Report No. NA-69-1

(DS-68-27)

FINAL REPORT

Agreement No. FA67NF-AP-20

Project No. 520-005-02X

EVALUATION OF EXPERIMENTAL SAFETY FUELS IN A CONVENTIONAL GAS TURBINE COMBUSTION SYSTEM

APRIL 1969

Prepared for

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
National Aviation Facilities Experimental Center
Atlantic City, New Jersey 08405

by

NAVAL AIR PROPULSION TEST CENTER
Aeronautical Engine Department
NAVAL BASE, PHILADELPHIA, PA. 19112

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EVALUATION OF EXPERIMENTAL SAFETY FUELS IN A CONVENTIONAL GAS TURBINE COMBUSTION SYSTEM

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Prepared by
Andrew J. Atkinson

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FOREWORD

This report was prepared by the Naval Air Propulsion Test Center for the Federal Aviation Administration. The work effort was part of a program of the Engineering and Safety Division, Aircraft Development Service, Washington, D. C. The work was administered under the direction of Mr. Robert F. Salmon who served as project engineer for the Propulsion Section, Aircraft Branch, Test and Evaluation Division, National Aviation Facilities Experimental Center, Atlantic City, New Jersey.

ABSTRACT

Performance evaluation of a typical gas turbine engine combustion system was conducted to determine the combustion characteristics of two gelled Jet A fuels (Jet A plus 1.5% N-coco-γ-hydroxybutyramide, and Jet A plus 2% of a styrene type polymer).

Testing of an emulsified fuel was terminated due to separation of the emulsion by the shearing action of the boost pump in the system. The conclusions reached: (1) indicate the feasibility of employing gelled fuels from a combustion standpoint and, (2) demonstrate filtration, atomization, and deposition problems.

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INTRODUCTION

Studies indicate that aircraft-crash casualty and fatality rates increase in those situations where post-crash fire exists. Under crash impact and fuel tank rupture, fuel is exposed to various ignition sources (hot surfaces, friction sparks, electrical sparks, etc.); a situation which lends itself to disastrous conditions. In order to control this hazard, various approaches can be taken. These approaches include the modification of fuel tanks, the elmination of ignition sources and the alteration of fuel characteristics.

Modified fuels, in the form of gels, have been investigated by the Federal Aviation Administration (FAA) and others to evaluate them for candidacy as "safe" fuels. It has been shown that a gelled fuel, being a jelly-like solid, will not flow as readily from a fuel tank in a crash situation, will not readily mist, and has a reduced rate of vaporization. Because of these characteristics, the susceptibility of the fuel to ignition is mitigated and its burning rate is reduced. Another type of modified fuel, in the form of an emulsion, having properties similar to those of a gel, has undergone a number of sea level engine tests. Since investigations of the safety characteristics of gelled fuel have shown promise, an examination of its compatibility with present engine components was initiated.

The purpose of this project was to compare the performance of a typical gas turbine engine combustion system when using gelled turbine fuels to that when using a conventional turbine fuel. The gelled fuels were evaluated at various combustor operating conditions for such performance parameters as: (1) combustion efficiency, (2) discharge temperature profile, and (3) range of operation.

Under agreement with the FAA, the principal candidate to be evaluated contained a gelling additive N-coco-γ-hydroxybutyramide and was designated gelled fuel X. A second candidate containing a styrene-type polymer in powder form was also investigated, but in less depth. This candidate was designated gelled fuel Y.

Some difficulty was encountered when testing with gelled fuel X which necessitated equipment modification. These changes included: (1) the installation of a positive pressure feed to introduce the gel to the system, (2) the installation of two low pressure pumps preceding the fuel flow measuring elements, and (3) the closing of all filter bypass modes. With both gels, it was necessary to remove all filters with fine porosity.

This report presents the details of the work performed, the data obtained, and the conclusions established.

TEST PROGRAM

This program included a laboratory investigation to determine the operational characteristics of a J-79 combustor when subjected to modified fuels. Baseline performance for the gelled fuel evaluation was obtained using a kerosene type fuel conforming to Specification ASTM D-1655-65T grade Jet A. Emphasis was placed on evaluating gelled fuel X which is formulated by mixing N-coco-γ-hydroxybutramide with the base fuel at a concentration of 1.5% by weight. Combustion tests were performed over the following range of conditions.

Test Section Pressure in. Hg abs.	Fuel Temperature °F	Air Temperature °F	Air Flow lb/sec.	Approximate Fuel Flow Range lb/hr.
150	130, 60, 0	540	7.60	170 - 540
60	130, 60, 0	400	3.55	85 - 310
30	-30	-30	3.55	80 - 220

The gelled fuel Y tested contained 2% by weight of a styrene-type polymer mixed in powder form with Jet A fuel. Combustion tests were performed over the following range of conditions.

Test Section Pressure in. Hg abs.	Fuel Temperature °F	Air Temperature °F	Air Flow lb/sec.	Approximate Fuel Flow Range lb/hr.
150	60	540	7.60	170 - 540
60	60	400	3.55	85 - 310

Combustion testing was performed utilizing a one-tenth sector containing one burner can from a J-79 gas turbine engine. The combustor reference air velocity used for the test conditions was 95 feet per second. Since the volumetric air flow rate for the J-79 is relatively constant for all operating conditions over the fuel-air ratios tested, this reference air velocity applies for all test conditions. These test conditions are typical for gas turbine engine combustors and were selected to represent the more severe range of altitude cruise and sea level cold start operation. The fuel-air ratio was varied beyond a range of values representative of those which present-day gas turbine engine combustion systems are required to operate. For this range, lean and/or rich blowout occurrence was investigated. At each condition, the gelled fuel was compared to Jet A for such things as (1) temperature rise (combustion efficiency), (2) exhaust temperature profile, (3) operating range, (4) nozzle pressure requirements, and (5) combustor flame radiation.

It was also planned to test an emulsified fuel supplied by the Federal Aviation Administration; however, this phase was terminated due to problems explained in the results portion of this report.

DESCRIPTION OF TEST EQUIPMENT

Combustion tests were performed in the test facility shown schematically in figure 1. Compressor bleed air from a turbojet engine was used as the air source for all tests, excluding the simulated sea level cold start. Exhaust gas was discharged into the atmosphere. Air was obtained from low pressure blowers for the cold start test, and combustion products were ducted into the laboratory exhaust system.

Air flow quantity and test section pressure were controlled by electrically operated butterfly valves.

The fuel flow to the combustor was measured with two turbine type flowmeters, using a digital counter as a readout device.

Various methods to determine gelled fuel flow rates were considered; however, the use of a turbine type flow element was judged to be the most practical. With the use of these elements, it was necessary to shear gelled fuel X through two boost pumps in order to insure physical homogeneity. It should be mentioned that the turbine type flow elements were calibrated under conditions of use, thereby eliminating the effect of variations in shear on the calibration. It should also be mentioned that the shearing was not excessive relative to what the fuel would encounter in actual engine operation, since various shearing components (such as aircraft boost pump, fuel control system) were absent in our system.

