/A	N/A
10G6	7920.0	1300.0	405.0	78.00	11.00	155.0	82.0	19.5	78.0	28.80	0.120	50.8	51.7	1244.8	79.2	1.53	27280.1
10G7	8090.0	570.0	0.0	31.00	17.50	110.0	80.0	19.0	78.0	28.80	0.130	0.0	0.0	547.8	31.5	N/A	N/A
10G8	7910.0	1310.0	405.0	78.00	11.00	155.0	83.0	19.5	79.0	28.80	0.120	50.8	51.6	1252.0	79.4	1.53	27314.8
10G9	8090.0	565.0	0.0	31.50	17.50	110.0	80.0	19.0	80.0	28.80	0.130	0.0	0.0	543.0	32.0	N/A	N/A
10G10	7900.0	1300.0	405.0	78.00	11.00	155.0	82.0	19.5	80.0	28.80	0.130	50.7	51.6	1244.8	79.2	1.53	27349.4
10G11	8050.0	570.0	0.0	31.50	17.50	108.0	82.0	18.8	80.0	28.80	0.120	0.0	0.0	545.7	32.0	N/A	N/A
10G12	7970.0	1315.0	410.0	79.00	11.00	155.0	63.0	19.5	80.0	29.80	0.130	51.5	53.3	1304.9	80.7	1.51	26947.5
10G13	8090.0	565.0	0.0	31.50	17.50	105.0	81.0	19.0	80.0	28.80	0.130	0.0	0.0	542.0	32.0	N/A	N/A
10G14	7910.0	1310.0	405.0	79.00	11.00	155.0	83.0	19.5	80.0	28.80	0.130	50.8	51.6	1252.0	79.2	1.53	27314.6
10G15	8080.0	565.0	0.0	31.50	17.50	105.0	80.0	19.0	80.0	28.80	0.130	0.0	0.0	543.0	32.0	N/A	N/A
10G16	7900.0	1310.0	405.0	78.00	11.00	155.0	83.0	19.5	80.0	28.80	0.130	50.7	51.5	1252.0	79.2	1.53	27349.4

FIGURE 77

The duration of each test point may be found by referring to the segment descriptions discussed in Section VI, Paragraph 3.1.

A study of the data reveals that, within the accuracy of the instrumentation employed, no degradation in performance of the gas turbine engine was experienced as a result of operation with Shelldyne-H fuel. This conclusion is illustrated in Figure 78 by plotting corrected horsepower versus corrected exhaust temperature for the first and tenth cycles of the endurance test. In like manner, no significant change in specific fuel consumption was observed through cycle six (35 hours) of the test shown in Figure 79. At this point the technician's test log indicates difficulty with the recording equipment on the fuel flow channel, which necessitated amplifier changes. The subsequent data obtained during the seventh through tenth cycles, although in disagreement with the previous data, shows no performance degradation during the final 15 hours. No attempt was made to determine which of the two amplifiers was in error.

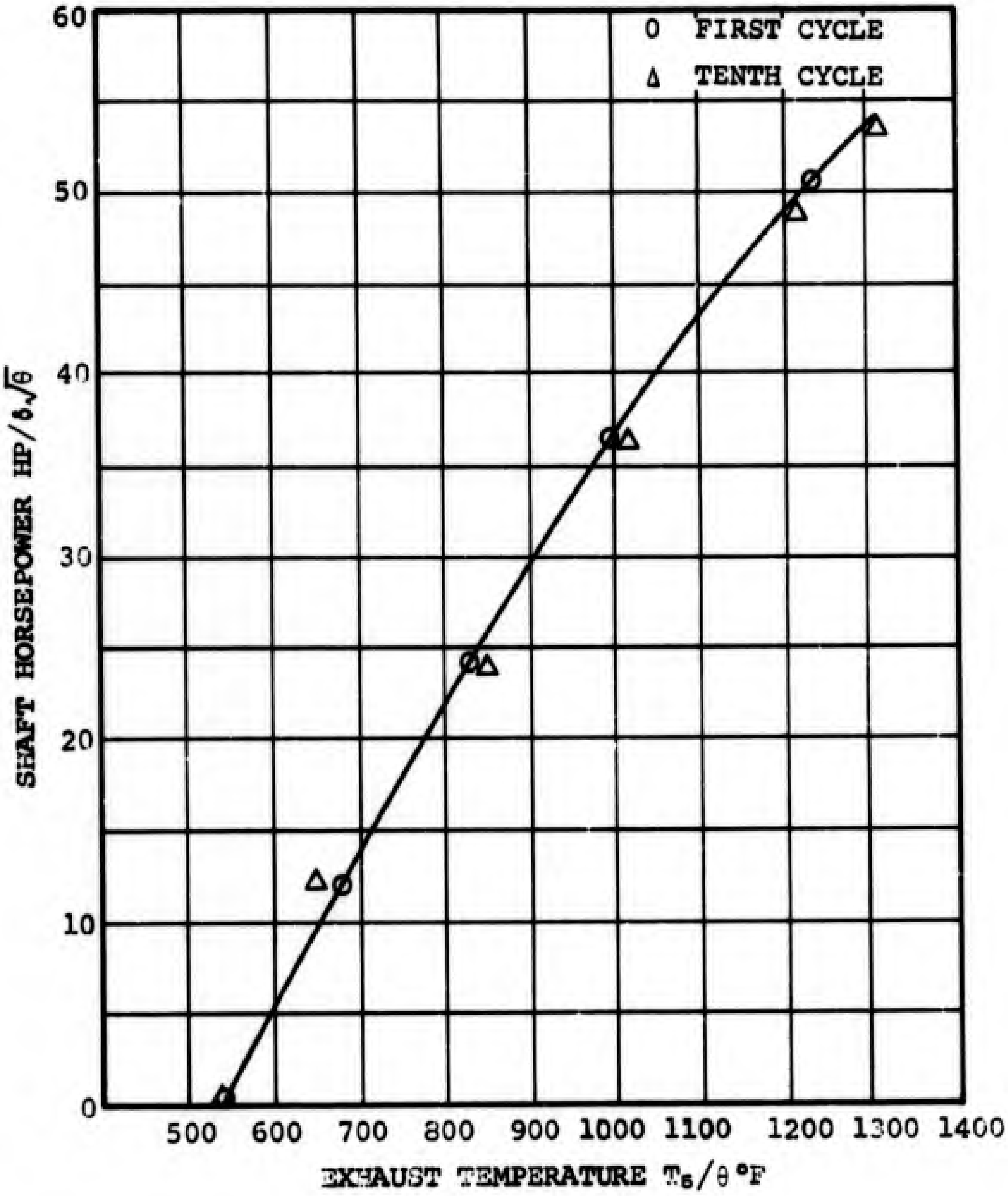
Turbine inlet (combustor discharge) temperature measurements were not included during complete engine testing. Such measurement would provide data for correlation with combustion rig testing results. Combustor temperature profiles obtained during rig tests indicated that the profiles varied with power setting and that a singular thermocouple location that would provide continuously correlatable data did not exist. Adequate correlation would have required the installation of an averaging thermocouple rake. However, introduction of so much blockage in the combustor discharge section would have, in itself, altered the combustor temperature profile.

Consequently, this parameter was deleted because a singular thermocouple would not have provided usable data. Alternately, incorporation of a multiple measurement would have required retesting the combustor with a thermocouple rake installed. Retesting the combustor would have involved program slippage and costs which were inordinate to the limited realizable benefits.

The only operational difficulty experienced during the course of the endurance engine test with Shelldyne-H fuel was the tendency of the engine to overshoot governed speed during the start-cycle. Normal operation of the Model GTP30 Engine with Grade JP-4 fuel results in an overshoot of approximately 3 percent, while with Shelldyne-H fuel an overshoot of 6 to 8 percent was observed.

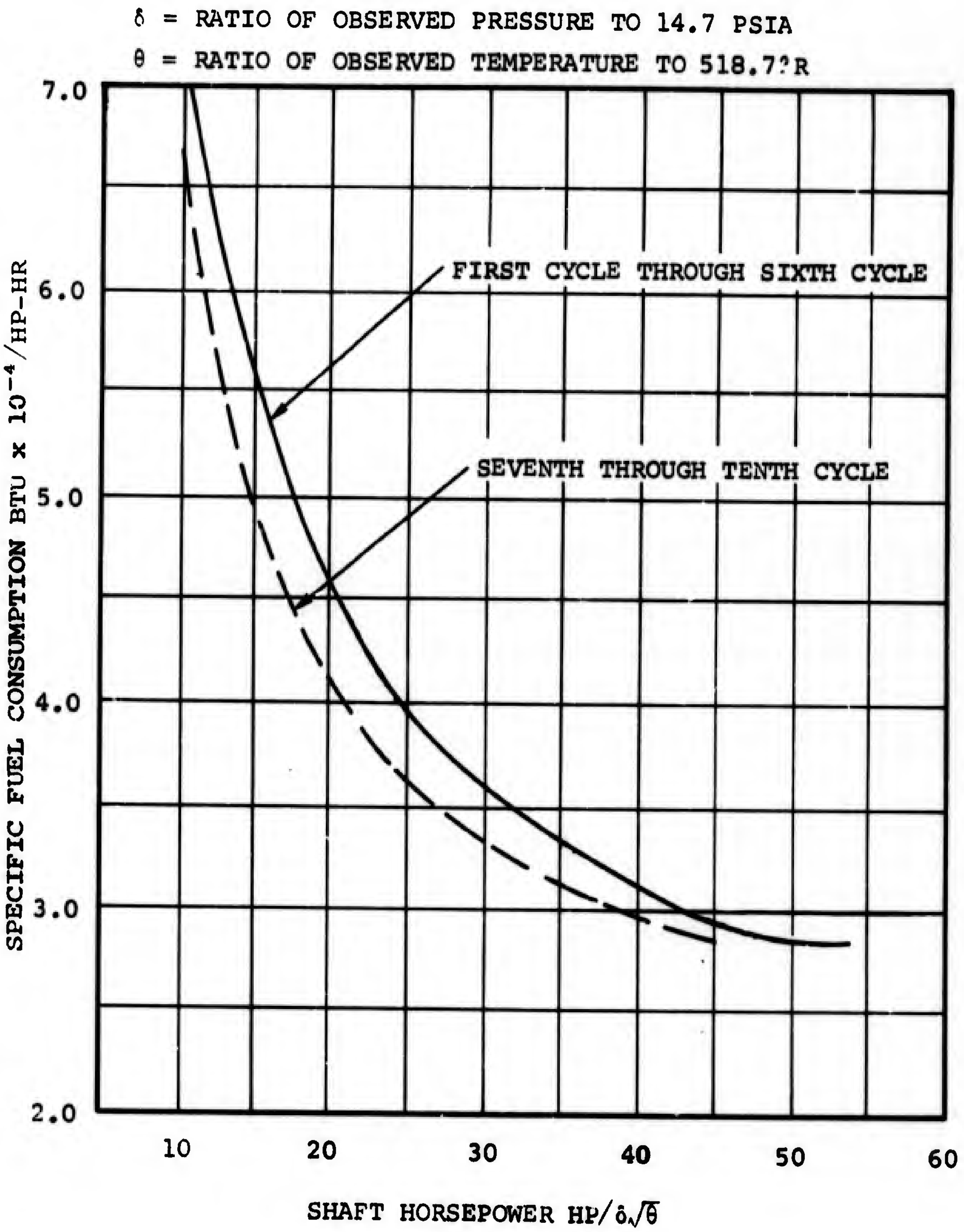
δ = RATIO OF OBSERVED PRESSURE TO 14.7 PSIA

θ = RATIO OF OBSERVED TEMPERATURE TO 518.7°R

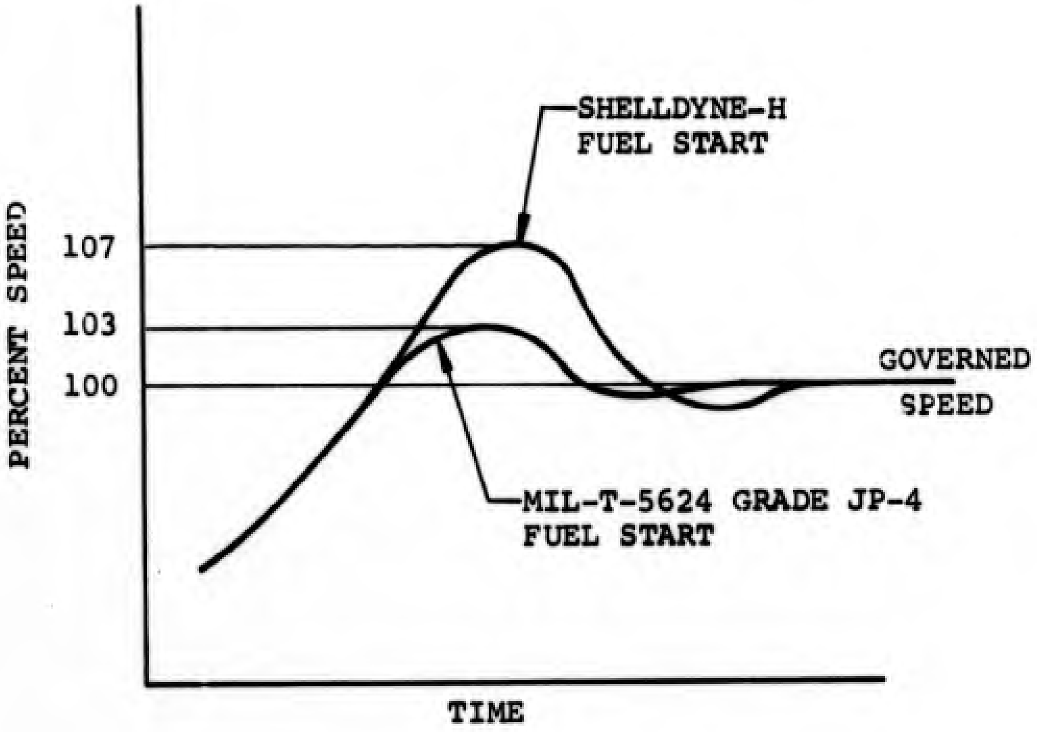


ENDURANCE ENGINE PERFORMANCE

FIGURE 78



ENDURANCE ENGINE PERFORMANCE
FIGURE 79



This observation was attributed to increased fuel system time-constants resulting from operation with a much more viscous fuel than that for which the control system was designed.

