Report No. FAA-DS-70-6

STUDY OF TURBINE ENGINE OPERATION WITH GELLED FUELS

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MAY 1970

INTERIM REPORT

Prepared for

FEDERAL AVIATION ADMINISTRATION

Aircraft Development Service

Washington D. C., 20590

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.
FAA-DS-70-6

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
STUDY OF TURBINE ENGINE OPERATION WITH GELLED FUELS

5. Report Date
May 1970

6. Performing Organization Code

7. Author(s)
ROBERT F. SALMON

8. Performing Organization Report No.
FAA-NA-70-6

9. Performing Organization Name and Address
National Aviation Facilities Experimental Center
Atlantic City, New Jersey 08405

10. Work Unit No.

11. Contract or Grant No.
Project No. 520-005-02X

13. Type of Report and Period Covered
Interim Report
1968 - 1969

12. Sponsoring Agency Name and Address
FEDERAL AVIATION ADMINISTRATION
Aircraft Development Service
Washington, D. C. 20590

14. Sponsoring Agency Code

15. Supplementary Notes
None

16. Abstract
Three types of gelled Jet A-1 fuels were tested to determine the compatibility of the thickened fuels with typical turbojet engines. The three fuels were: (1) Gel A, a 2-percent concentration of a styrene polymer additive in Jet A-1, (2) Gel B, a 2-percent concentration of a sodium-free styrene polymer additive in Jet A-1, and (3) Gel C, an aluminum octoate gel in Jet A-1, concentrations ranging from 0.2 to 1.0 percent. The two polymer gels had a 13,000-centipoise reading on the Brookfield Viscometer, RVT model, and the aluminum octoate ranged from 2,800 to 13,000 centipoises. Spray pattern tests were run with the fuels and a 1-hour engine test was conducted on a J47 engine. Comparison of engine performance when using regular JP-4 and polymer gelled Jet A-1 fuels indicated that the gel did not markedly affect the engine performance in the power range from 70 to 95 percent of rated engine r/min. The polymer gels, however, could not be used from engine light-off to idle power in the J47 engine since they required higher fuel manifold pressures for vaporization than the engine could produce during the starting sequence. A 15-minute test using Gel A was conducted on a J57 engine. When operating the J57 engine, the Gel A was used from light-off to maximum power, and no difficulty was experienced in running the unmodified engine with this fuel. Gel C could not be used successfully in the J47 engine even when providing fuel manifold pressures of 250 psi, corresponding with 82 percent of rated engine rotor speed. Combustion could not be maintained and a relight could not be effected when switching back to JP-4 fuel. Preliminary chemical analysis of a combustion can, after 1 hour of engine operation using the sodium-free polymer Gel B, indicated no corrosive effects or excessive carbon buildup in the combustion chamber.

17. Key Words
Combustion
Gelled Fuel
Safety

18. Distribution Statement
Availability is unlimited. Document may be released to the Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151, for sale to the public.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	25	$3.00 *

Form DOT F 1700.7 (8-69)

* For sale by the Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

INTRODUCTION

Purpose

The purpose of this project was to determine the overall compatibility of a typical turbine engine and its fuel system components with gelled and emulsified fuels. This Interim Report deals with the testing of three types of gelled fuels in a J47 and a J57 turbojet engine.

Background

The Controlled Flammability Fuels (C.F.F.) Program conducted at the National Aviation Facilities Experimental Center (NAFEC), Atlantic City, New Jersey, deals with a variety of problems associated with the use of thickened fuels. Previously tests had been conducted using these fuels in a small-scale simulated crash test wherein 1-gallon samples of fuel were atomized by impact on a heavy grid. The results of the simulated crash tests indicated that these three gels reduced the crash fire hazard considerably by greatly reducing the atomization of fuel when a tank is ruptured under severe impact. It was decided, therefore, that actual engine tests would provide additional useful information about the potential values of the new fuel formulations.

Description of Fuel

Two of the three types of fuels which were used in these tests used a polymer additive as the gelling agent. They are designated Gel A and Gel B in this report. The third fuel was an aluminum octoate gel designated as Gel C. Gels A and B used a styrene polymer additive which was mixed under high-shear action with the base fuel, Jet A-1. It was added to the fuel and the shearing action of a gear pump, effectively dispersed the additive throughout the fuel and resulted in a homogeneous fluid. The appearance of the resulting gel was that of a silky, clear fluid. In order to standardize the viscosity measuring system used in comparing various gels, it has been the practice at NAFEC to test them with a Brookfield Viscometer, RVT model. Using a No. 6 spindle at 10 r/min, both the A and B gels have a 13,000-centipoise rating. The concentration of additive used in the fuels ranged from 2.0 to 2.5 percent by weight. Both of these gels were deceptively fluid and flowed readily into a pump under gravity. To the eye, Gel B appeared to be more fluid than Gel A despite the viscometer readings. This apparently greater fluidity of Gel B was borne out by the engine tests described later in this report. The temperature sensitivity of the fuels was not measured specifically, but over the range from 32°F to 115°F no change in viscosity was apparent. The additive manufacturer claimed that the fuel when gelled was insensitive to temperature over the range from -60°F to +160°F. Once the gel had been formed, it appeared to be only slightly affected by the shear action of the pump. The gel relaxed somewhat immediately after being pumped but recovered its initial viscosity within a short time. No tendency to bleed or separate was noted during the tests; however, Gel A could be instantly degelled by the addition of very small quantities of alcohol. Gel B was much less sensitive to this chemical; however, both gels were diluted somewhat by the addition of small quantities of water.

The aluminum octoate gel (Gel C) was mixed at NAFEC. A range of concentrations from 0.2 to 1.0 percent was used. This gel had a very high cohesive characteristic and the 1.0-percent concentration produced the same reading (13,000 centipoises) on the Brookfield Viscometer with the lowest gel concentration (0.2 percent) ranging down to 2,800 centipoises. It displayed strong tendencies to hold together and flowed readily from a can. A peculiar characteristic of Gel C was demonatrated by allowing it to flow out over the lip of a tilted container. When the container was returned to an upright position, the fuel which had actually flowed out would be drawn back into the can due to the cohesive nature of the gel. This characteristic seemed to indicate that there would be problems in handling the fuel in a typical engine fuel system. The degree of temperature sensitivity and the effect of pumping on the gel were not explored because it was felt that the fuel nozzle spray pattern test and engine performance test would provide sufficient information about the feasibility of using this fuel.

In mixing the gels, the base fuel used was Jet A-1. The thickening additives work with either Jet A fuel or JP-4 fuel, but since the program is set up for safety investigation in commercial aircraft operation and Jet A-1 is the fuel used by commercial jets, Jet A-1 was used exclusively as the base fuel for the gel in the engine tests. When using the additives with JP-4 fuel, it was found that a higher concentration of additive was necessary in order to achieve the same viscosity as that obtained with Jet A-1 fuel.