Gelled fuel X was supplied to the boost pumps by inflating a bladder in the closed supply tank, thus forcing the gel from the tank. Bladder pressure was maintained at 25 psig. Gelled fuel Y was delivered to the boost pump under gravity flow. Both gels were filtered using two 40 mesh filters, and the bypass modes of these filters were closed.

Two six-foot and one three-foot counterflow heat exchangers were used to condition the fuel to specified inlet temperatures. Isopropanol with dry ice was used as the cooling medium for the low temperature tests and water-steam was used for the high temperature runs.

Test section instrumentation consisted of:

1. Inlet Station
    a. Two rakes of three total pressure probes.
    b. One rake of three thermocouples (No. 20 gage iron-constantan).
2. Exhaust Station
    a. One rake of three total pressure probes.
    b. Three rakes of three thermocouples (No. 20 gage platinum-platinum plus 13% rhodium).

All stream measurements were taken at centers of equal areas. Fuel temperature was measured at the fuel nozzle.

A total radiation pyrometer (Leeds and Northrup Rayotube) was stationed approximately 11 inches downstream from the fuel nozzle to determine the relative radiation intensities of the combustion flames.

RESULTS AND DISCUSSION

Gelled Fuel X

The evaluation of combustor performance indicates there is no significant change in any of the combustor performance parameters when using gelled fuel X, as compared to conventional Jet A. Figures 2 through 8 illustrate comparative temperature rises and combustion efficiencies as a function of fuel-air ratio for the conventional and additive X fuels. These plots cover a range of various test section pressures and air temperatures. It can be observed that there are essentially no differences in temperature rise, combustion efficiency, or range of operation when using this gelled fuel.

Combustion efficiency values slightly above 100% were obtained in several instances. This situation results from the combustion discharge temperature pattern causing the measured average discharge temperature to be slightly higher than the actual average discharge temperature.

The occurrence of blowout or flame instability with either the test or conventional fuel was observed only for the sea level cold start condition. One blowout occurred using conventional Jet A and one instance of flame instability occurred when employing gelled fuel X.

Figure 9 shows a comparison of temperature profiles at the combustion exhaust plane for the conventional and the test fuel. These profiles are typical of those obtained throughout our testing with Jet A and gelled fuel X and indicate that temperature profile is not significantly changed through the use of this modified fuel. The comparison of combustor flame radiation readings shown in figure 10 illustrates there is no significant difference in flame radiation of the gelled fuel relative to baseline. This fact, together with the lack of change in combustion efficiency, indicates there is no significant change in flame shift or combustion reaction mechanism with the employment of this gelled fuel.

Gelled Fuel Y

The evaluation of combustor performance employing gelled fuel Y as compared to conventional fuel, indicates that the change in certain performance parameters varies, depending on the operating condition. Figures 11 and 12 show comparative temperature rises and combustion efficiencies as a function of fuel-air ratio for operating pressures of 150 in. Hg abs. and 60 in. Hg abs., respectively. At the higher operating pressure there is no reduction in temperature rise or efficiency when using gelled fuel Y. However, at 60 in. Hg abs. test section pressure there is a reduction in comparative performance of the gel, the magnitude of which is dependent on fuel-air ratio.

This decrease in performance can be attributed to a combination of factors. The conversion of chemical energy to heat energy in a combustion system may be considered to occur in the following order: (1) atomization of the fuel, (2) vaporization of the fuel, (3) mixing of the fuel and air, (4) ignition, and (5) oxidation of the fuel to final products. Any phenomenon interfering with the above steps has an adverse effect on the combustion process. Visual observation of the gelled fuel nozzle spray indicates that the fuel droplets maintain their gel properties. They have a thick appearance, and coalesce readily into their original bulk state when sprayed into a container. These droplets then, have a reduced rate of vaporization--a condition which is adverse to efficient combustion. For lower fuel flow rates, it was noted that nozzle atomization was poor and the fuel spray angle was relatively acute. These characteristics deter proper mixing, a condition which not only reduces combustion efficiency but also effects unsatisfactory temperature profiles. Because of the characteristic problems mentioned, the gel Y performance is relatively sensitive to operating pressure. A reduction in test section pressure is adverse to combustion for the following reasons: (1) decreased turbulent air forces, (2) increased ignition energy and temperature requirements, and (3) reduced fuel-air reaction rates.

Figure 13 illustrates comparative exhaust temperature profiles for Jet A and gelled fuel Y. When using Jet A, rakes 1 and 3, which are closer to their respective side walls, normally yield a lower average temperature measurement than the center rake (rake 2). This result is normally expected when testing with a single can combustor, since higher radiation losses are encountered near the wall and also because of the lack of perfect mixing. When employing gelled fuel Y, however, the reverse trend occurred, with the lowest average temperature for the center rake. This results in an unsatisfactory temperature profile, indicating a serious mixing problem.

The difference in comparative flame radiation readings for the conventional and gelled fuel Y is shown in figure 14. These results indicate that at the station instrumented there would be no detrimental change in liner temperature when using gelled fuel Y. Despite some scatter in the Jet A data it can be seen that the curve illustrating flame radiation for the gelled fuel differs characteristically from that for the Jet A fuel. This is apparently due to a difference in the manner in which the flame shift with changing fuel-air ratio occurs when using gelled fuel Y. However, there may be some difference in the degree of radiation between these fuels. Because of the limited investigation in this area it would be difficult to state precisely the exact mechanism causing the illustrated phenomenon.

Upon completion of the tests, the combustor test rig was disassembled for inspection. A sample of the excessive liner deposition, shown in figure 15, was analyzed spectroscopically and was shown to be sodium sulphate. This result was expected since it is known that there is sodium present in the gelling agent Y.

Emulsified Fuel Z

Although combustor testing with an emulsified fuel was to be included in the test program, certain problems arose which limited the testing considerably. The emulsion used was designated Emulsified Fuel Z. This is a 2% aqueous emulsion of JP-4 fuel. This fuel separated, due to the shearing action of the boost pump, yielding approximately 93% free JP-4 and 7% of a much heavier emulsion. After three minutes of running time, even 40 mesh filters clogged (with the heavy emulsion) to such an extent that fuel flow was reduced to zero. This problem was discussed with the sponsor and it was jointly decided to terminate the emulsion testing.

General

Various filtering problems were encountered with the use of gelled fuel. Fifteen micron paper filters (normally used in our combustor test system) had to be removed because they were completely blocked by the modified fuel. Forty mesh metal screen filters were then placed in the system; however, further filter modification was needed. Since in some instances the pressure drop across the filter exceeded 45 psi (that which is needed to open the bypass mode of the filter), it was necessary to close the bypass valve to insure fuel filtration. Thus, conventional fuel filters which have finer porosity would be incompatible with gelled Jet A due to excessive pressure drop.

Figure 16 shows the gelled fuel X buildup on a 40 mesh filter. Analysis of the material held up on the filter showed it contained no increase in the gelling additive, indicating there is no significant separation of the additive from the fuel. No buildup of gelled fuel Y was observed when the fuel filter was inspected.