During the course of the preliminary setup period and the formal engine endurance testing, a total of 71 engine starts were attempted. Of these, one was aborted with no light-off, 8 achieved momentary light-off but an insufficient Grade JP-4 fuel lead was used to sustain combustion on Shelldyne-H, 8 achieved lightoff and acceleration but were automatically terminated due to governor overshoot, and 54 were normal. A summary of the data obtained during 25 of the successful starts, taken at random, is shown in Figure 80, which is a reproduction of the computer printout. These starts were made over an inlet air temperature range from 80°F to 115°F, with engine initial conditions from "dead cold" to "just run." This data revealed very consistent starting performance for the conditions described when

ENDURANCE ENGINE START DATA

FUEL USED SHELLDYNE-H

START NO.	SEC. TO IGNITION	SEC. TO STARTER CUT OUT	SEC. TO GROUND IDLE	RPM AT IGNITION	RPM AT STARTER CUT OUT	MAXIMUM EXHAUST TEMP. F
1.	0.90	5.80	11.60	900.	3950.	960.
2.	1.40	5.30	10.60	1150.	4150.	1110.
3.	0.70	6.25	13.40	600.	4000.	840.
4.	0.75	5.90	12.00	700.	4100.	1000.
5.	0.90	6.10	12.75	800.	4000.	980.
6.	1.10	5.70	11.40	1200.	4050.	1020.
7.	1.40	6.05	11.90	1450.	4000.	1010.
8.	2.70	5.85	12.05	2400.	3900.	1130.
9.	3.25	6.25	15.95	2550.	3950.	965.
10.	1.85	6.75	14.30	1100.	3900.	1140.
11.	2.10	4.80	10.50	2200.	4050.	930.
12.	0.70	6.00	12.80	800.	3800.	1110.
13.	0.70	4.90	9.70	800.	4200.	1090.
14.	1.00	5.40	9.30	1100.	4050.	1200.
15.	0.60	5.50	9.60	700.	4200.	1220.
16.	0.80	5.10	9.00	800.	4300.	1350.
17.	0.90	5.60	13.10	1200.	4000.	1110.
18.	2.90	5.60	9.65	2500.	4000.	1105.
19.	1.10	5.60	12.00	1000.	4000.	1090.
20.	0.90	6.00	12.40	750.	4100.	900.
21.	1.70	6.40	13.10	1400.	4000.	1020.
22.	1.30	4.60	10.20	1700.	4200.	790.
23.	0.07	5.10	11.10	900.	4000.	910.
24.	0.08	5.90	11.10	900.	4000.	1050.
25.	2.00	6.10	14.20	1900.	4000.	1050.

FIGURE 80

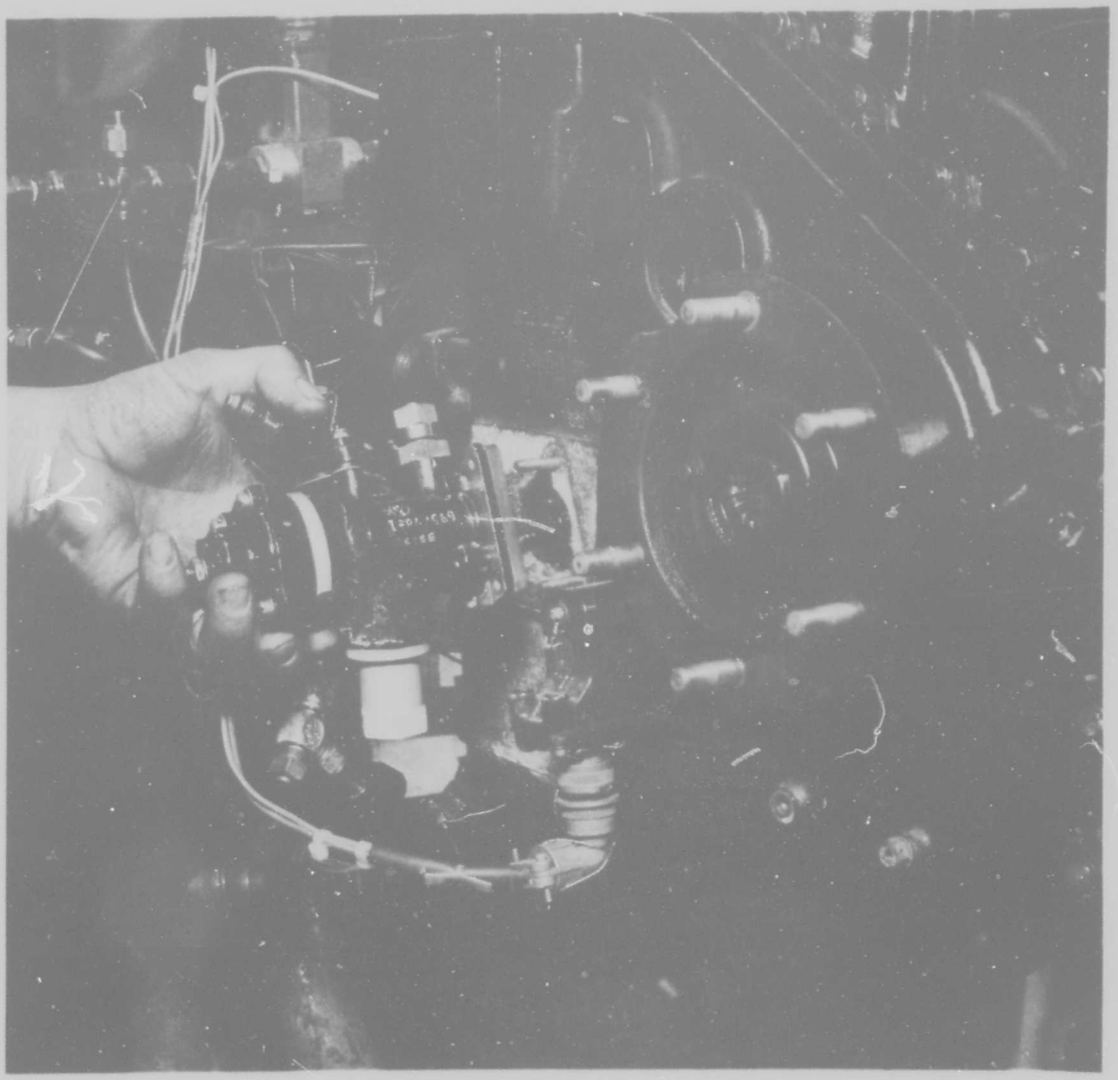
considering that minimal time was available for the development of the combustor ignition characteristics and that the fuel control was in no way modified to compensate for fuel viscosity variations.

3.3 Post-Endurance Teardown and Inspection. At the conclusion of the endurance test the engine was removed from the test cell to the test model shop, where it was disassembled for inspection and evaluation. A photographic record of the major steps of the engine teardown is given in Figures 81 through 89.

Upon disassembly of the gearbox it was found that the ball separator in one of the two high-speed pinion bearings had failed, causing excessive race and ball wear. The bearing, shown in Figures 90 and 91, is not a current production item and had accumulated, along with the entire gearbox, many hours of service in an earlier installation. This failure was, of course, not attributable to operation with Shelldyne-H fuel, and close examination of the bearings and engine oil temperature data indicated no appreciable power loss that would affect the accuracy of the performance data presented in the previous section.

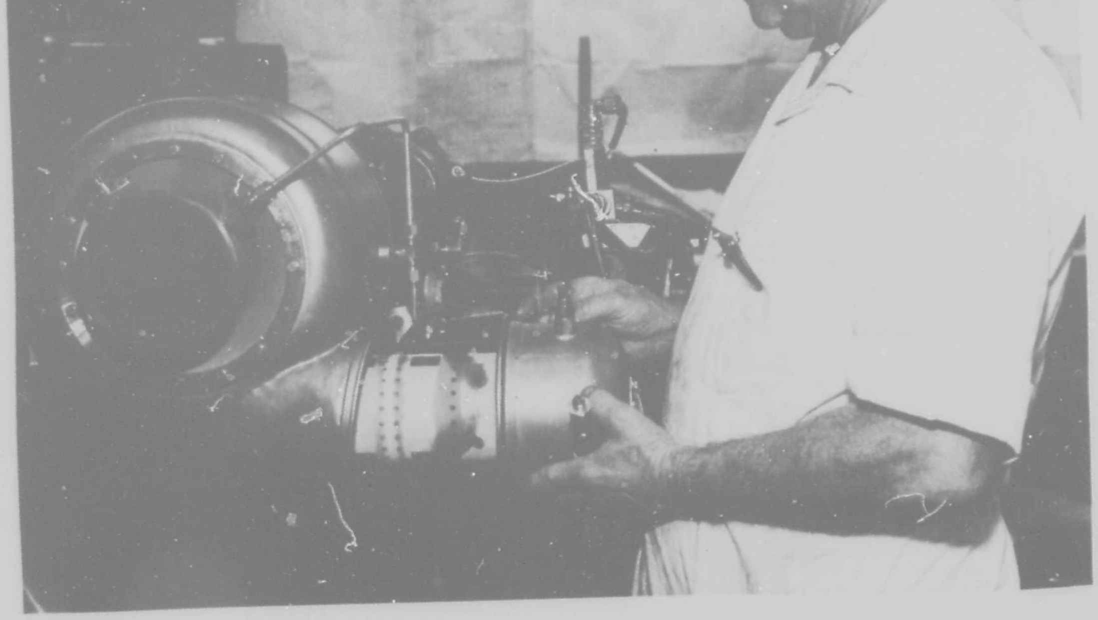
Inspection of the Shelldyne-H combustor revealed that no external deformation or material damage was present. The combustor was coated with Thermindex paint prior to initiation of the endurance testing and, although the normal duration of testing by use of this method is much shorter, several hot spots can be detected. As discussed in Section of this report, one such spot is evident in the area directly adjacent to the ignition chamber and another on the combustor dome, as shown in Figure 92. These areas, which were operating at a temperature of approximately 1500°F, could be cooled through further development of the combustor design.

In addition, two new hot spots became apparent in the primary zone, one on either side of the ignition chamber. These were caused by the change in airflow patterns within the combustor associated with the buildup or deposit of carbon in the primary zone. This deposit, as shown in Figure 93, was firmly attached to the underneath and downstream side of the primary fuel pipe. The principal reasons for this deposit were the cooling effect of the fuel-air mixture passing through the inside of the primary pipe and the lack of an adequate supply of compressor air to complete the combustion process in this area.