In comparing engine performance when using the gels and regular fuel, JP-4 was used as the regular fuel throughout the tests. Regular JP-4 was used as the reference fuel because the engine test facilities at NAFEC use this fuel exclusively in all their test work. Had Jet A-1 fuel been used as the reference fuel in the tests, the results of the comparison would have been only slightly different, roughly in proportion to the relative heating values of the two fuels.

Test Equipment

A description of the test equipment is divided into three categories:

1. Equipment used for mixing the gels.

2. Equipment used in running the burner fuel nozzle spray pattern tests.

3. Equipment used in operating the engines with the gel.

Mixing Equipment: The mixing unit used in the test work consisted of the following components:

1. A 500-gallon capacity vessel.

2. A hopper for the additive with a venturi feed into the fuel line.

3. High-shear gear pump; 1,800 r/min and 100 gal/min capacity.

4. A recirculating line returning the fuel to the tank.

5. An electric immersion heater.

A schematic of the mixing apparatus is shown in Figure 1. The electric immersion heater was used to study the effect of temperature on the fuel during the mixing process. It was noted that fuel at low temperatures seemed to require higher shearing action to properly absorb the polymer additive and produce a satisfactory gel. The actual definitive answer on this aspect of the mixing process will require more work.

Spray Pattern Test Equipment: In conducting burner-can nozzle spray pattern tests, the equipment required was as shown in Figure 2. The purpose of these tests was to observe the pattern of the fuel when being forced through an engine fuel nozzle at various engine fuel pump pressures. To accomplish this, one fuel line running from the fuel manifold was diverted to an externally mounted engine fuel nozzle. By opening a valve, the fuel could be diverted from its regular path and forced through the external nozzle. The measurement of percent rated engine r/min and fuel manifold pressure was recorded while simultaneously photographing the fuel spray pattern.

Engine-Operating Equipment: The test arrangements used when operating a J47 and a J57 engine on gelled fuel are shown in Figure 3. Essentially, the gel fuel system consisted of a tank containing the fuel, a submerged fuel boost pump in the tank, and a two-way valve in the fuel line located between the boost pump and the engine fuel line. The engine was operated on regular JP-4 fuel during normal operation and at the discretion of the engineer, the two-way valve setting was changed cutting off the flow of the regular fuel and opening the passage for the gelled fuel. In this way, a data point was taken at a