Figure 17 illustrates comparative fuel flow rates as a function of nozzle pressure drop at 60°F for a combustor test section pressure of 150 in. Hg abs. The gelled fuel Y exhibits flow properties unlike either the Jet A or gel X in the power relationship between flow rate and pressure drop. For a nozzle pressure drop above 170 psi, there is a higher fuel flow rate for gelled fuel than for Jet A. This result should not be unexpected since rheological properties vary with shear rate in non-Newtonian fluids; however, without ample rheological information a detailed explanation would be purely conjectural.

An investigation of the effect of fuel temperature on combustor system performance was done for gelled fuel X. Although no effect on the combustion performance parameters was noted, fuel nozzle pressure requirements, at the low temperature run, increased as much as 300% in order to maintain the metered flow rate.

CONCLUSIONS

This investigation has provided information on the evaluation of thickened fuels in a conventional gas turbine combustion system which substantiates the following conclusions:

(1) There is no significant change in combustion performance parameters such as: temperature rise, combustion efficiency, range of operation, temperature profile, and flame radiation reading when using gelled fuel X as compared to conventional Jet A.

(2) There can be a substantial change in temperature rise, combustion efficiency, temperature profile, and flame radiation reading, when employing gelled fuel Y, depending on fuel flow rate and operating pressure.

(3) There is no significant separation of the additive from either gel due to shear.

(4) The sodium present in gelled fuel Y reacts to produce a sodium sulphate deposition on the combustor liner.

(5) Conventional fuel filters are incompatible with gelled fuels X and Y due to excessive pressure drop across these filters.

(6) Emulsified fuel Z separated due to the shearing action of the boost pump in the system.