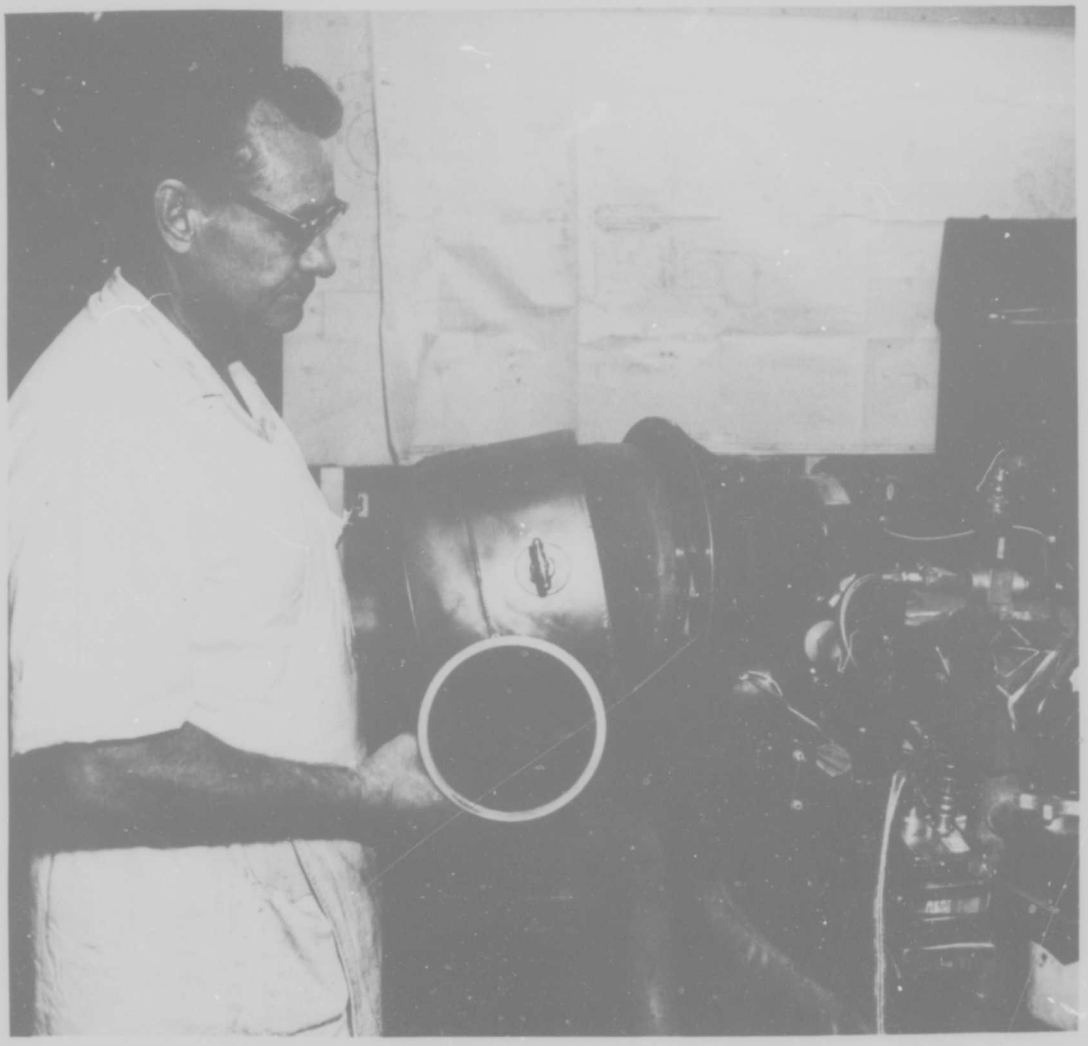
REMOVAL OF FUEL CONTROL UNIT

FIGURE 81



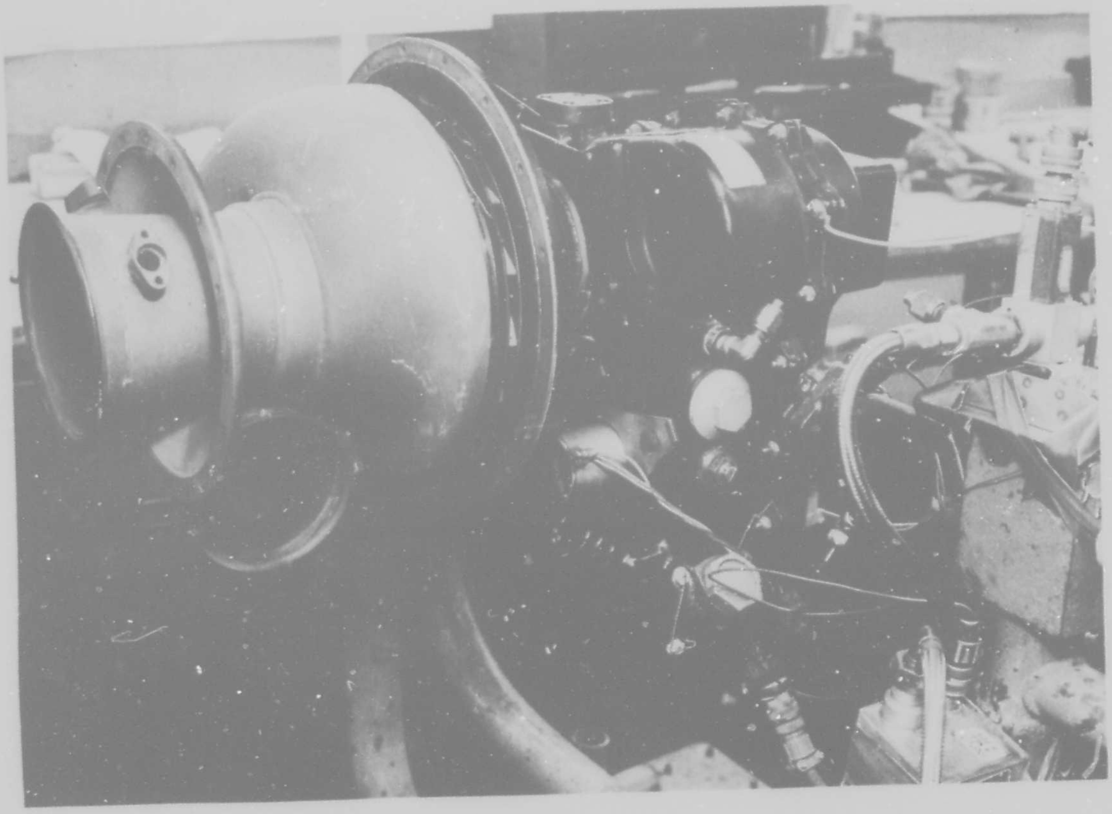
REMOVAL OF COMBUSTOR CAP AND LINER

FIGURE 82



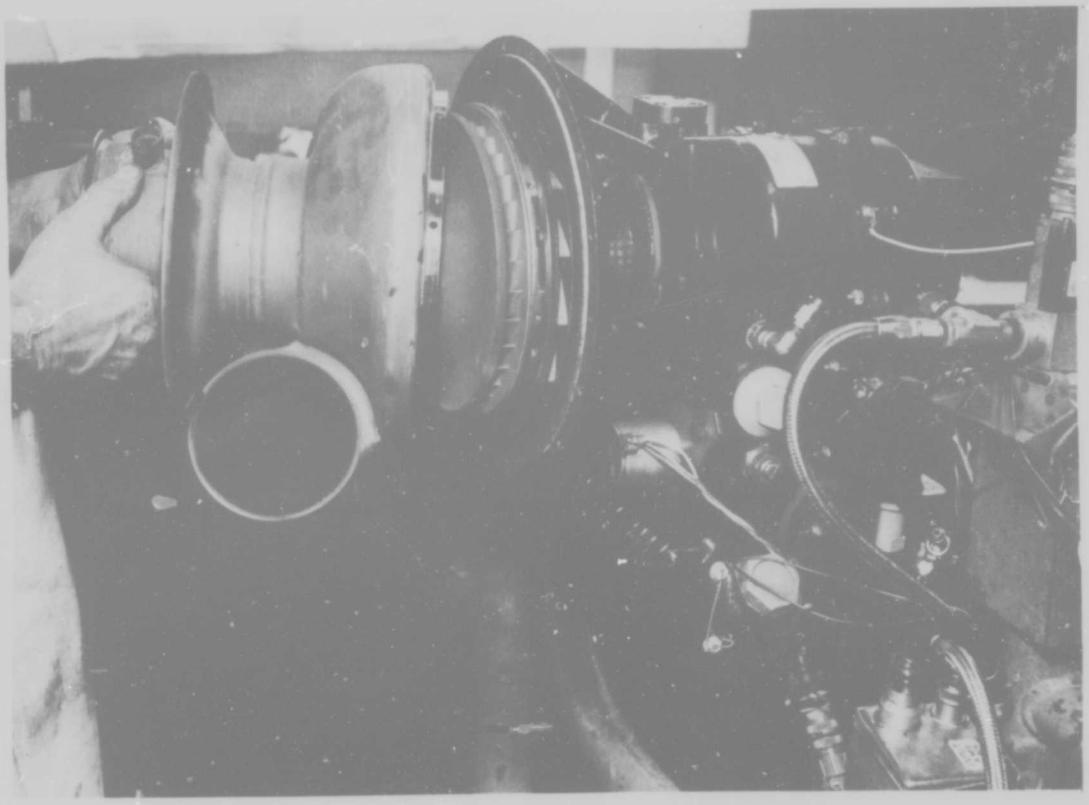
REMOVAL OF PLENUM CHAMBER

FIGURE 83



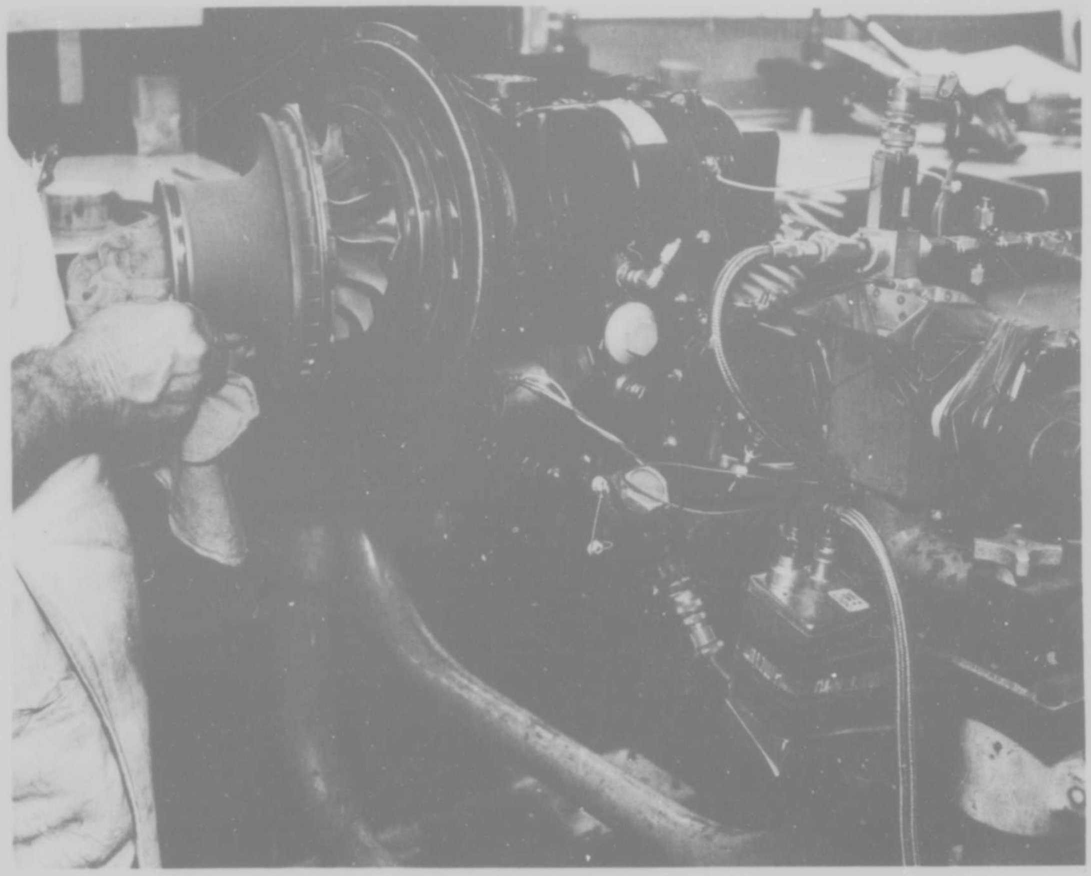
VIEW OF TORUS AND COMPRESSOR DIFFUSER

FIGURE 84



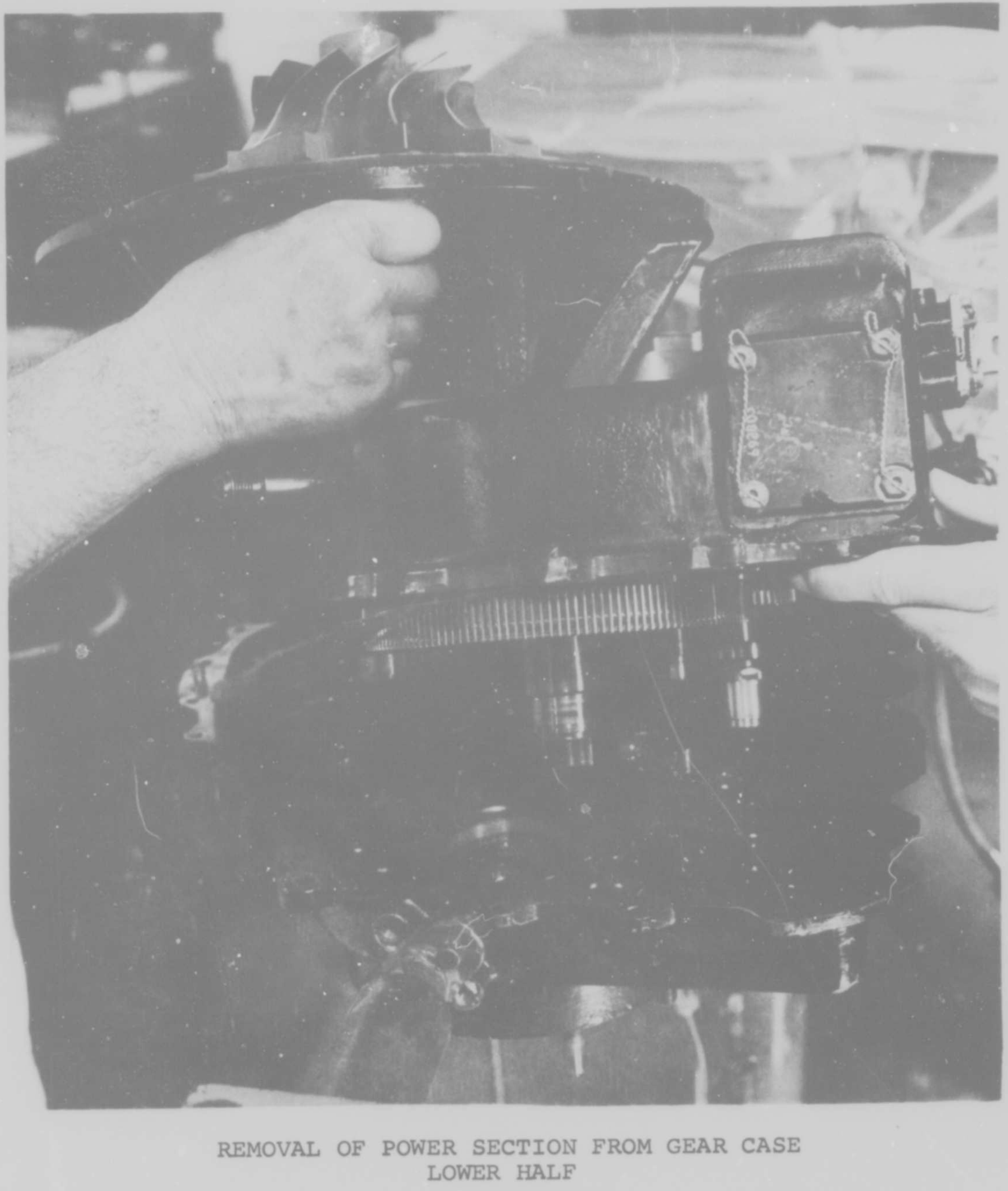
REMOVAL OF TORUS

FIGURE 85



REMOVAL OF TURBINE NOZZLE

FIGURE 86



REMOVAL OF POWER SECTION FROM GEAR CASE
LOWER HALF

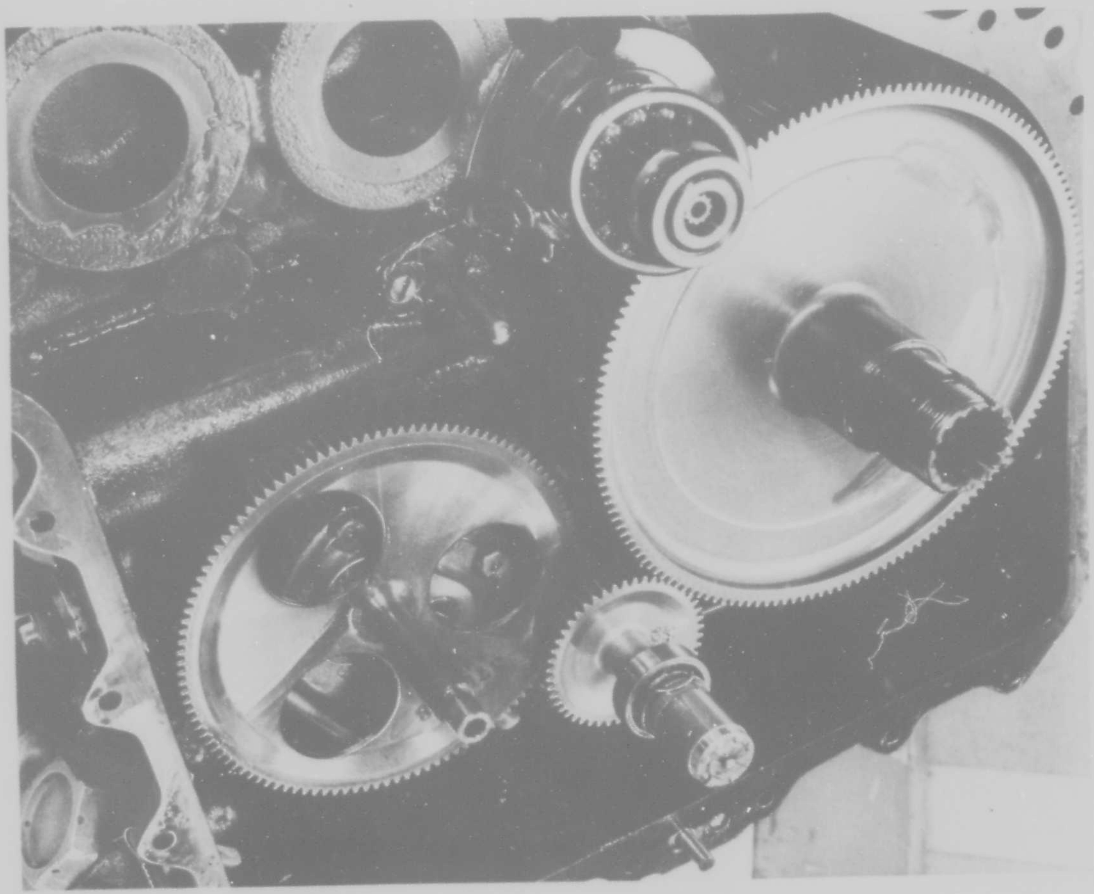
FIGURE 87

REMOVAL OF ROTATING GROUP FROM GEAR CASE UPPER HALF

FIGURE 88

REMOVAL OF COMPRESSOR DIFFUSER FROM ROTATING GROUP

FIGURE 89



VIEW OF TURBINE SIDE OF GEARBOX
SHOWING FAILED PINION BEARING

FIGURE 90

FAILED PINION BEARING

FIGURE 91

MP-25249

COMBUSTOR

FIGURE 92

MP-25251

INSIDE VIEW OF COMBUSTOR
SHOWING CARBON DEPOSIT

FIGURE 93

MP-24911

It should be noted in Figure 93 that no carbon was formed where air leakage occurred around the tack-welded connection joint between the primary pipe and the combustor liner. It is believed that this carbon or soot formation could be eliminated with minimal combustor development through proper distribution of air along the outer surface of the primary pipe.

Inspection of the deposit after 10 hours of operation and again at the conclusion of the endurance testing indicated that the formation had reached a limiting size and was burning and sloughing off.

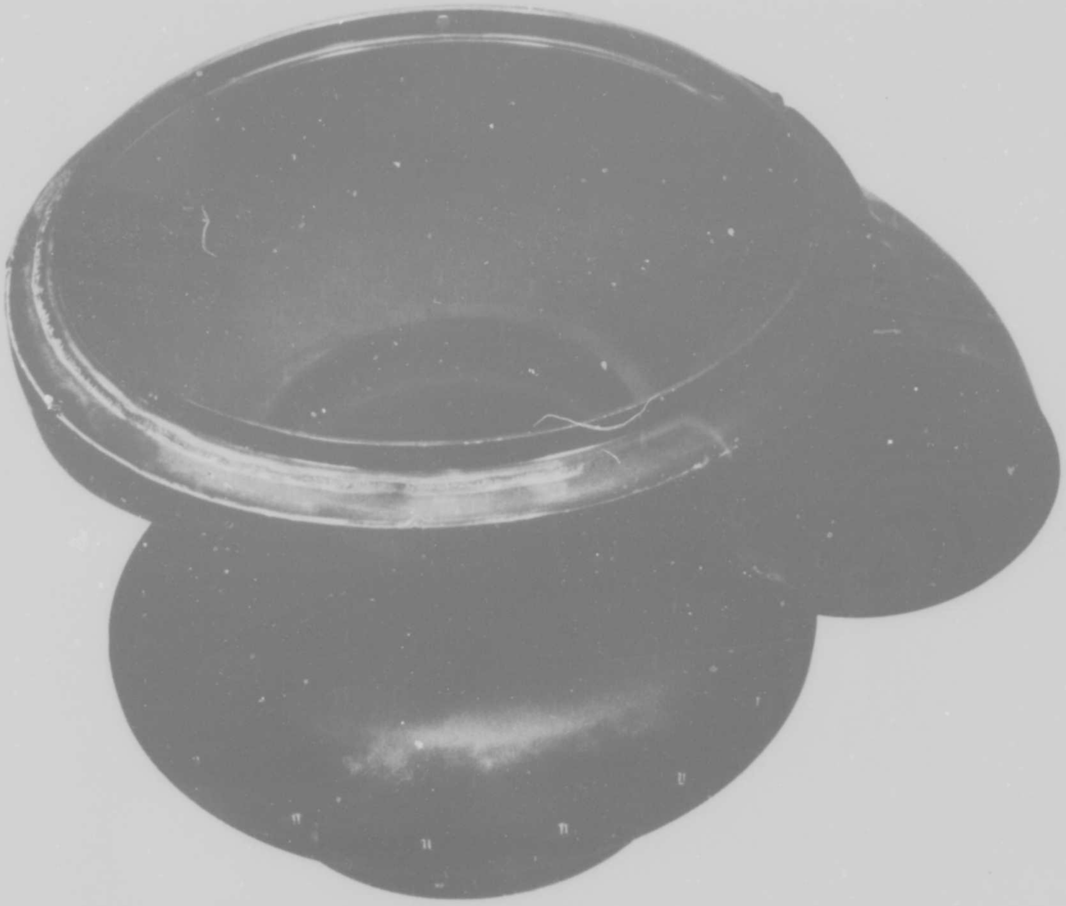