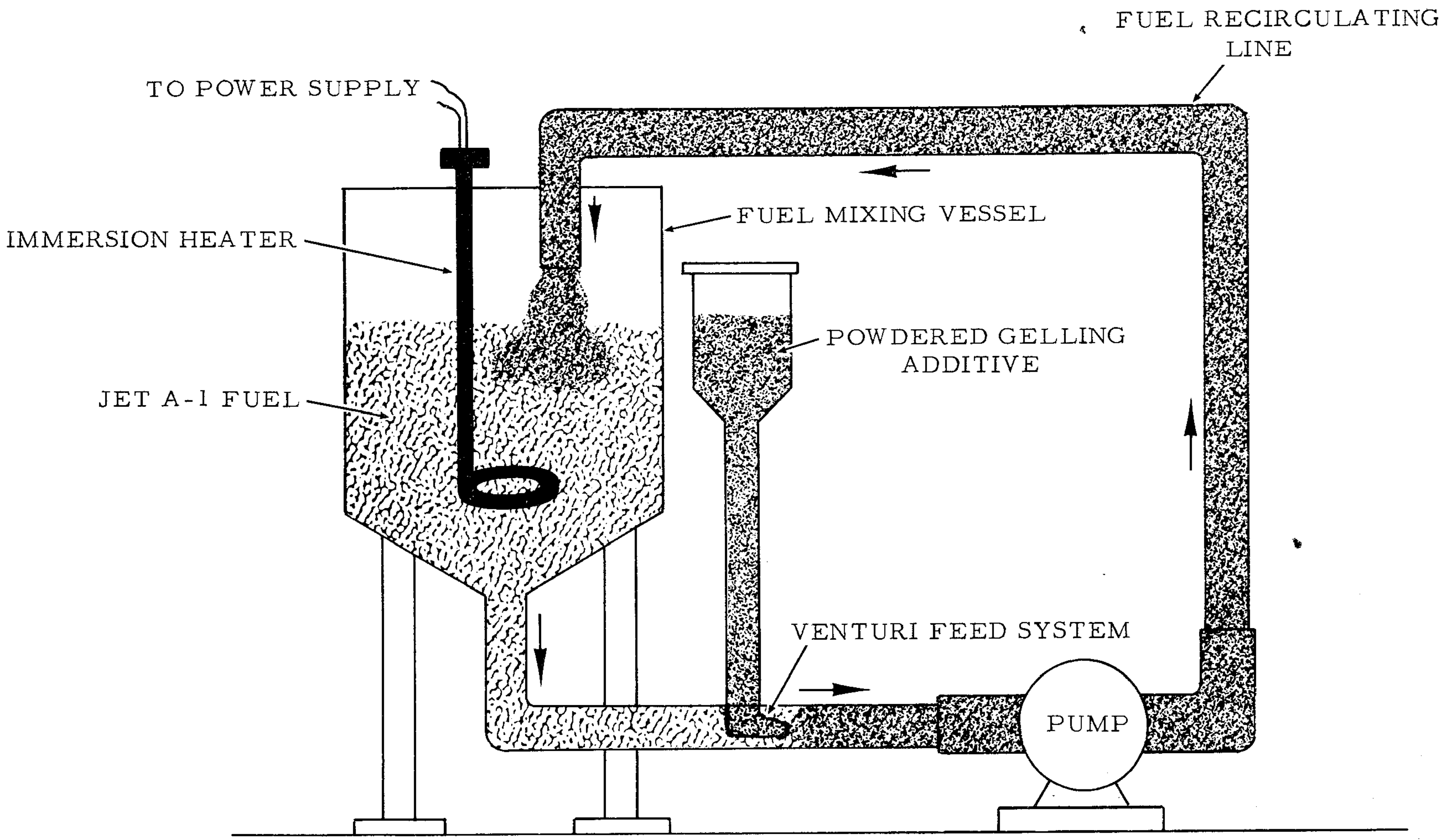


FIG. 1 SCHEMATIC OF MIXING APPARATUS

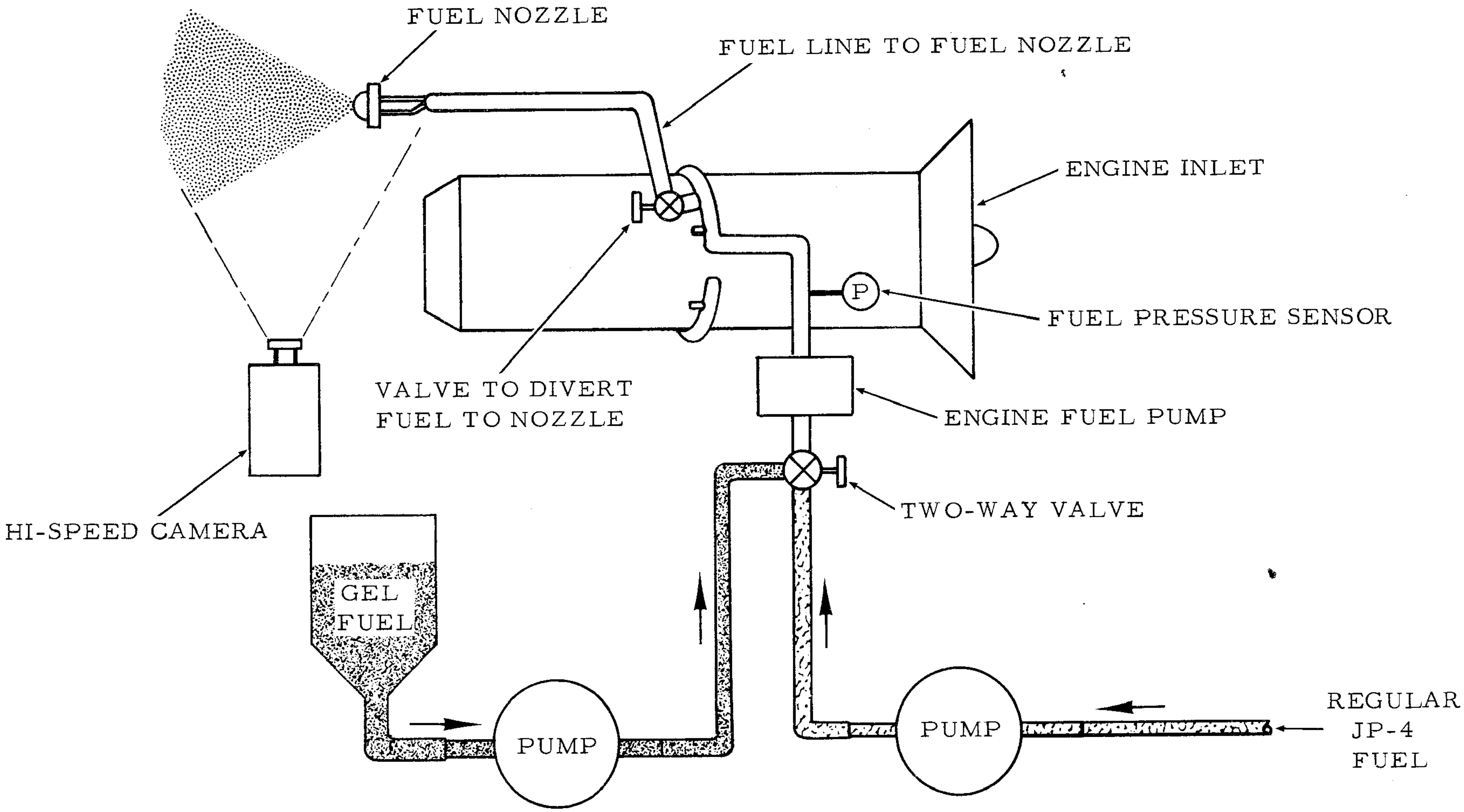


FIG. 2 SCHEMATIC OF FUEL NOZZLE SPRAY PATTERN TEST EQUIPMENT

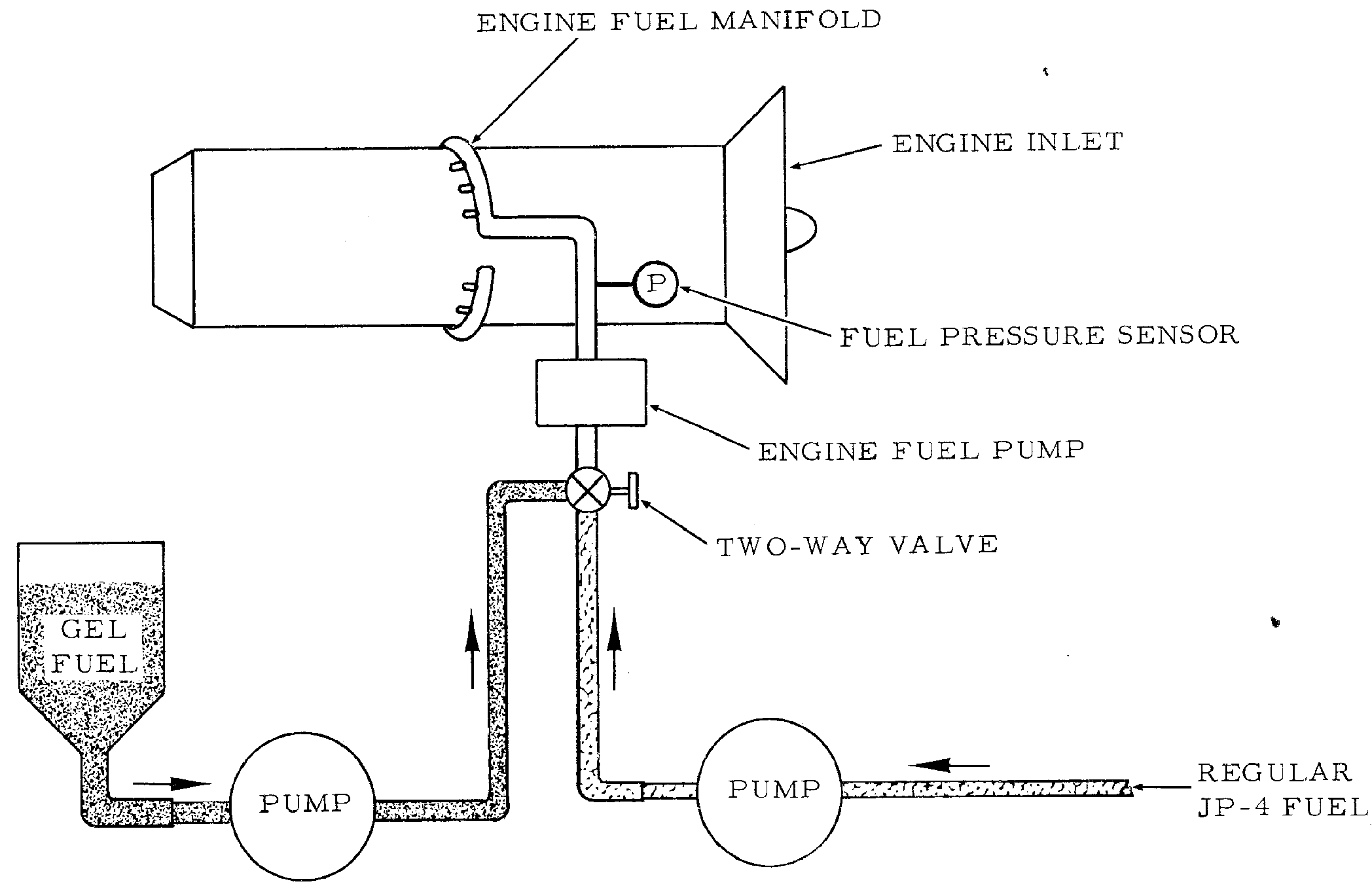


FIG. 3 SCHEMATIC OF J47 AND J57 ENGINE TEST EQUIPMENT

steady-state condition with regular fuel, and immediately thereafter a comparable data point was taken for the gelled fuel operation.