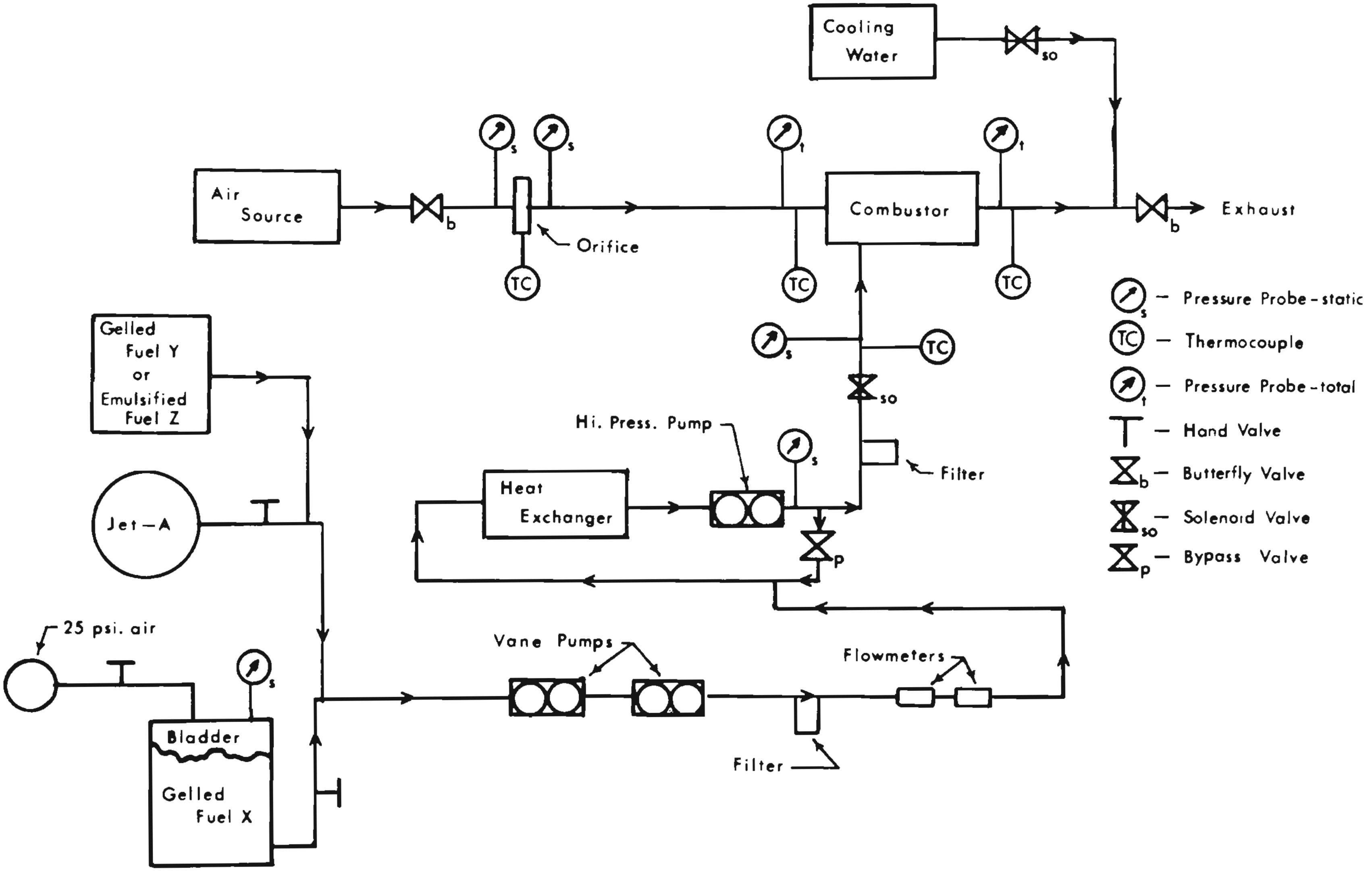


FIGURE 1

Schematic of Test Facility

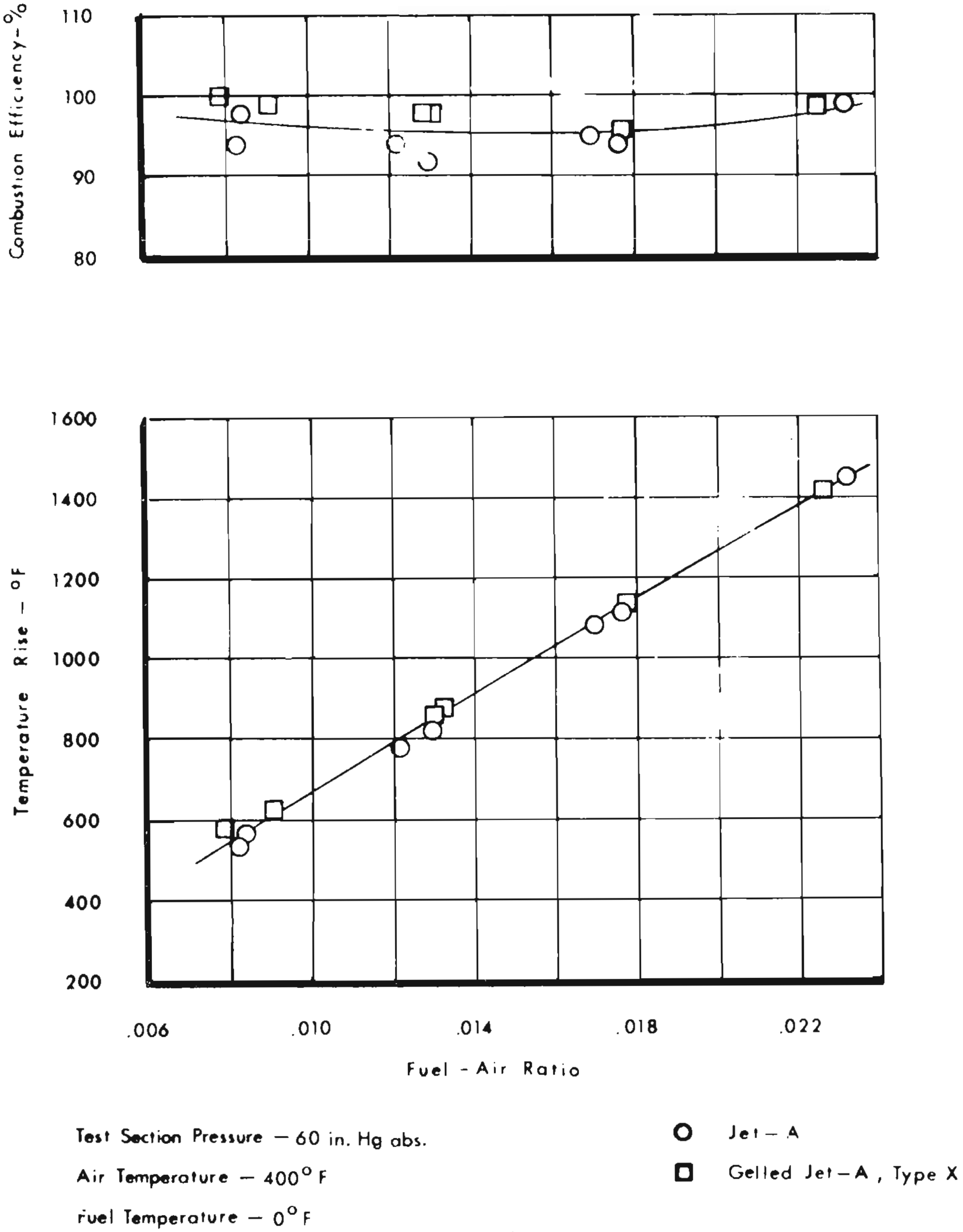


FIGURE 2

Variation of Combustion Efficiency and Temperature Rise with Fuel-Air Ratio for Conventional and Gelled Fuel X at 60 in. Hg abs. Test Section Pressure, and 0°F Fuel Temperature

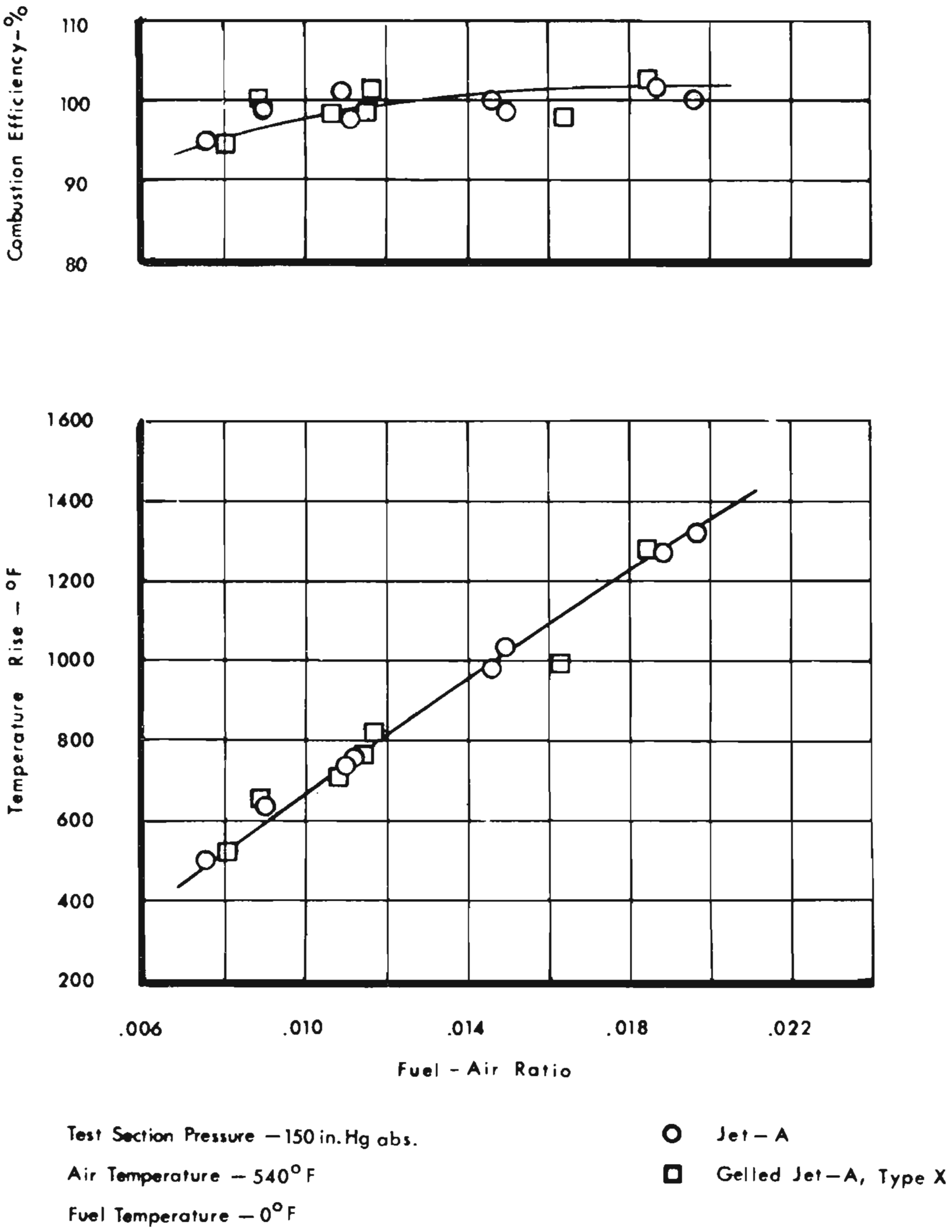


FIGURE 3

Variation of Combustion Efficiency and Temperature Rise with Fuel-Air Ratio for Conventional and Gelled Fuel X at 150 in. Hg abs. Test Section Pressure, and 0°F Fuel Temperature