Post-endurance inspection of the torus scroll confirmed the latter occurrence by revealing a small number of loosely attached carbon particles near the combustor discharge port, as shown in Figure 94. No other unusual effects were observed. The torus as it appeared prior to the test is shown in Figure 95.

Figure 96 shows the turbine nozzle and shroud housing at the conclusion of the endurance test. Careful inspection of the nozzle, with primary emphasis on the nozzle vanes, as this is the area within the engine of highest metal temperature and gas velocity, revealed no erosion, corrosion, or other abnormality. Figure 97 shows the turbine nozzle housing prior to endurance testing.

In equally excellent condition following the endurance test was the radial-inflow turbine wheel, as shown in Figure 98. No adverse effects to the turbine wheel as a result of operation with Shelldyne-H fuel could be detected. A pretest photograph of the turbine wheel is shown in Figure 99 for comparison.

A phenomenon that was observed in connection with the inspection of all hot-end parts, for which discussion has been deferred to this portion of the report, was the reddish-brown appearance of all surfaces that came in contact with the combustor exhaust products. This discoloration was caused by the depositing on the torus, nozzle, turbine wheel, and exhaust diffuser of a thin, uniform layer of a relatively soft powder, which chemical analysis proved to be iron oxide.

Various tests were undertaken to determine the source of the iron, with the result that four parts per million of iron were found in the Shelldyne-H fuel itself. This data was obtained by use of spectrographic-analysis techniques with samples from two "as received" epoxy-lined fuel barrels which showed no signs of rusting.