A second arrangement (Figure 4) was used when running the engine to determine the effects on the combustion chamber while using gelled fuel. In this test, the fuel line to the No. 9 combustion can was plumbed to receive only the gel fuel. The engine was started and operated at a particular power setting using JP-4 fuel but with the No. 9 can not receiving any JP-4 fuel. When the switch to gel fuel was made, the No. 9 can would receive gel fuel along with the rest of the engine.

DISCUSSION

Spray Pattern Tests

The spray pattern tests were run to determine the pressure level required to effectively vaporize the gelled fuel when forced through a dual-mode fuel nozzle. The nozzle used in the tests was taken from a J47 engine and had a primary and secondary flow system. At lower engine fuel pump pressures, only the primary nozzle orifices permitted the passage of fuel.

As the pressure was increased beyond a certain level, a spring-loaded piston opened more and more passages for fuel. The secondary fuel formed an increasingly longer and longer conical pattern. The characteristics of the regular JP-4 fuel spray pattern were photographed over a range of engine speeds and pump pressures (Figure 2). These characteristics were then compared to those observed with gel fuel at the same engine speeds and pump pressures. It was observed that Gel A was vaporized and had a pattern similar to the regular liquid fuel at nozzle pressures in excess of 160 psi. The spray pattern tests can only define the problem areas for the gel fuel when using the particular fuel nozzles employed in these tests. Different nozzles would probably be able to vaporize the fuel at lower pressures, but definite indications of a potential problem area for engine operation with thickened fuels became apparent during these tests.

The spray pattern tests using the Gel C, which were run on a bench rig, indicated the problems which would arise when testing the engine. The fuel would not vaporize at pressures below 250 psi, and even at that level, there was a stringiness to the appearance of the fuel. When the valve was closed, stopping flow to the fuel nozzle, the fuel in the line downstream of the valve flowed slowly in a continuous stream through the nozzle orifices and built up in a lump on the ground. This flow actually overcame gravity forces and flowed "uphill" due to the cohesiveness of the gel, and over a period of time, drained

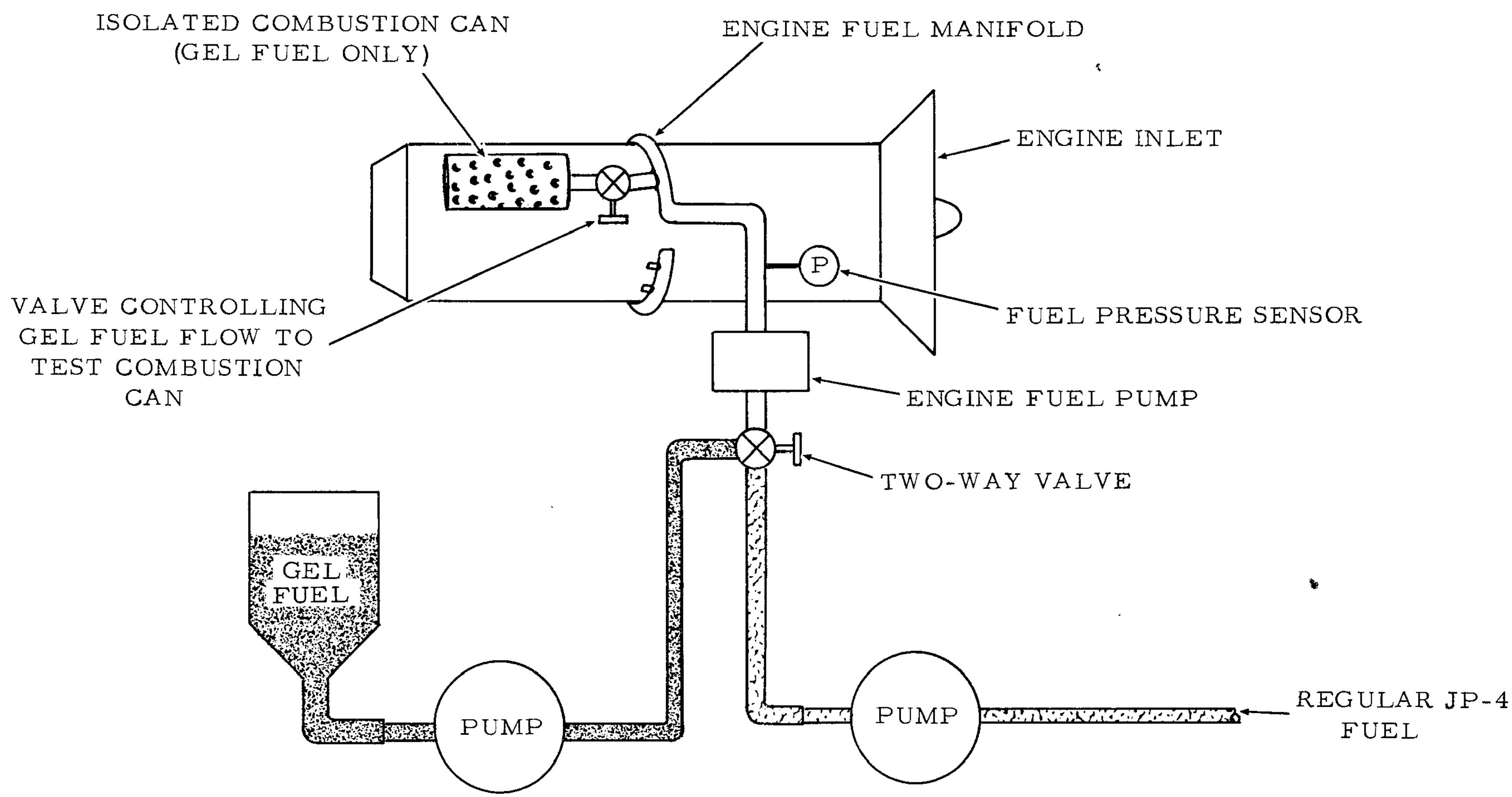


FIG. 4 SCHEMATIC OF ENGINE TEST EQUIPMENT WHEN OPERATING WITH ISOLATED COMBUSTION CAN

completely from the line. It was obvious that this type of seepage would prove very harmful to a jet engine if no modifications were made to the overboard dump valve system. A buildup in the combustion can of a lump of fuel after engine shutdown could prove damaging to the engine during a subsequent engine start due to the development of hot spots, etc., in the combustion can.