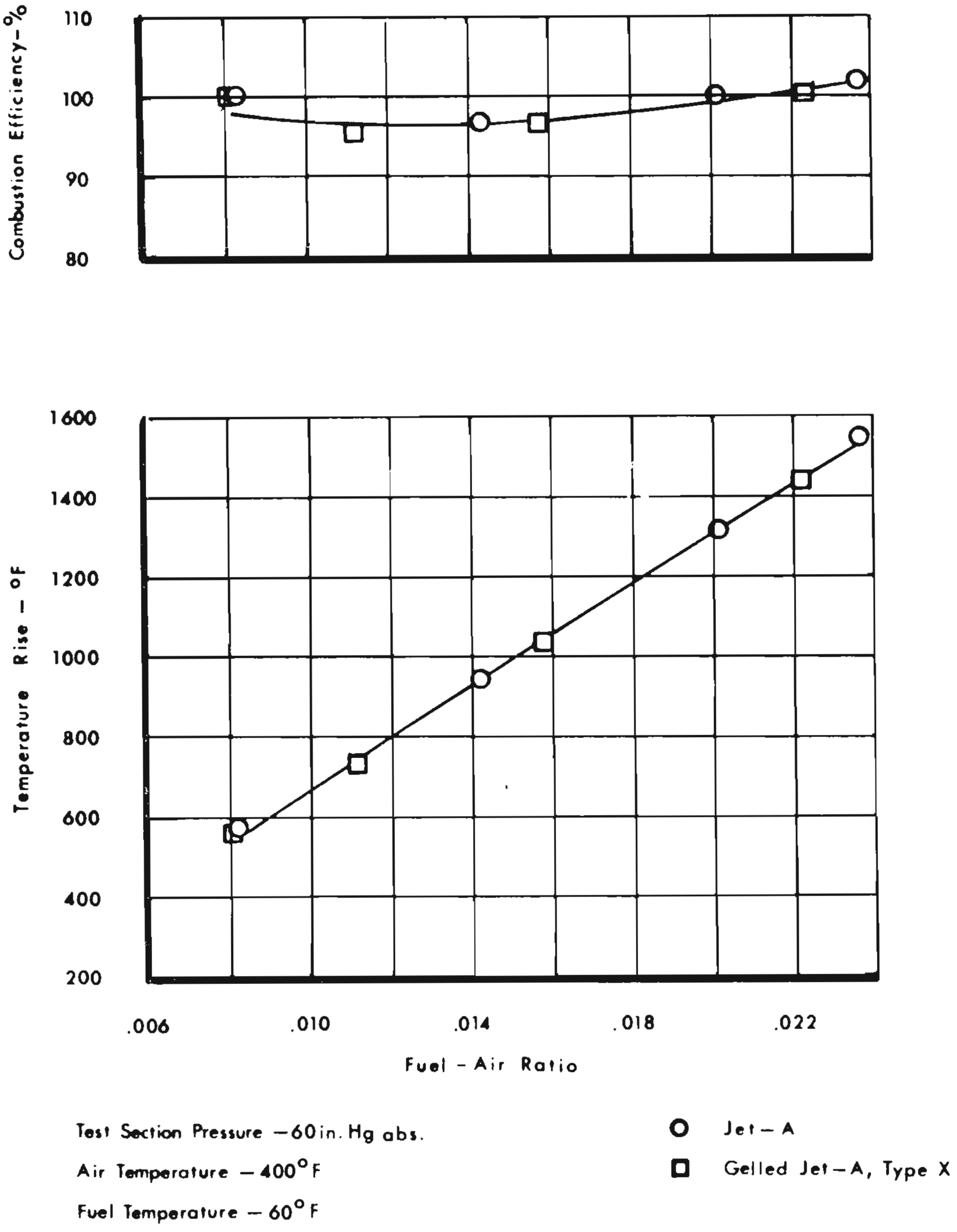


FIGURE 4

Variation of Combustion Efficiency and Temperature Rise
with Fuel-Air Ratio for Conventional and Gelled Fuel X
at 60 in. Hg abs. Test Section Pressure, and 60°F Fuel Temperature