TORUS AFTER ENDURANCE TEST
SHOWING CARBON FLAKES

FIGURE 94

MP-25253

TORUS PRIOR TO ENDURANCE TEST

FIGURE 95

MP-25233

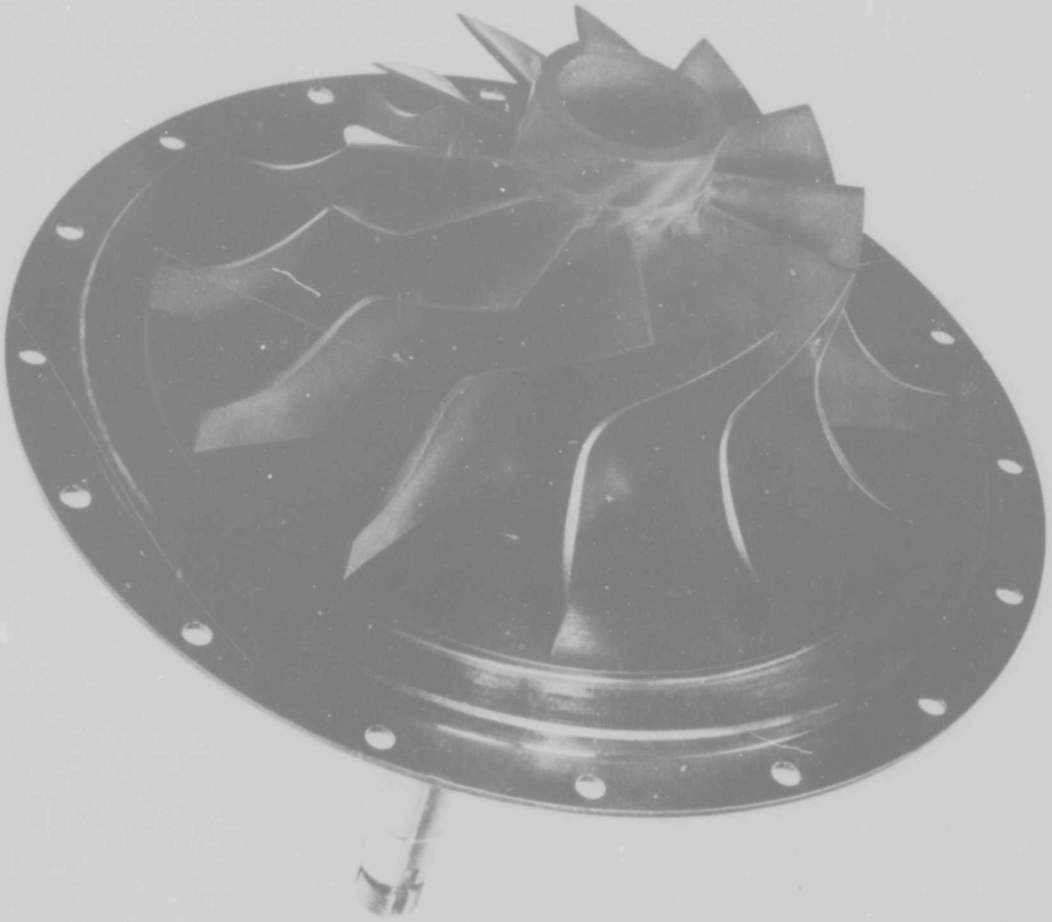
TURBINE NOZZLE AFTER ENDURANCE TEST

FIGURE 96

MP-25210

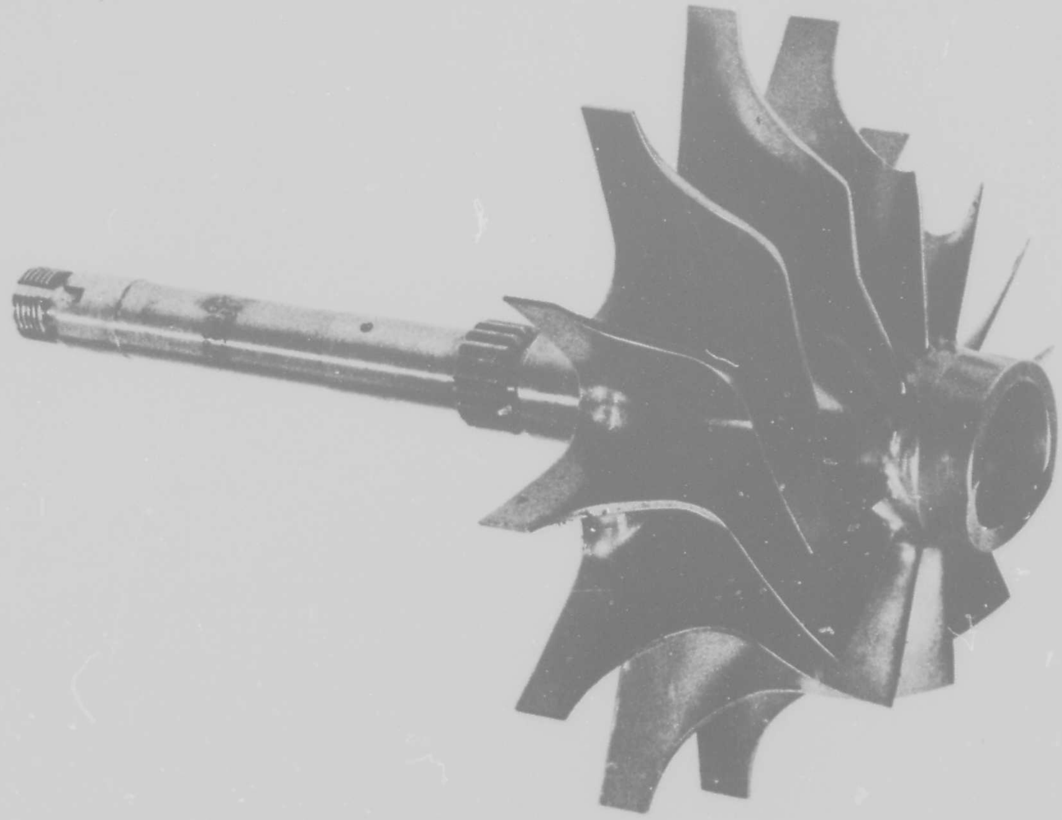
TURBINE NOZZLE PRIOR TO TEST

FIGURE 97



TURBINE WHEEL AFTER ENDURANCE TEST
FIGURE 98

MP-25252



TURBINE WHEEL PRIOR TO ENDURANCE TEST

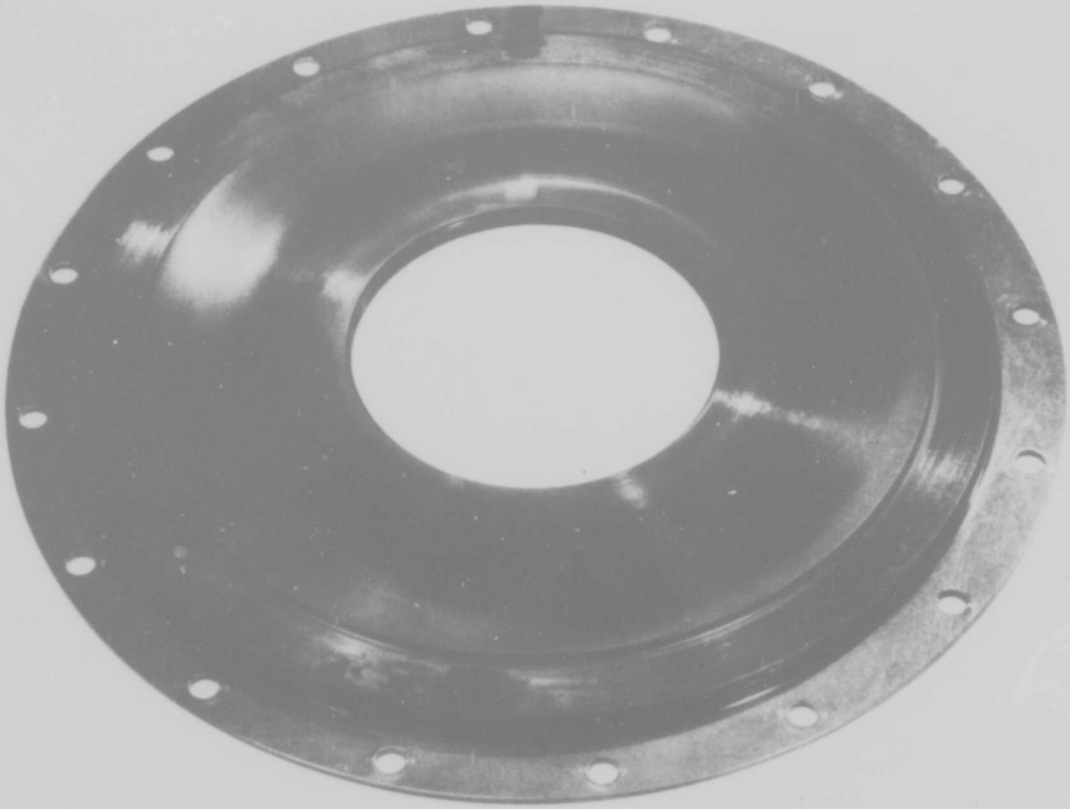
FIGURE 99

An additional confirming test was conducted in the laboratory, wherein a sample of Shelldyne-H fuel was evaporated in a crucible and the residue oven-heated to 1400°F. This residue was then ignited to burn off the remaining organic compounds. The resulting deposit revealed traces of a reddish substance, which was identified as iron oxide.

The presence of iron oxide is, from a chemical standpoint, in no way detrimental to the materials normally employed in the combustion and turbine sections of jet engines. However, if this deposition were of such magnitude as to affect the aerodynamic configuration or surface roughness of such items as nozzle vanes and turbine blades, a long-term reduction in power output could be observed. In view of the soft, non-hydroscopic nature of iron oxide, further buildup beyond the level experienced during this endurance test is unlikely, due to the scrubbing action of the high-velocity gases in these areas.

Figure 100 shows the compressor/turbine seal, sometimes referred to as the "back shroud," at the conclusion of the endurance test. The heat discoloration evidenced at the outer periphery, which operates at combustor discharge temperatures, is considered normal for the amount of full-load operation experienced during this test. The reddish-brown areas again reflect the iron oxide deposits. Figure 101 shows this seal prior to endurance testing.

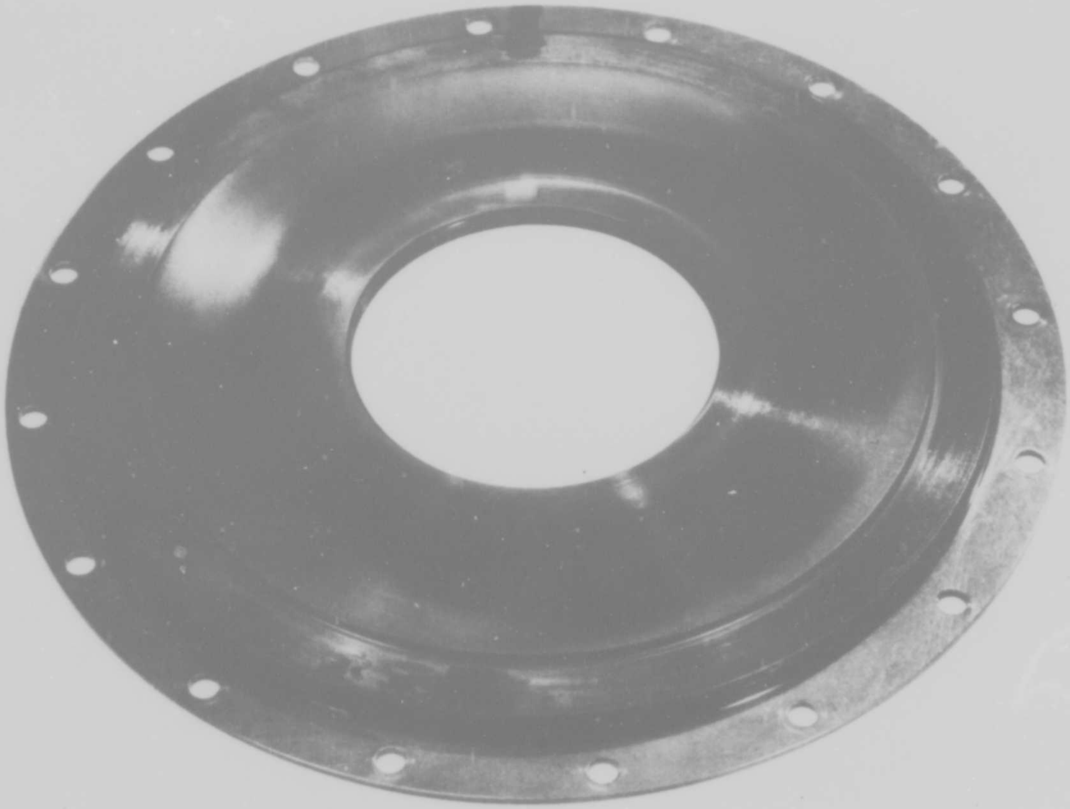
Disassembly and inspection of the fuel-control unit, which had accumulated an additional 50 to 60 hours of operation during component testing, exhibited excellent fuel-control component compatibility with Shelldyne-H fuel. All metering and bearing surfaces revealed the absence of measurable wear or surface-finish reduction, and all elastomeric components such as O-rings and diaphragms showed no tendency to swell or distort. Figures 102 through 105 illustrate these findings for several selected areas of the fuel control for which a high degree of reliability is required.