Engine-Operating Tests

In operating the engine on gelled fuel, the following series of tests was made:

1. J47 engine operation using 2.0 percent Gel A (Jet A-1 Fuel).

2. J57 engine operation using 2.0 percent Gel A (Jet A-1 Fuel).

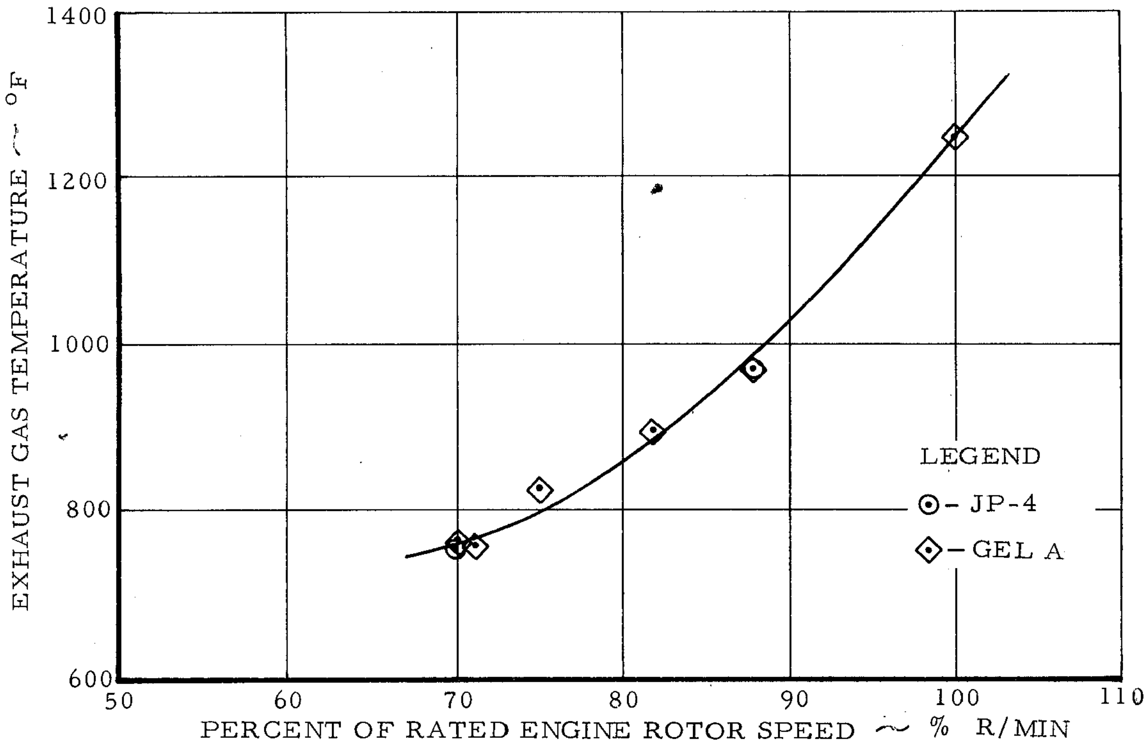
3. Engine starts on a J57 engine after leaving 2.0 percent Gel A in the fuel system overnight.

4. J47 engine operation using 2.0 percent Gel B and 1.0 percent Gel C.

5. One-hour J47 engine test using 2.5 percent Gel B.

J47 Engine Operation with Gel A: The first engine tests conducted with the gel fuel were run using a J47 engine and the original gel, Gel A. The gel was a 2.0-percent concentration of additive in Jet A-1 fuel. The test was conducted with the equipment as shown in Figure 3. These data are plotted in Figure 5 wherein an engine performance comparison is made between JP-4 fuel and Gel A. It is apparent from the figure that the engine performance when using the gel was comparable to that obtained with regular JP-4 fuel. The slight difference noted could be attributed to the differences in heating value of JP-4 and Jet A-1 fuels. The engine could not operate below 70-percent rated engine r/min using the gel. This corresponded with a fuel pump pressure of 150 psi. The earlier spray pattern tests showed that the fuel would not atomize satisfactorily at pressures below this level when using a J47 fuel nozzle, and the engine tests substantiated the earlier work. An engine relight could not be accomplished even though the regular JP-4 fuel was switched into the system as soon as the engine faltered.

J57 Engine Operation with Gel A: The J57 engine tests were conducted with essentially the same test equipment as that used in the J47 tests. The J57 is a more modern turbojet and the commercial model of this engine is still in use on transport aircraft. The fuel control system of the J57 engine is a sophisticated hydromechanical type and



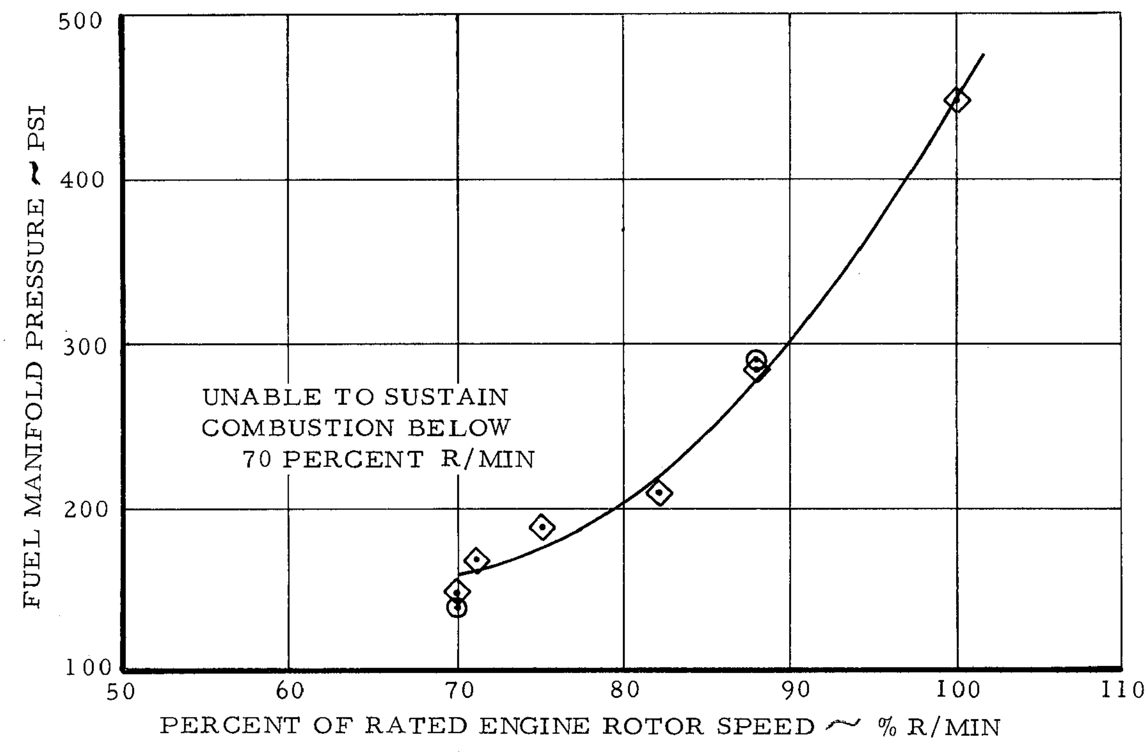


FIG. 5 J47 ENGINE PERFORMANCE USING REGULAR JP-4 & GEL A

would prove to be a more challenging device to the gelled fuel than the relatively simple unit used on the J47 for this purpose. A series of data points was obtained ranging from idle to 95 percent of rated N2 rotor speed. A comparison of the performance of the J57 engine when operating on regular JP-4 fuel and Gel A is shown in Figures 6 and 7. It can be seen in these comparisons that the engine thrust when using Gel A was approximately 2.0 percent lower than the JP-4 fuel powered engine for the same percent of rated N2 rotor speed. The data also indicated that the fuel pressure as it entered the fuel nozzles ranged from 300 psi at light-off to 590 psi at 95 percent of rated N2 rotor speed.