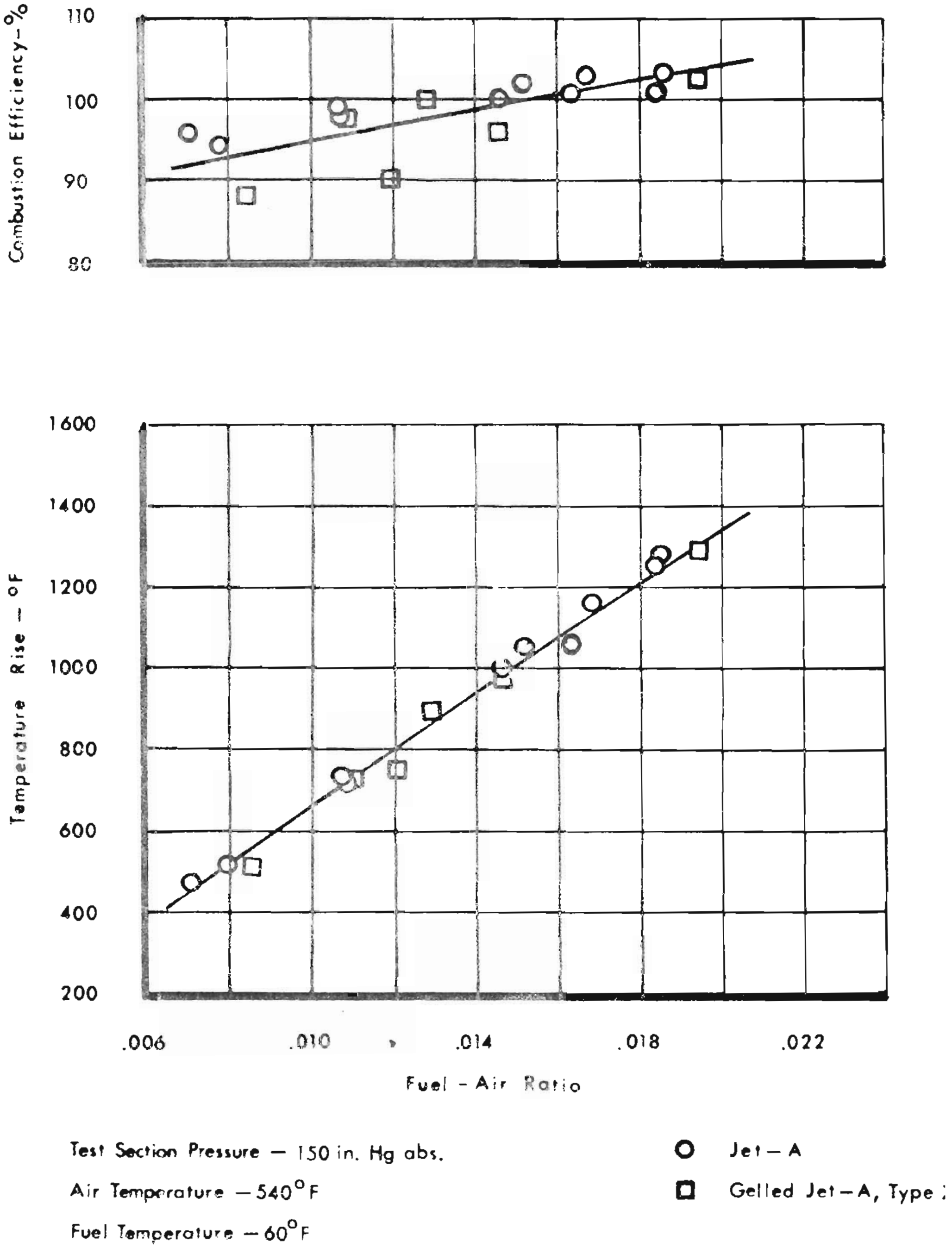
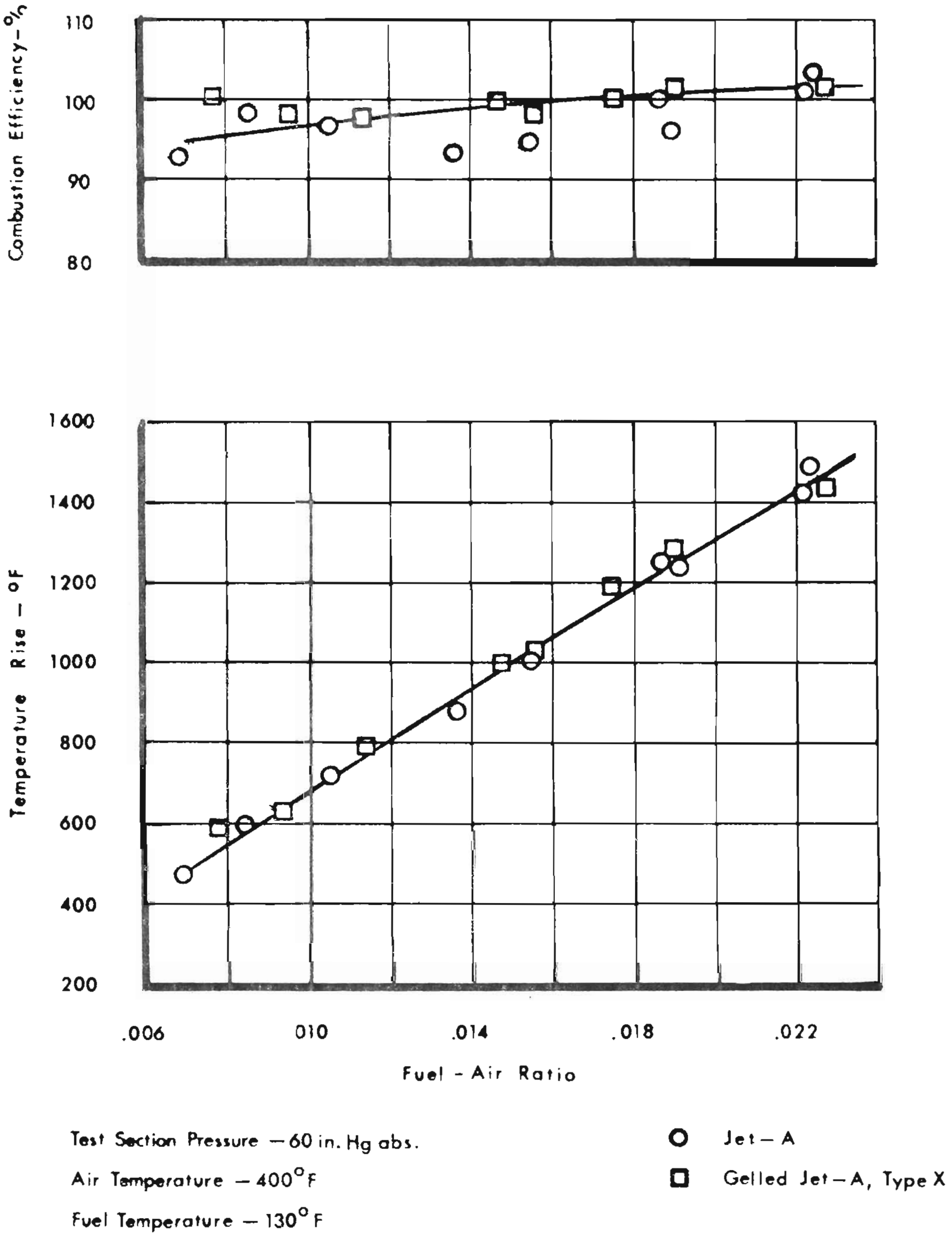


FIGURE 5

Variation of Combustion Efficiency and Temperature Rise with Fuel-Air Ratio for Conventional and Gelled Fuel X at 150 in. Hg abs. Test Section Pressure, and 60°F Fuel Temperature



Test Section Pressure – 60 in. Hg abs.
Air Temperature – 400°F
Fuel Temperature – 130° F

FIGURE 6

Variation of Combustion Efficiency and Temperature Rise
with Fuel-Air Ratio for Conventional and Gelled Fuel X
at 60 in. Hg abs. Test Section Pressure, and 130°F Fuel Temperature