COMPRESSOR/TURBINE SEAL AFTER
ENDURANCE TEST

FIGURE 100

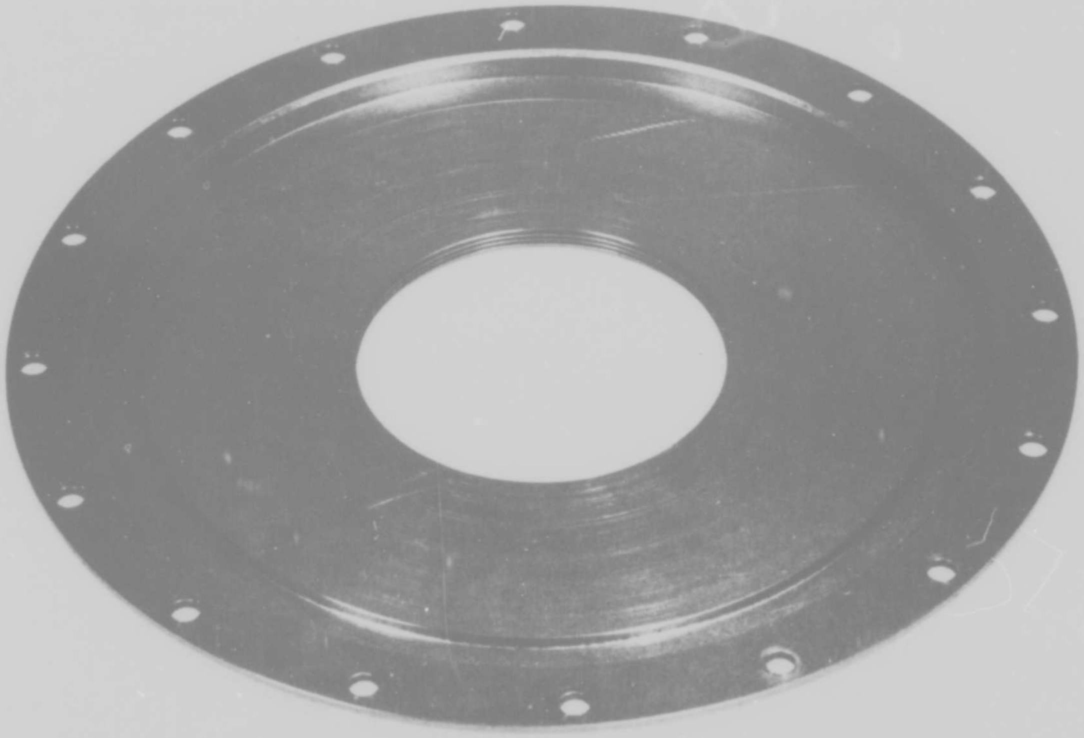
MP-25250



COMPRESSOR/TURBINE SEAL AFTER
ENDURANCE TEST

FIGURE 100

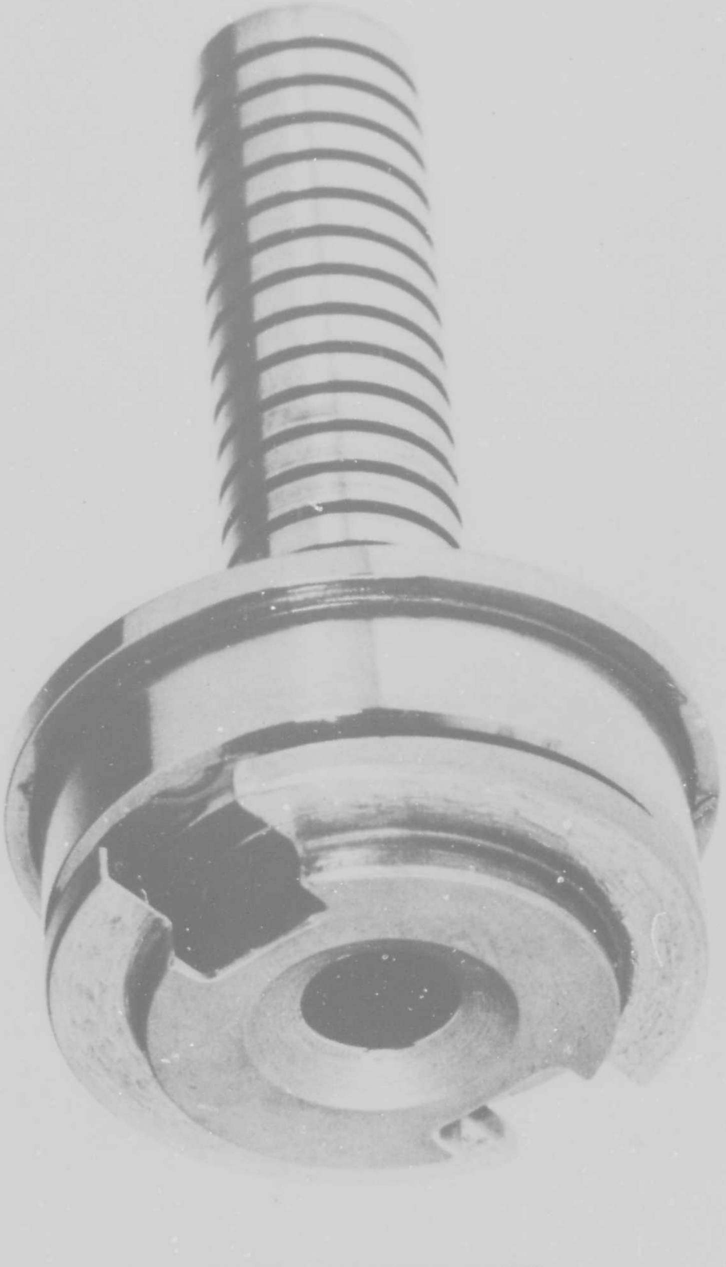
MP-25250



COMPRESSOR/TURBINE SEAL
PRIOR TO TEST

FIGURE 101

MP-25220



FUEL CONTROL METERING VALVE

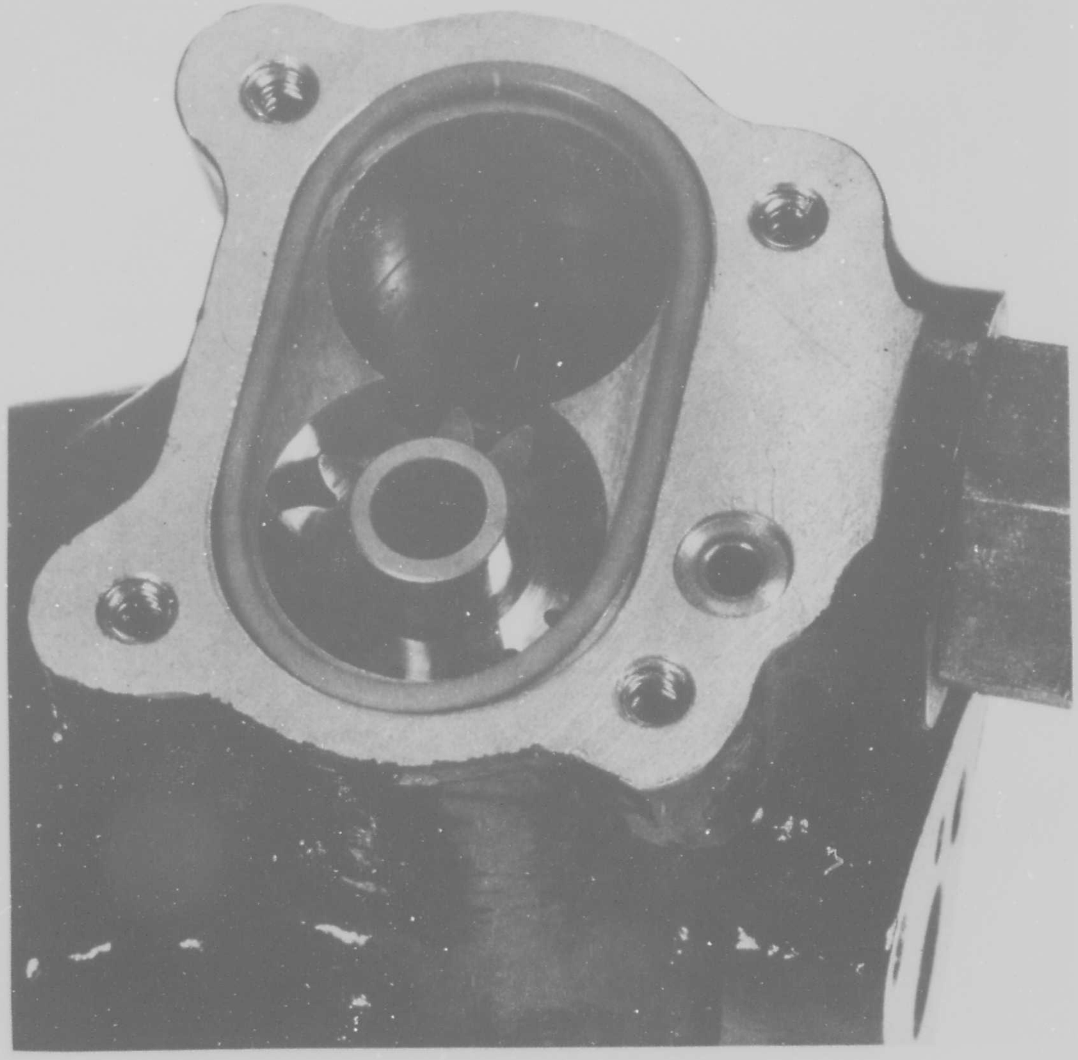
FIGURE 102

MP-25214

ACCELERATION-LIMITER DIAPHRAGM
AND BALL VALVE

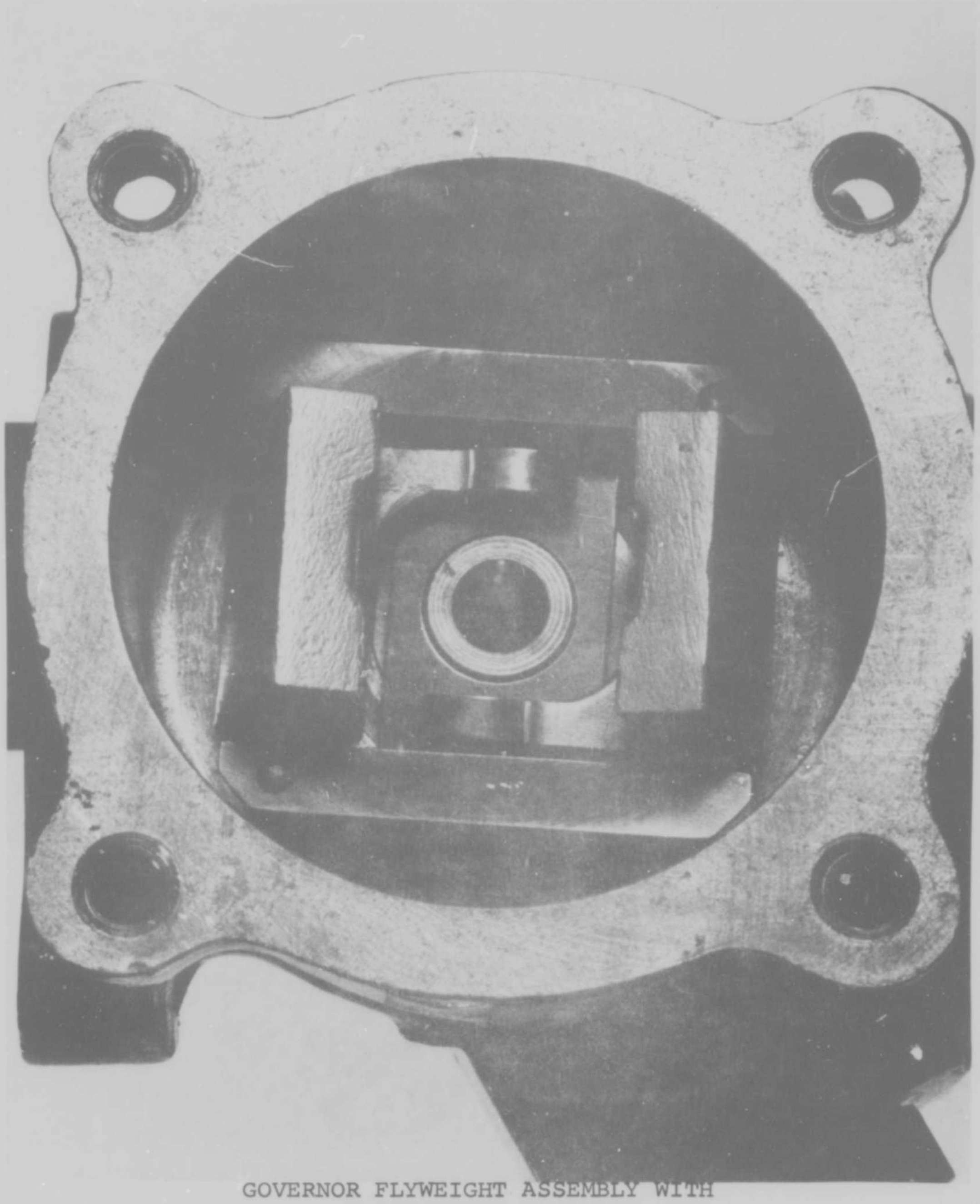
FIGURE 103

MP-25213



FUEL PUMP HOUSING SHOWING
O-RING, CARBON BUSHING, AND PUMP GEAR

FIGURE 104



GOVERNOR FLYWEIGHT ASSEMBLY WITH
SPOOL VALVE REMOVED

FIGURE 105

SECTION VII

LOW-TEMPERATURE START TESTS

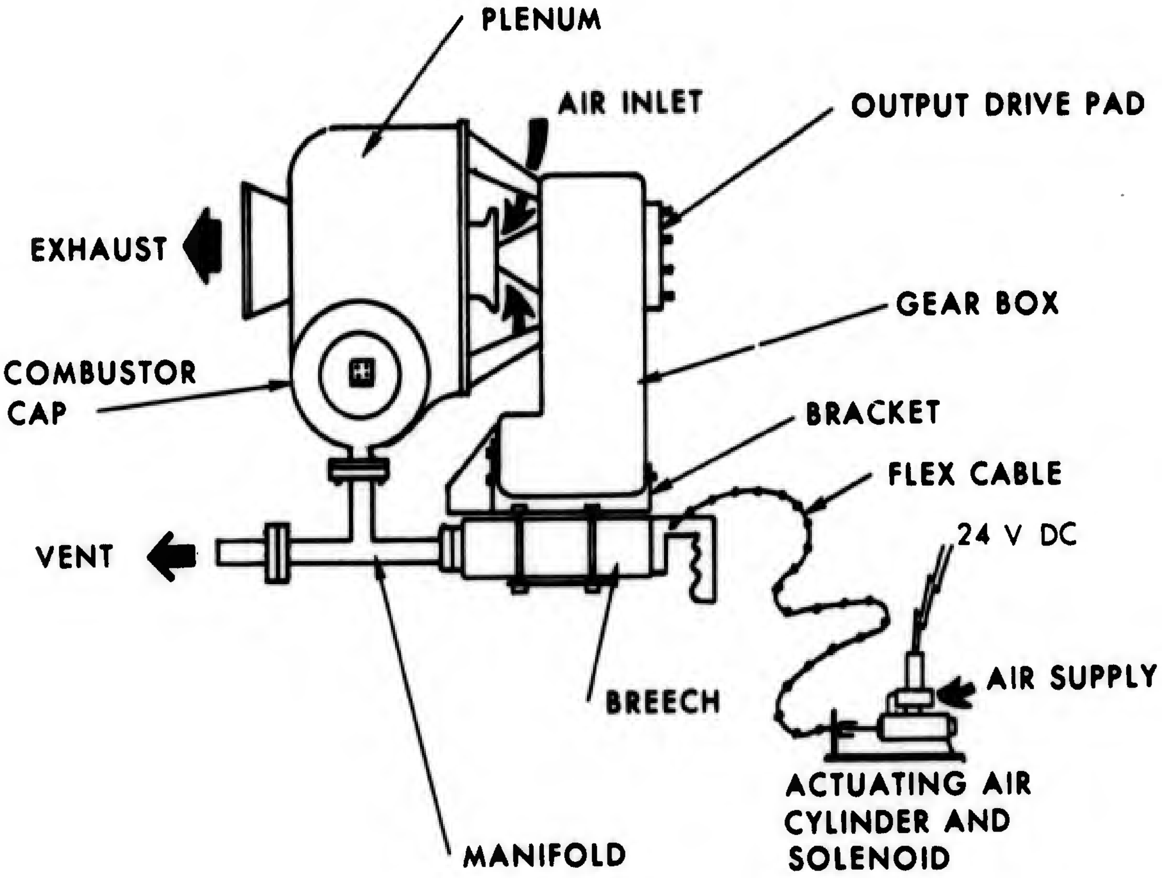
1. **OBJECTIVES**. The low-temperature ignition and engine starting characteristics of Shelldyne-H fuel were investigated through a series of cold-chamber tests with use of a Model GTP30 APU. In addition, one optional starting technique with use of an alternate starting fuel was evaluated.

2. **SUMMARY OF RESULTS**. Successful starts with Shelldyne-H fuel were made at a soak temperature of 10°F through the use of a solid-propellant hot-gas injector and conventional igniter system. The addition of a small amount of MIL-T-5624. Grade JP-4 fuel, as a "lead" in the fuel line allowed starts to be accomplished at minus 20°F. A larger quantity of Grade JP-4 fuel "lead" permitted a start to be made at minus 40°F.

3. **ENGINE BUILDUP**. At the conclusion of the endurance engine inspection period, the gas turbine was rebuilt, with new component parts utilized throughout the hot-end section. These parts included the torus, turbine nozzle, turbine wheel, bearings, seals, and O-rings. All other engine parts, including the Shelldyne-H combustor, were thoroughly cleaned and reused. All hot-end components could have been reused; however, their retention for further photographic documentation and iron deposition evaluation tasks was required.

After assembly, the engine was fitted with a special mounting bracket to support the solid-propellant breech and manifold system described in Section V of this report. This installation is shown schematically in Figure 106.

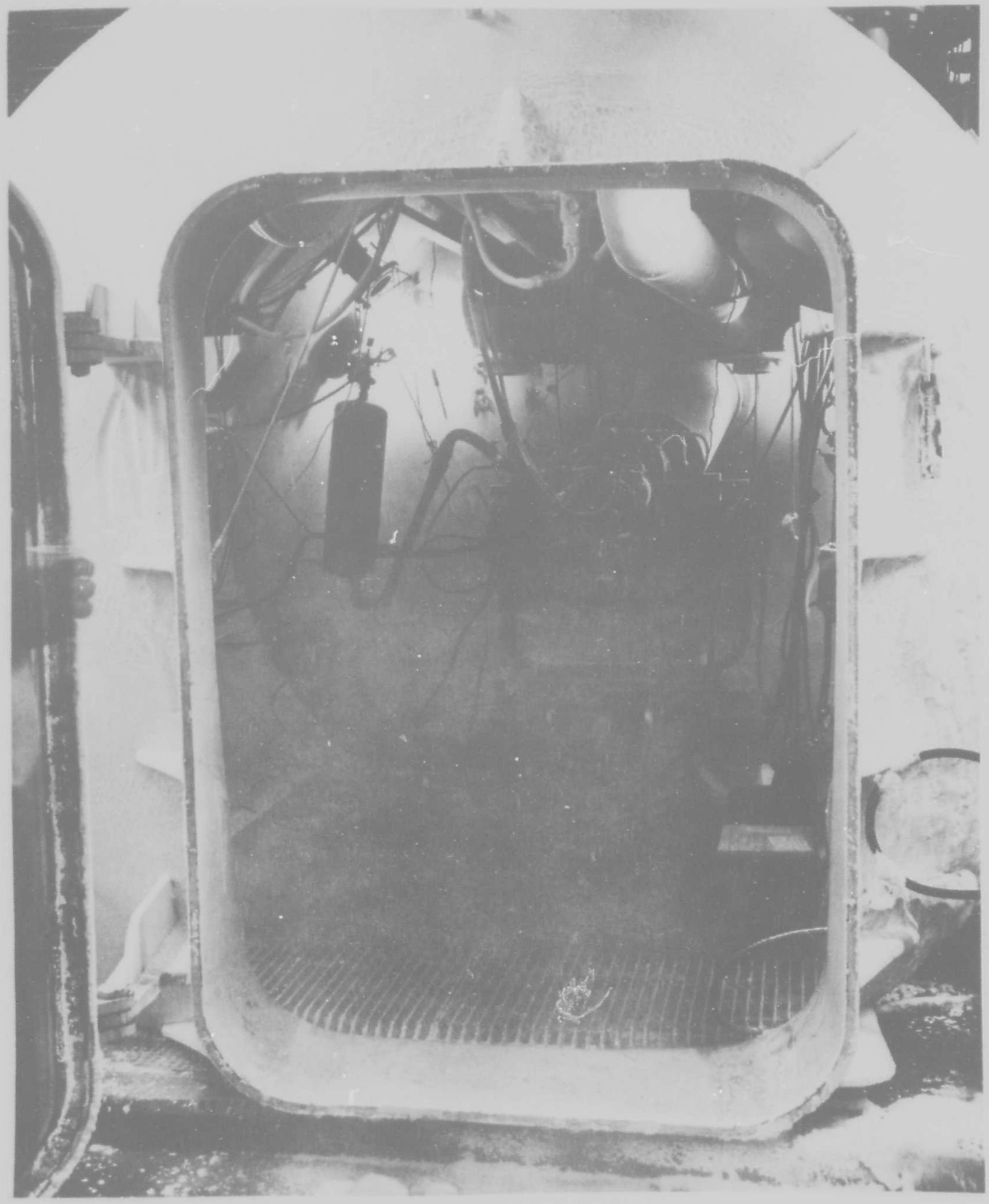
4. **TEST SETUP**. The Shelldyne-H start-test engine was mounted in a standard engine cradle and installed in a small altitude tank as shown in Figure 107. As can be seen in the figure, a large cylinder of Shelldyne-H fuel was located near the engine and connected to the fuel-control inlet by means of a 2-inch line to minimize inlet pressure losses during low-temperature, high-viscosity operation. The Shelldyne-H cylinder was pressurized from a regulated dry-nitrogen supply located outside the test cell. A laboratory slave electrical starter motor was provided in lieu of the normal starter/generator employed on the engine. This slave starter and its accompanying water brake dynamometer, which was not utilized during these tests, are shown in Figure 108 in the center. foreground.