The comparison of exhaust gas temperature and fuel manifold pressure versus percent rated engine r/min (Figure 6) shows almost identical performance for JP-4 fuel and Gel A. The only differences noted were at the low percent of rated-engine r/min level where the fuel manifold pressure of the Gel A was about 8 percent lower than the regular JP-4 fuel. When it was apparent that the engine performed satisfactorily over the entire speed range and the fuel nozzle pressure level was considerably higher than the critical range noted in the J47 tests, it was clear that engine start tests should be run. Three successful engine starts were made and the only difference noted in the starting cycle was the fact that it took several seconds longer than usual for the engine to accelerate from light-off to idle. The engine was then shut down with the gel in the lines. The following day another start was attempted with the gel fuel in the lines from the previous day's tests. This start was also successful, and no change from the performance previously observed was noted.

The J57 engine tests indicated that the use of Gel A did not introduce any major problems to the successful operation of a relatively modern turbojet engine. This conclusion was drawn from very limited test data, and more extensive testing might have shown some problem areas.

In referring to FAA Report NA-69-1 (Reference 1), a report which deals with combustion characteristics of gelled fuels, it is noted that at 60 inches HgA and 400°F (pressure and temperature of air in combustor) the combustion efficiency of Gel A deteriorates markedly. The flight condition which would approximate these parameters would be 35,000 feet, 0.6 Mn and flight idle power for a J57 engine. This is a marginal flight condition and at the worst would only slightly diminish an aircraft's flight envelope.

<u>J47 Engine Operation with Gel B</u>: The next phase of the engine test program dealt with an improved polymer additive gel. This fuel, Gel B, used a sodium-free styrene polymer as the gelling agent. In most respects, the gel was similar to the original Gel A but appeared to be somewhat smoother in addition to being sodium free. The viscometer reading for Gel B was 13,000 centipoises, identical to the Gel A