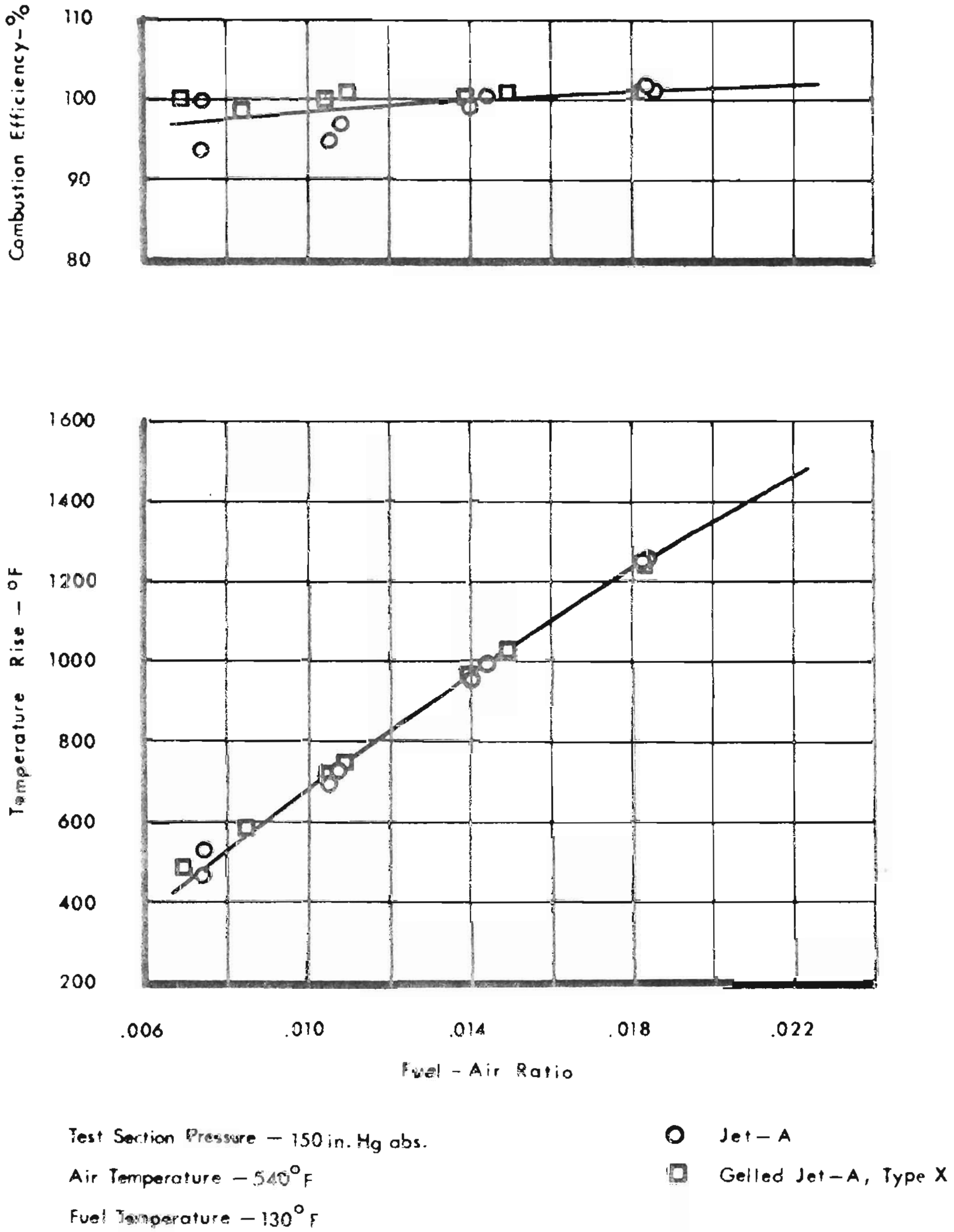


FIGURE 7

Variation of Combustion Efficiency and Temperature Rise with Fuel-Air Ratio for Conventional and Gelled Fuel X at 150 in. Hg abs. Test Section Pressure, and 130°F Fuel Temperature

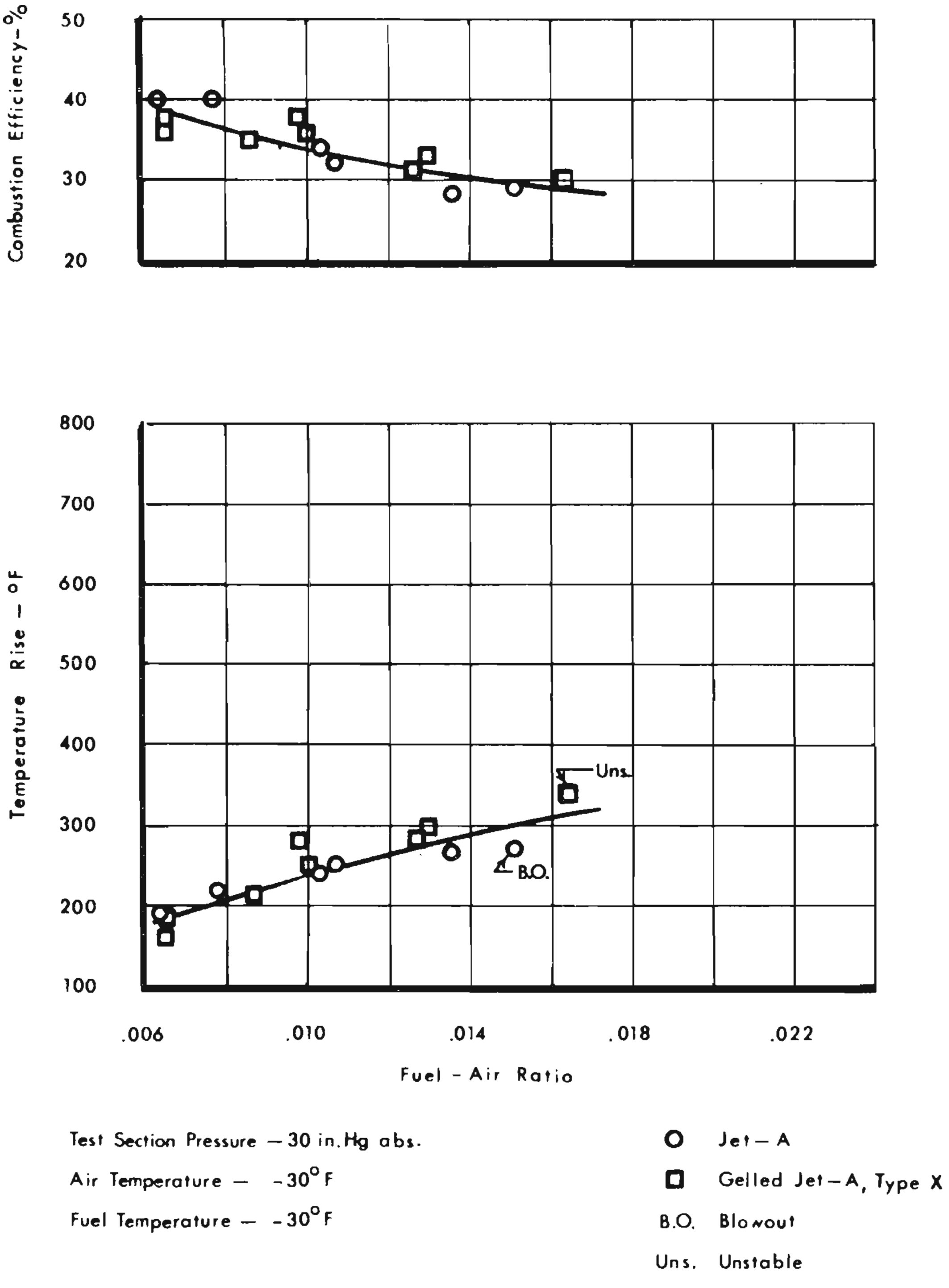


FIGURE 8

Variation of Combustion Efficiency and Temperature Rise
with Fuel-Air Ratio for Conventional and Gelled Fuel X
at 30 in. Hg abs. Test Section Pressure, and -30°F Fuel Temperature