SHELLDYNE-H FUEL
START TEST ENGINE

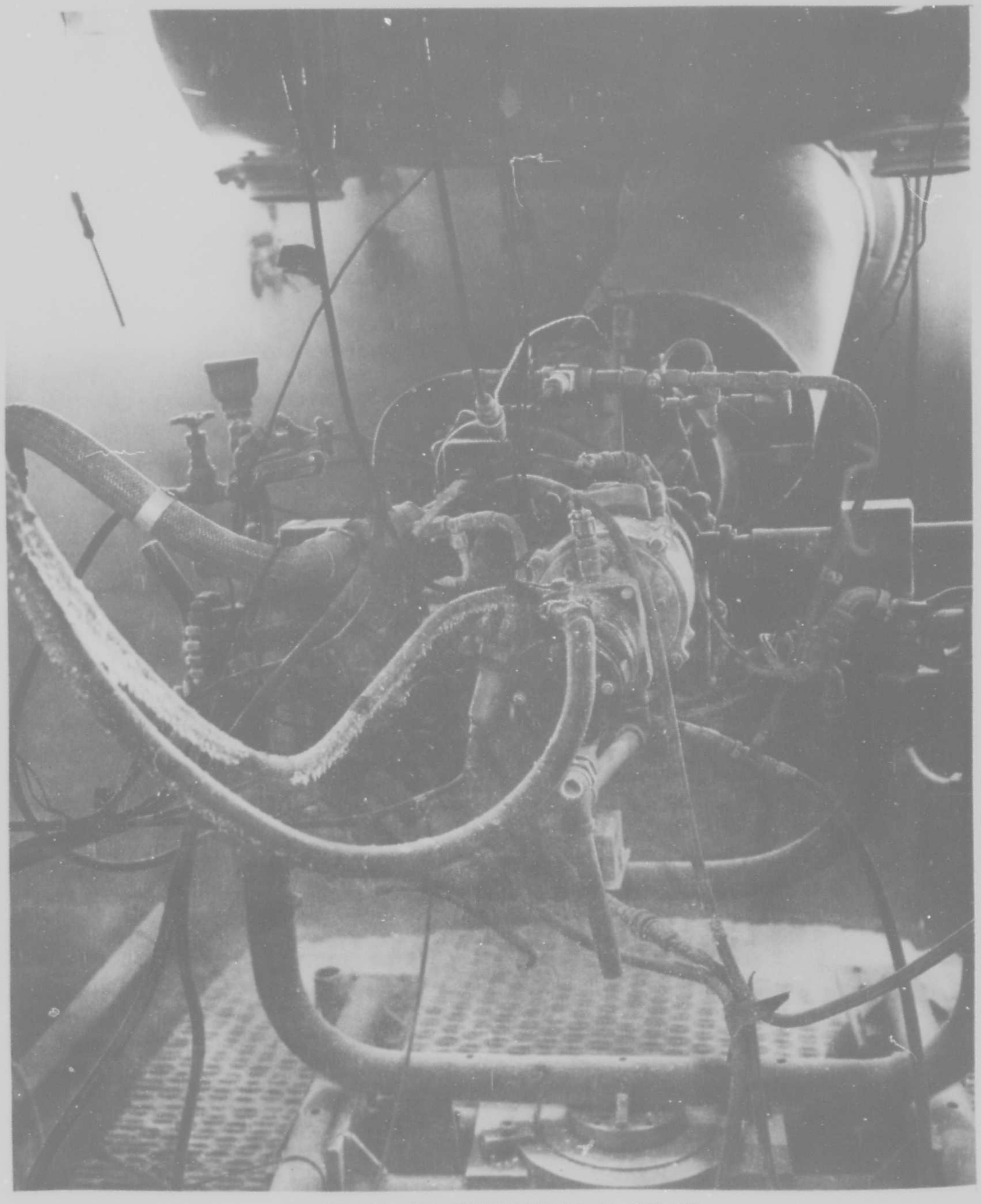
HOT GAS SYSTEM
INSTALLATION SCHEMATIC

FIGURE 106



SHELLDYNE-H START TEST ENGINE
INSTALLED IN COLD TANK

FIGURE 107



CLOSE-UP OF SHELLDYNE-H START
TEST ENGINE

FIGURE 108

Instrumentation was provided to measure the following prestart system parameters: fuel supply pressure, fuel supply temperature, oil sump temperature, and test-cell ambient temperature. Parameters that were recorded with Sanborn equipment during each start included: solid-propellant breech pressure, turbine exhaust temperature, combustor inlet temperature, engine speed, fuel inlet pressure and temperature, compressor inlet air temperature, and starter voltage. After governed speed had been attained after each successful start, the additional steady-state parameters of compressor discharge pressure, engine oil pressure, and engine vibration were also measured.

4.1 Conduct of the Test. Through the extensive combustor testing described in Section V of this report, the minimum combustor inlet air temperature required for ignition of Shelldyne-H fuel with conventional spark igniters was found to be 265°F. This lower limit was, of course, partially dependent upon the combustor design itself, for which little development time was available. Due to the limitations imposed by lubricants, elastomers, and other components of the Model GTP30 Engine, which is not designed for operation at these very high ambient temperatures, full-scale engine start-tests at 265°F were considered impractical. Therefore, for purposes of low-temperature engine testing, the standard starting technique with Shelldyne-H fuel included the use of the solid-propellant hot-gas injector system.

All test runs were made by cold-soaking the engine until all instrumented temperature parameters stabilized within a 3°F temperature spread. After each successful start, the soak temperature was lowered 10°F and the procedure was repeated until a condition of no light-off was attained. This test point was then attempted several times to confirm the lower ignition limit.

5. SHELLDYNE-H FUEL TEST RESULTS. Testing was initiated at the Shelldyne-H ignition limit (with hot gas injection) of 30°F as determined during the combustor component tests. At this temperature, a very normal start was achieved with almost immediate (0.3-second) ignition and rapid (9.2 seconds) time to governed speed. Comparable results were also obtained at soak temperatures of 20°F and 10°F with slightly longer ignition delays--3.0 seconds and 2.8 seconds, respectively. Repeated attempts at a soak temperature of zero °F resulted in no light-off or measurable exhaust temperature rise. A summary of pertinent data obtained during these starts is presented in Table IV. The reduction in minimum ignition

TABLE IV

LOW-TEMPERATURE START PERFORMANCE SHELLDYNE-H FUEL WITH SOLID-PROPELLANT GAS INJECTION

Soak Temp. °F	Time To Ignition Seconds	Time To Starter Cutout Seconds	Time To Governed Speed Seconds	RPM* At Ignition	RPM* At Starter Cutout	Maximum Exhaust Temp. °F	Cartridge Burn Time Sec
30	0.3	5.3	9.2	400	4100	1350	5.3
20	3.0	6.2	8.2	2000	4300	1350	5.3
10	2.8	5.8	10.2	1900	4000	720	5.0
0	-	-	-	-	-	-	5.0

*Output speed (8000 rpm = 52,800 rpm turbine speed) temperature from 30°F observed during combustor component tests, to approximately 10°F with the entire engine, can be attributed in part to the compressor temperature rise in the latter case. In addition, slight variations in geometry between the combustor simulator test rig and actual engine components may have affected the airflow patterns within the combustor.

6. ALTERNATE START-METHOD TEST RESULTS. An alternate method of starting the gas turbine engine was tested wherein ignition was achieved with use of a small amount of Grade JP-4 fuel in the fuel line between the fuel control and the combustor. This placement of the Grade JP-4 fuel in the fuel line downstream from the fuel control assured that all fuel scheduling and governing was being accomplished with Shelldyne-H fuel.

As discussed in an earlier section, the combustor had been developed only as far as successfully maintaining combustion with Shelldyne-H fuel, with no attempt being made to obtain optimum ignition characteristics. As a consequence, the minimum ignition temperature with Grade JP-4 fuel and a conventional igniter was found to be 8°F during combustion-rig testing. Therefore, all low-temperature testing with a Grade JP-4 fuel "lead" required the use of the solid-propellant gas-injection system.

Due to the progressively increasing viscosity of Shelldyne-H fuel at the reduced temperatures, it was found that start-flow adjustments to the fuel-control downstream restriction were required through a trial and error procedure to achieve satisfactory ignition. This was expected, however, as the control used on the Model GTP30 Engine is designed for far less viscous fluids, with no provision for compensation.

Despite these limitations, a completely successful start was made at a soak temperature of minus 20°F. Ignition delay for this start was moderate (4.3 seconds) while the acceleration was normal, with a time to governed speed of 10.0 seconds. Several additional start attempts were made at lower soak temperatures, one of which, at minus 40 degrees, was partially successful. The ignition delay experienced during this start was quite long (13.8 seconds) and engine acceleration was very slow--28.7 seconds elapsed before governed speed was reached. These results were attributed to an insufficient opening of the fuel-control downstream restriction, as evidenced by the very low exhaust-gas temperature observed during this start. The engine was operated at governed speed for approximately 5 seconds, when a test-cell electrical short shutdown the engine. It was not possible during this brief run to determine whether the Grade JP-4 fuel "lead" had been consumed and Shelldyne-H was actually being burned. However, the fuel scheduling and governing for both this start and the previous minus 20°F start were being accomplished on Shelldyne-H fuel. A summary of data obtained during these starts is presented in Table V.

Testing was terminated at this point due to the failure of the electronic "black box" which controls the sequencing of starter and ignition events during acceleration of the GTP30 Engine. It was believed that the principle of alternate fuel starting was adequately demonstrated and that any further additional delay brought about by the replacement of this long-lead-time item would not be consistent with the overall program objectives.

TABLE V

ALTERNATE START-METHOD
(MIL-T-5624, GRADE JP-4 FUEL LEAD)

Soak Temp. °F	Time to Ignition Seconds	Time to Starter Cutout Seconds	Time to Governed Speed Seconds	RPM* at Ignition	RPM* at Starter Cutout	Maximum Exhaust Temp. °F	Cartridge Burn Time Sec
-20†	4.3	6.9	10.0	2000	4000	640	5.7
-40†	13.8	17.4	28.7	2500	3800	340	5.0

*Output speed (8000 rpm = 52,800 rpm turbine speed)

†15 cubic centimeters of MIL-T-5624, Grade JP4, Fuel lead

SECTION VIII

CONCLUSIONS AND RECOMMENDATIONS

The principal conclusion reached through this Shelldyne-H evaluation program is that state-of-the art gas turbine technology is more than sufficient to meet the combustion, fuel-handling, and material requirements associated with the use of Shelldyne-H as a primary fuel. Certain areas of present-day engine design were found to be wholly acceptable, while others will require a degree of refinement and development to achieve optimum performance.

With the exception of those organic compounds containing silicone, all elastomeric and metallic materials tested were judged acceptable for use with Shelldyne-H fuel. It is believed that these samples are typical of the materials utilized in a majority of current turbine engines and that, apart from the usual confirmation tests of specific elastomers, the compatibility of fuel-handling or hot-end components with Shelldyne-H fuel is of little concern. In fact, the excellent lubricating characteristics of Shelldyne-H fuel were apparent through inspection of bearing and metering surfaces subjected to the fuel during control component tests. Further research of these properties and their effects upon overall engine lubrication is recommended.

The fuel-control component tests, although highly successful when the simplicity of the control used is considered, revealed several areas for which additional study is recommended. Fuel tanks, slosh baffles, fuel-pickup tubes, boost pumps, and fuel lines and fittings must be designed so as to minimize the amount of fuel "carryover" (which would reduce the inherent range advantages of Shelldyne-H fuel) and to minimize the fuel-tank pressures required to prevent low-temperature pump cavitation.

Depending upon the local Reynolds number, the flow characteristics within the fuel-control passages and metering sections may be laminar. Therefore, sizing calculations must be made at the highest viscosity levels anticipated by mission ambient-temperature requirements. In addition, provision must be made for compensation of the control system as a function of fuel temperature and, therefore, viscosity.

By contrast, the high-viscosity and adhesive properties of Shelldyne-H fuel substantially improved the volumetric efficiency of the fuel gear pump. This increased performance will allow reductions in fuel-pump size and weight for systems using only Shelldyne-H fuel.

Observations made during vacuum combustor rig tests showed that Shelldyne-H fuel could be ignited with conventional igniters; however, flame propagation could not be achieved. It is believed that through additional development effort in this area, a combustor capable of direct ignition with Shelldyne-H fuel could be designed. The considerable reduction in ignition temperatures achieved through solid-propellant gas injection indicated that further development of this technique would lead to direct ignition of Shelldyne-H fuel at the lowest ambient temperatures. Using alternate fuels for ignition with a transition to Shelldyne-H fuel was found to be a very satisfactory method of engine starting.