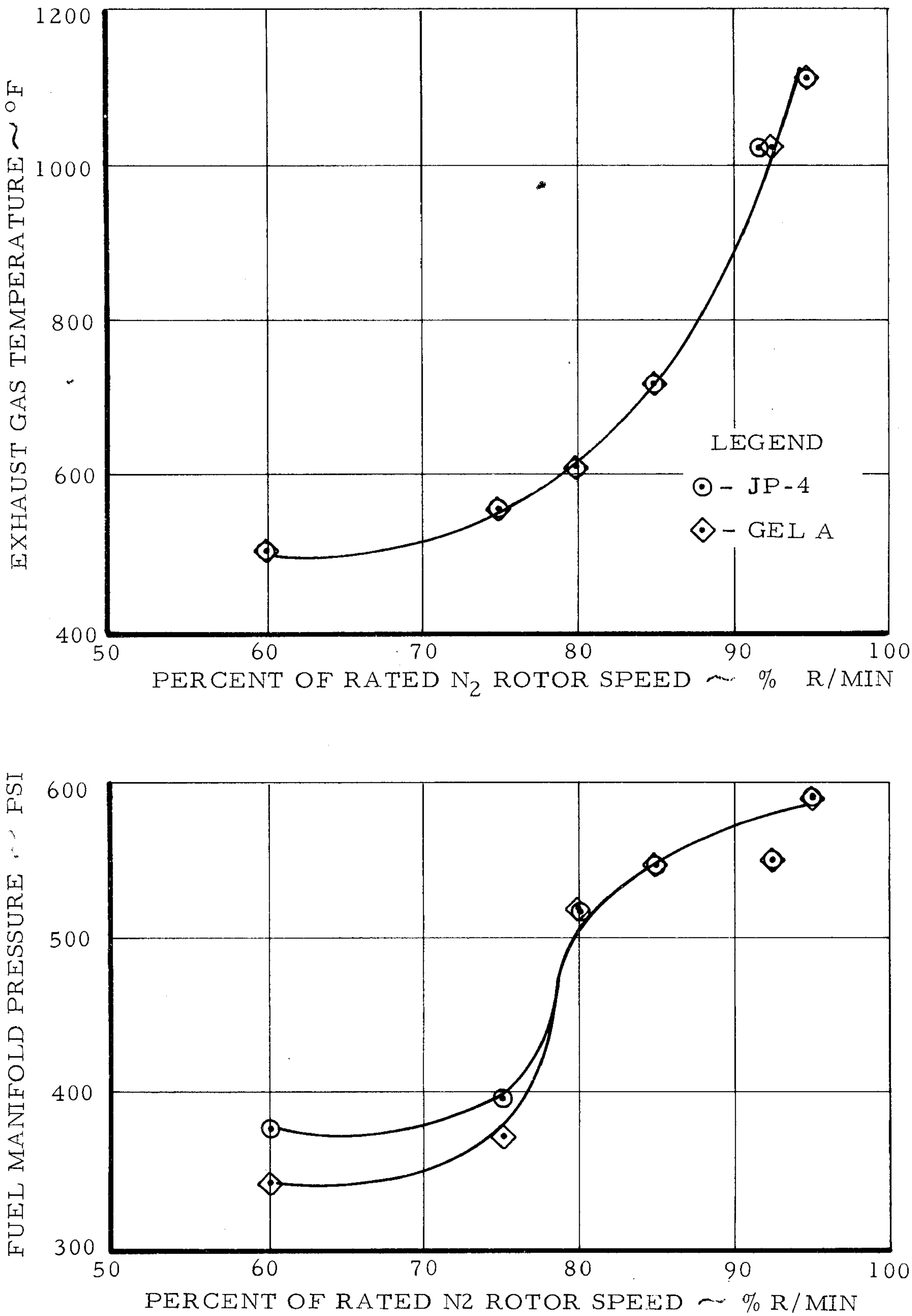


FIG. 6 J57 ENGINE PERFORMANCE USING REGULAR JP-4 & GEL A

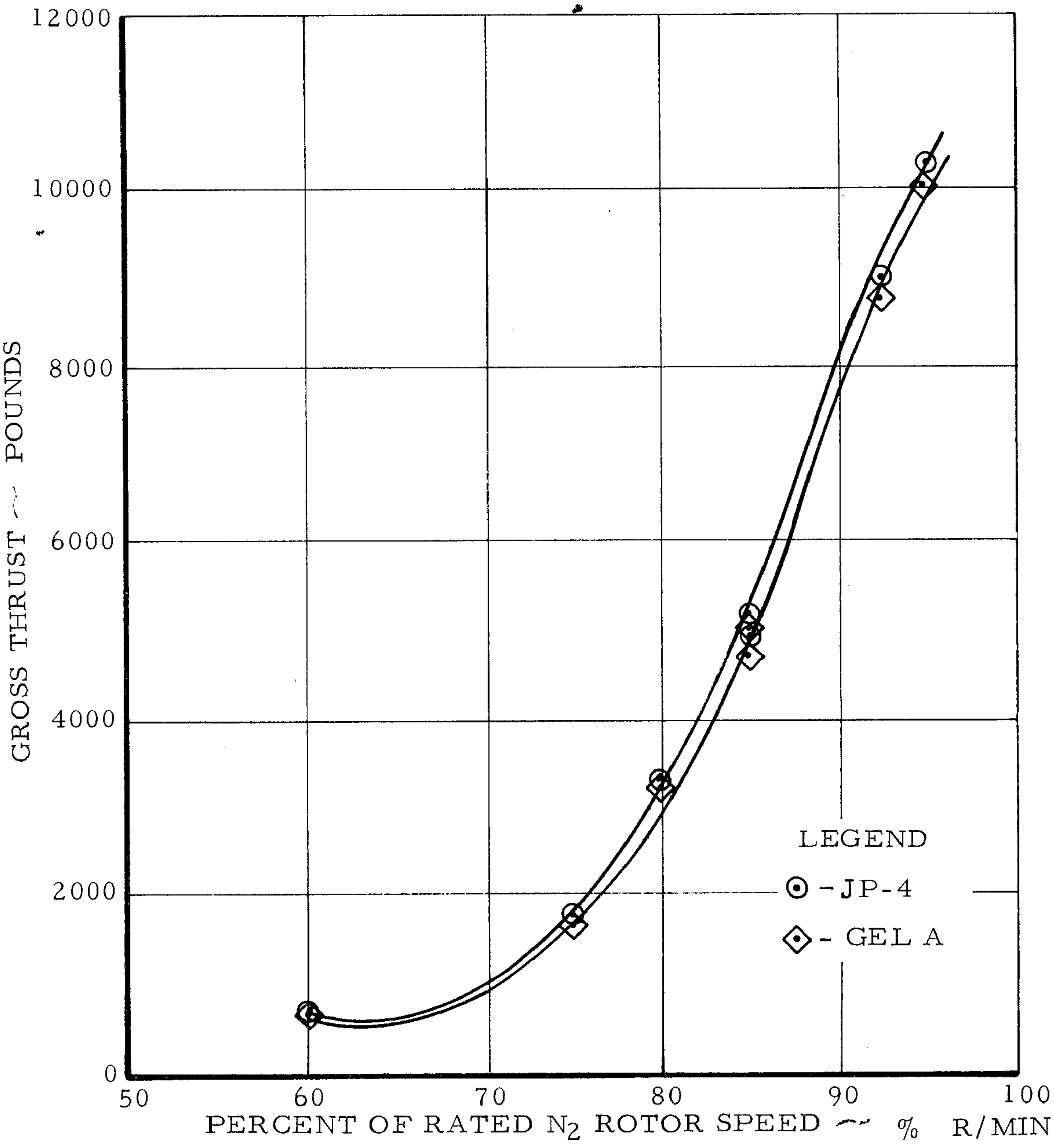


FIG. 7 J57 SEA LEVEL STATIC THRUST USING REGULAR JP-4 & GEL A

at the same spindle speed on the Brookfield Viscometer. Two types of tests were run with this fuel in the J47 engine. The first series compared engine performance when using regular JP-4 fuel with engine performance when using 2.0 percent Gel B in Jet A-1 fuel. The results of this comparison are shown in Figure 8. It is apparent from the curves that the fuel pressures of Gel B at the lower engine power settings was higher than the regular JP-4 fuel at these same settings. The higher fuel pressures and presumably better spray characteristics of the Gel B compared to Gel A contribute to the increase in the power range over which the J47 engine operated when using this fuel. The exhaust gas temperature of the engine when using Gel B (see Figure 8) was almost identical to that of JP-4 fuel at power settings above 70 percent of rated engine r/min. At the lower power settings, Gel B yielded higher exhaust gas temperature readings. The cause of this higher reading is difficult to explain since the gel had a lower heating value than the regular JP-4 fuel. It is possible that the temperature harness, which was used to measure the average gas temperature, sensed a distorted flow pattern at the very low power settings when the gel was not burned in accordance with the design of the system. At low manifold pressures, the vaporization of the fuel is marginal and larger droplet sizes occur. This would tend to delay complete combustion and move the flame farther and farther back in the can and even have burning occur through the turbine. In such a situation, the averaging temperature harness could sense local high temperatures which would result in an inordinately high average temperature reading.

No attempt was made to start the J47 engine on Gel B since the fuel nozzle spray pattern tests indicated that the relatively low manifold pressures which occur during the starting sequence would make operation in this regime impossible without some modification to the engine and fuel system combination. The reason for the higher fuel pressures experienced when using the gel (Figure 8) is not explainable at this time, and further investigation of this area would be worthwhile. There were no measurements made of the actual gel fuel flow because the flowmeters used in the system were calibrated for JP-4 fuel. A precise on-line flow measuring system for the gel is being investigated and will be in use in future tests.

A 1-hour engine test was made using Gel B fuel. In this test, one combustion can was removed from the J47 engine and cleaned before reinstalling it on the engine (Figure 4). A valve was put in the fuel line supplying fuel to the spray nozzle in this can. This valve remained closed when the engine was operated on JP-4 fuel and was only open when Gel B fuel was being burned in the engine. Due to the starting limitations of the engine, JP-4 fuel was used from light-off to idle power. Engine time using the Gel B was only recorded during the time the valve was open and Gel B was actually burning in all nine