Some applications require that engine exhaust gases be smoke-free or at least that they be visually undetectable. Tests with Shelldyne-H fuel indicated that the GTP30 did not produce visually detectable smoke. The smoke-production tendency increases with increased combustor absolute pressures--i.e., increased cycle pressure ratios. Because the GTP30 operates at relatively low pressure ratios, smoke-free operation of this engine is not necessarily conclusive evidence that Shelldyne-H fuel would not tend to produce exhaust smoke at the higher pressure ratios used in propulsion engines. Additional effort should therefore be directed toward evaluating the smoke-production characteristics of Shelldyne-H fuel at high combustor pressures.

APPENDIX I

COMBUSTION EFFICIENCY AND TEMPERATURE RISE

Combustion efficiency η_c is defined as the actual temperature rise divided by the ideal temperature rise, or:

$$\eta_c = \frac{\Delta T\ \text{actual}}{\Delta T\ \text{ideal}} \tag{1}$$

The actual combustor temperature rise, ΔT actual, was determined from the area-averaged temperature readings obtained from 120 thermocouple data points.

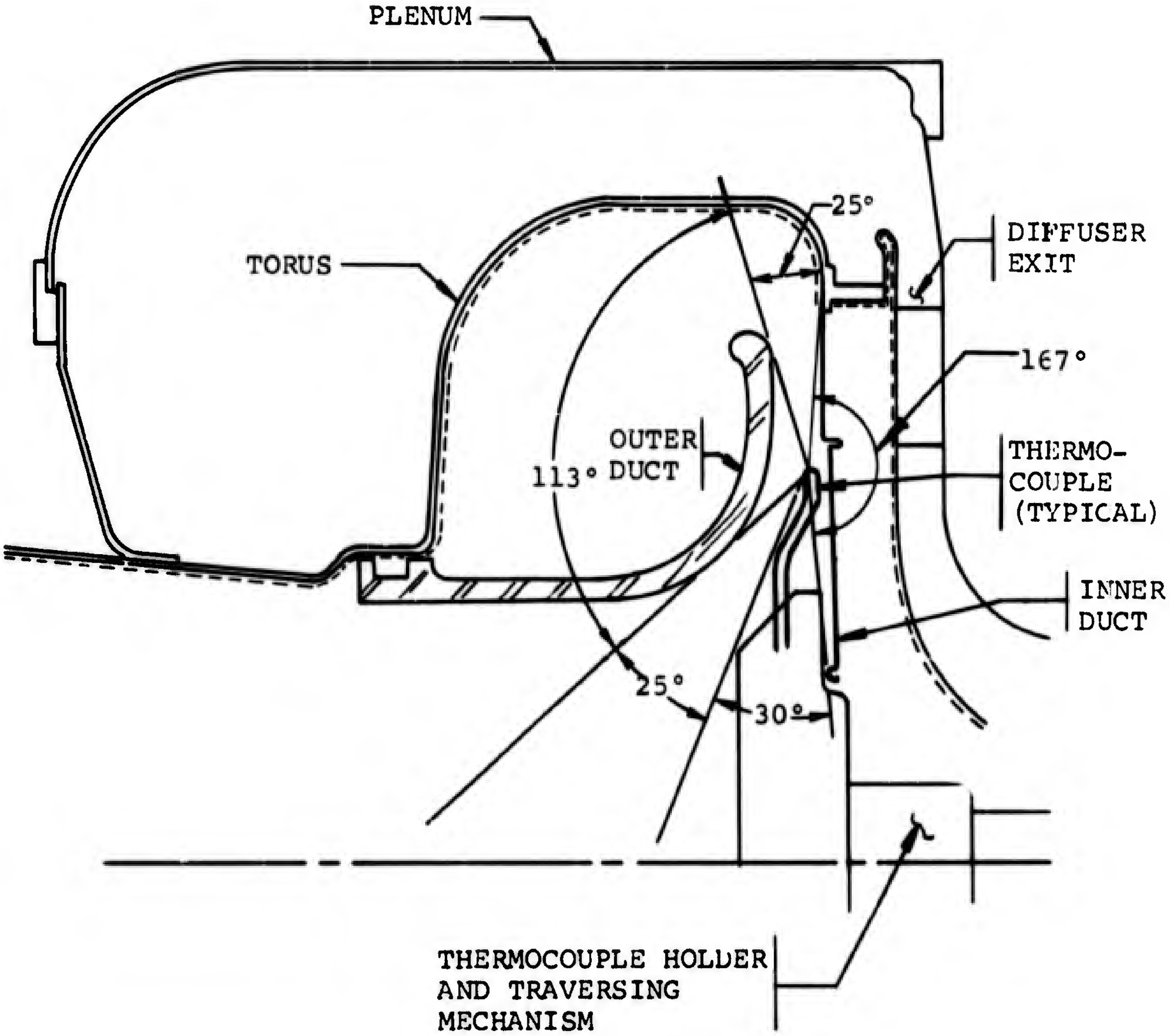
$$\Delta T_{\text{actual}} = \frac{\sum_{0}^{N=120} T_{\text{meas}} \times \Delta A}{A} - T_3 \tag{2}$$

Where: T_3 is measured inlet air temperature, °R; T_{meas} is discharge temperature for each of 120 thermocouple measurements, °R; and A is area.

The turbine inlet temperature was measured with an array of 10 thermocouples. Temperature readings were made on each thermocouple at 12 circumferential positions, yielding 120 individual temperature measurements. A cross section of the thermocouple installation is shown on Figure 109.

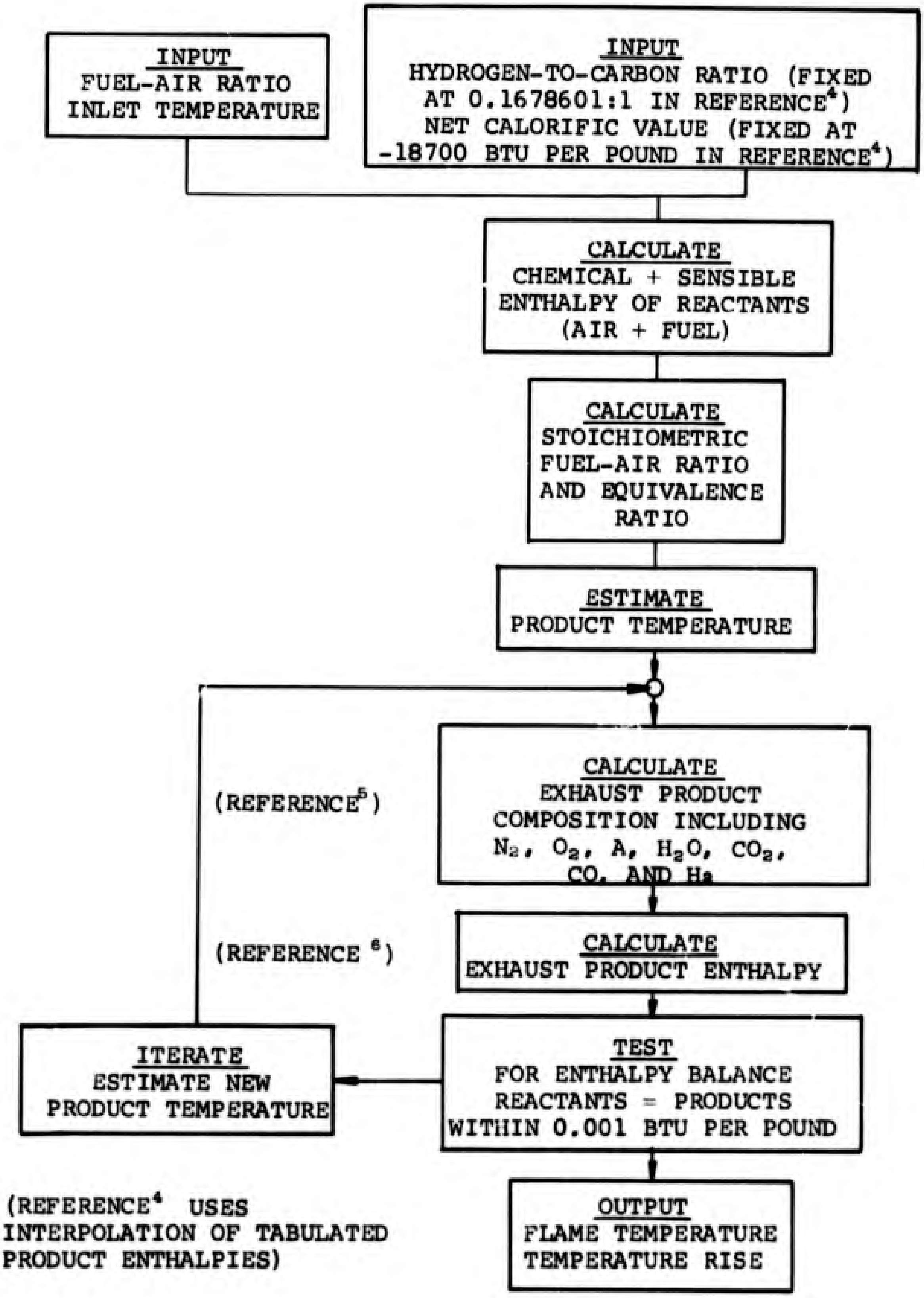
When measuring gas temperature, the normal practice is to correct the indicated thermocouple temperature for conduction and radiation errors. Radiation errors would be incurred primarily because of outer and inner duct effects. The outer duct blocks 113 degrees of the thermocouple field and the inner duct blocks 167 degrees of the thermocouple field. A test was conducted to determine the relationship between measured gas temperature, the outer and inner duct temperature, and the exposed portion of the torus. Test results indicated that all of these component temperatures were close to the measured gas temperature and that the incurred radiation error was negligible. Consequently, the measured temperatures were judged as true gas temperatures.

The ideal temperature rise, ΔT_{ideal}, for Shelldyne-H fuel-air mixtures was computed and was based on the method indicated in Reference[4]. A computational flow diagram of the program used is shown in Figure 110. This computer program includes capability for input values of fuel hydrogen-carbon ratio and net calorific value so that fuels other than MIL-T-5624, Grade JP-4, can be used.



TURBINE INLET TEMPERATURE MEASUREMENT
THERMOCOUPLE INSTALLATION

FIGURE 109



COMPUTATIONAL FLOW DIAGRAM

FIGURE 110

APPENDIX II

MONITORING OF MIL-T-5624, GRADE JP-4, FUEL

MIL-T-5624, Grade JP-4, fuel was sampled and evaluated for comparative performance as shown below:

Date 1969	Specific Gravity	Temperature °F	Specific Gravity Corrected to 60°F
8 Sept	0.760	86	0.771
1 Oct	0.763	81	0.773
2 Oct	0.765	78	0.772
22 Oct	0.774	79	0.782
23 Oct	0.770	77	0.776
24 Oct	0.774	75	0.780
27 Oct	0.770	76	0.776
			Average 0.7757 +0.80% -0.60%

Based on Reference[7], the heat of combustion of MIL-T-5624, Grade JP-4, fuel is relatable to its specific gravity in the form:

$$q_n = 22{,}130 + \frac{2560}{\rho_{60} - 1.53} \qquad (1)$$

where: q_n = net heat of combustion, Btu per pound
ρ_{60} = specific gravity at 60°F

Differentiating (1)

$$dq_n = -\frac{2560}{(\rho_{60} - 1.53)^2}\, d\rho_{60} \qquad (2)$$

Dividing through by q_n

$$\frac{dq_n}{q_n} = \frac{\dfrac{2560\rho_{60}}{(\rho_{60} - 1.53)^2}}{22{,}130 + \dfrac{2560}{\rho_{60} - 1.53}} \quad \frac{d\rho_{60}}{\rho_{60}} \qquad (3)$$

or for small changes in ρ_{60}, the percentage change in q_n for the change in ρ_{60} is:

$$\frac{\Delta q_n}{q_n}(100) = -\frac{\dfrac{2560\rho_{60}}{(\rho_{60} - 1.53)^2}}{22{,}130 + \dfrac{2560}{\rho_{60} - 1.53}}(100)\frac{\Delta\rho_{60}}{\rho_{60}} \qquad (4)$$

Evaluating (4) at the average specific gravity observed, 0.7557:

$$\frac{\Delta q_n}{q_n}(100) = -0.1865\ (100)\frac{\Delta\rho_{60}}{\rho_{60}} \qquad (5)$$

The total range of observed specific gravities was 1.4 percent, which would result in a corresponding range of heat release of:

$$\frac{\Delta q_n}{q_n}(100) = 0.1865\ (1.4) = 0.261 \text{ percent} \qquad (6)$$

The results obtained during the course of this program were not normalized for the change in MIL-T-5624, Grade JP-4, fuel heat release because the maximum error so incurred is on the order of one-quarter of one percent. This inaccuracy is well within the accuracy to which the remainder of the data were taken.

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13. ABSTRACT

Shelldyne-H* fuel was evaluated with an AiResearch Model GTP30 Gas Turbine Engine, and some of its components. Fuel properties data supplied by Shell Oil Company were verified. Elevated-temperature aging tests of various elastomers indicated that Viton A, LS-53, and Buna N are compatible with Shelldyne-H fuel, and that materials containing straight silicone compounds are incompatible with Shelldyne-H fuel. Fuel control tests, including fuel-pump tests were performed at temperatures down to minus 65°F. Low temperature pump cavitation was experienced. Ignition was a problem, but combustion tests revealed good efficiency and temperature distribution after combustion was achieved. Engine starts with Shelldyne-H fuel could be made above plus 10°F with the use of a cartridge starter gas system. Engine starts could be made above minus 40°F, if ignition was initiated with MIL-T-5624 Grade JP-4 fuel. A system problem, identified at low temperatures, was a means to get all usable fuel from the fuel tank to the engine because fuel adhered to the tank walls.

degrees

*Shelldyne-H is a trademark of the Shell Oil Company.