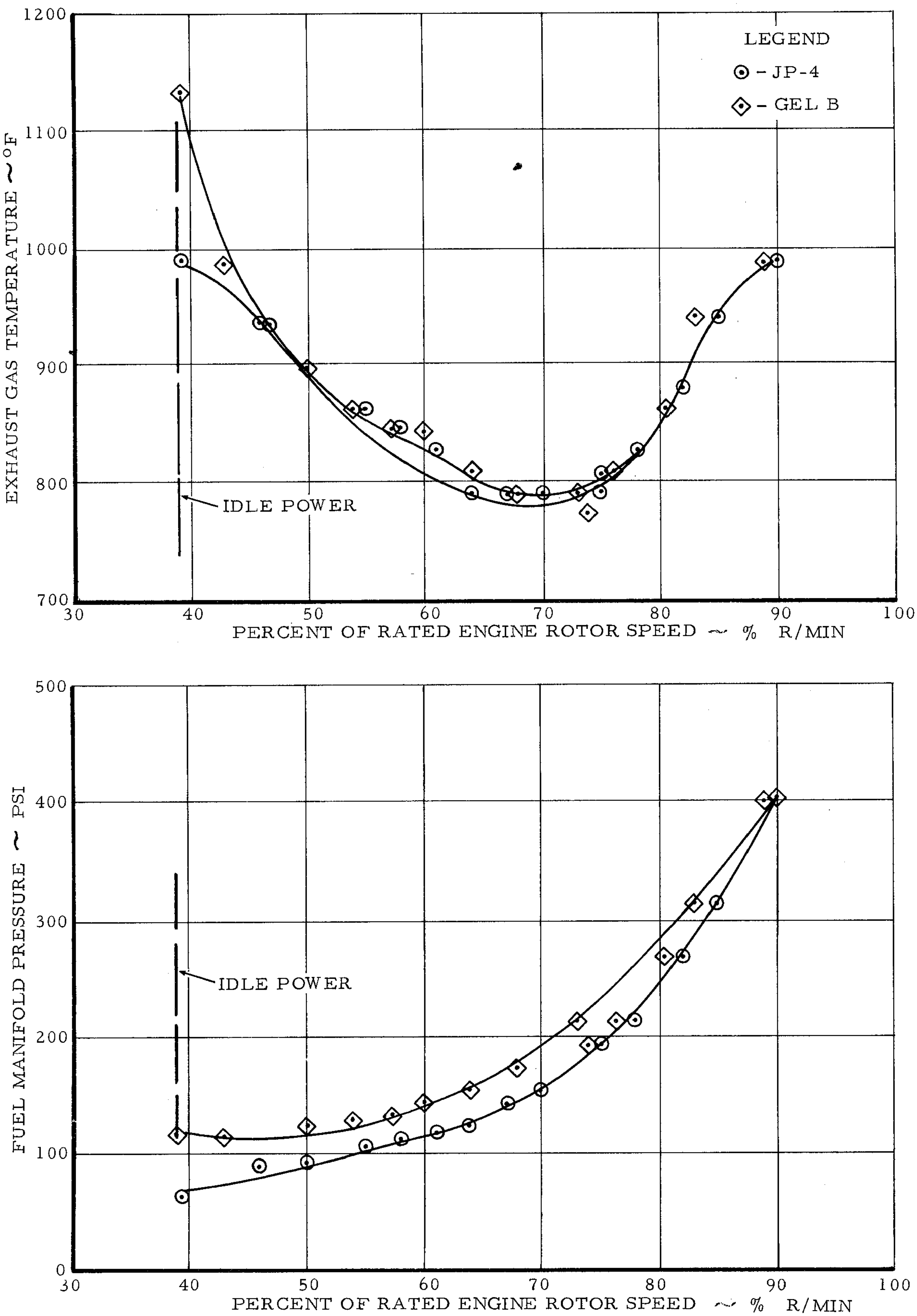


FIG. 8 J47 ENGINE PERFORMANCE USING REGULAR JP-4 & GEL B

combustion cans. The procedure used in cycling the engine was to vary the power setting from 70 to 95 percent of rated engine r/min in 5-percent increments. Each condition was held for 2 minutes and data were recorded at the end of the 2-minute period. The engine was then decelerated from 95 to 70 percent of rated engine r/min rapidly and the time recorded. After this, the engine was accelerated from 70 to 95 percent of rated engine r/min rapidly and the time recorded again. After the deceleration-acceleration cycle, the rated engine r/min was reduced from 95 to 70 percent in 5-percent increments. This sequence of operations was continued until the total amount of gel fuel available was exhausted, at which time the valve to the test combustion can was closed and the engine was switched over to JP-4 fuel.

The performance of the engine did not change during the test and the acceleration-deceleration times remained the same at the finish as at the start. No problem of operation seemed to be introduced by the use of the gel despite the fact that no modifications were made to the engine or fuel system. A preliminary chemical analysis of the residue scraped from the test combustion can indicated that the majority of the material found in the can was carbon (70 percent) and gelling additive polymer (30 percent). This was not a rigidly conducted type of chemical analysis since the percentages were only those resulting from scraping a 1-inch-wide swath along one side of the can where the most pronounced discoloration was present. The residue in the can did not build up to any appreciable degree and seemed to be almost like a plating. The use of a 40-micron filter in the fuel line introduced no problems to the system. Inspection of the filter after the test indicated normal operation. Based on the experience gained in these J47 tests and the earlier work on the J57 engine, it was felt that the Gel B fuel would operate successfully in the J57 engine from light-off to maximum power.

J47 Engine Operation with Gel C: The engine tests with the aluminum octoate (Gel C) were held to a minimum because of the expected engine difficulties which subsequently materialized. The engine could not sustain combustion when the fuel was switched from JP-4 fuel to Gel C at a power setting of 82 percent of rated engine r/min and manifold pressure of 260 psi. The engine was incapable of relighting when it was switched back to regular JP-4 fuel. The gel in the lines seeped into the combustion cans and after the next engine start with JP-4 fuel, the gel in the cans burned on the walls of the cans. On examination after the tests were completed, the evidence of the seepage in the cans could be observed by the presence of burn spots in the cans directly below the fuel nozzle orifices. It was felt that this fuel would not be compatible with an operating engine due to its stringiness and difficulty in vaporizing.

SUMMARY OF RESULTS

The following pertinent information was obtained from these tests:

1. No problems of filtration or corrosion developed when using the polymer gel during the limited testing described in this report.

2. A gravity feed system utilizing a submerged boost pump performed satisfactorily in transferring the gels from the fuel tank to the engine. No special pressurizing system was required to supply the fuel to the boost pump.

3. No modifications to the engine fuel control were required to accommodate either Gel A or Gel B.

4. The aluminum octoate (Gel C) was not satisfactory for engine operation due to its highly cohesive characteristic. It would not vaporize readily even at pressures as high as 260 psi. Gel C would introduce problems in the plumbing and shutoff valves required for transfer of fuel through the system if no modifications were made to the engine fuel system.

CONCLUSIONS

Based on the limited tests conducted on the J47 and J57 engines reported herein, it is concluded that:

1. Gel A and Gel B polymer-based gels can operate in typical turbojet engines and fuel systems provided that the fuel pressure is sufficiently high to vaporize the gel in the combustion chamber. Although all engine testing was done at sea level static conditions, there is enough data on the combustion characteristics of the gels at simulated altitudes to indicate that the gel will perform adequately at altitude and will not severely limit the flight envelope of an aircraft.

2. Gel B at a concentration of 2 percent in Jet A-1 and a viscosity of 13,000 centipoises performs satisfactorily.

3. A lower viscosity gel with essentially the same characteristics as those of Gel B would perform at least as well and would, in all likelihood, enlarge the operational envelope in which it could perform.

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1. Atkinson, A. J., Evaluation of Experimental Safety Fuels in a Conventional Gas Turbine Combustion System, FAA Report No. NA-69-1 (DS-68-27), Naval Air Propulsion Test Center, Aeronautical Engine Department, Naval Base, Philadelphia, Pennsylvania. (April 1969, 25 pp.)