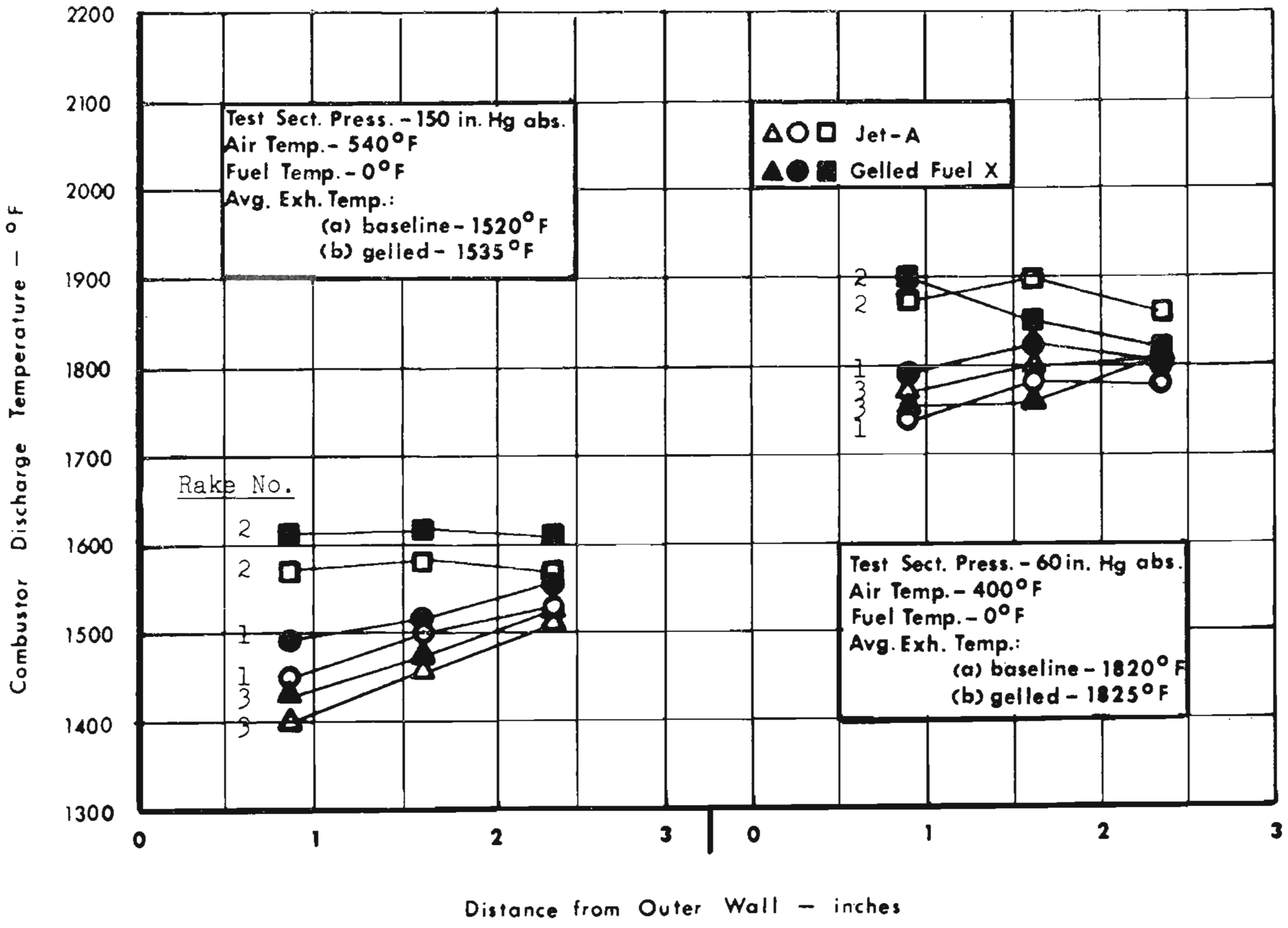


FIGURE 9

Exhaust Gas Temperature Profile for
Conventional and Gelled Fuel X

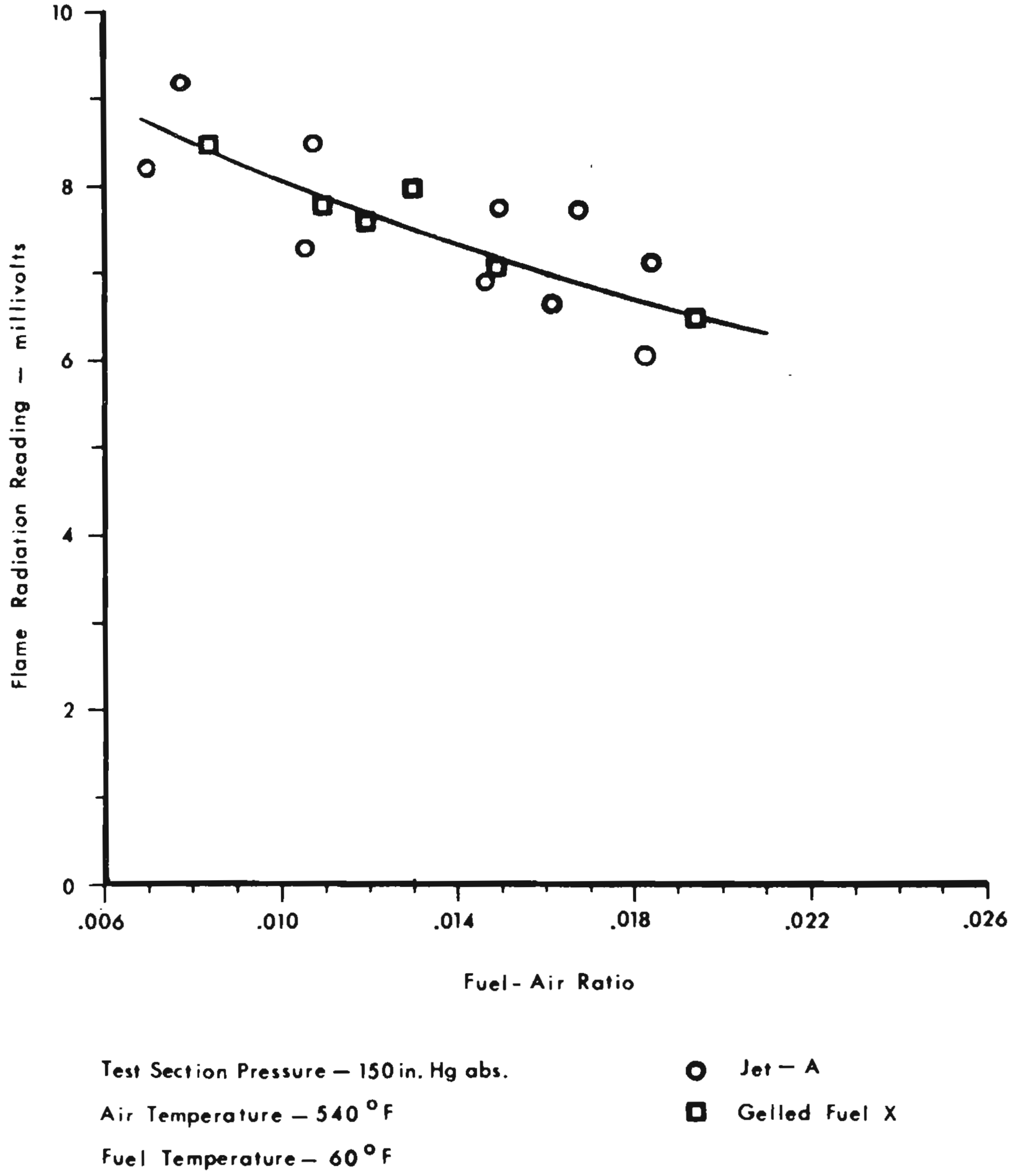
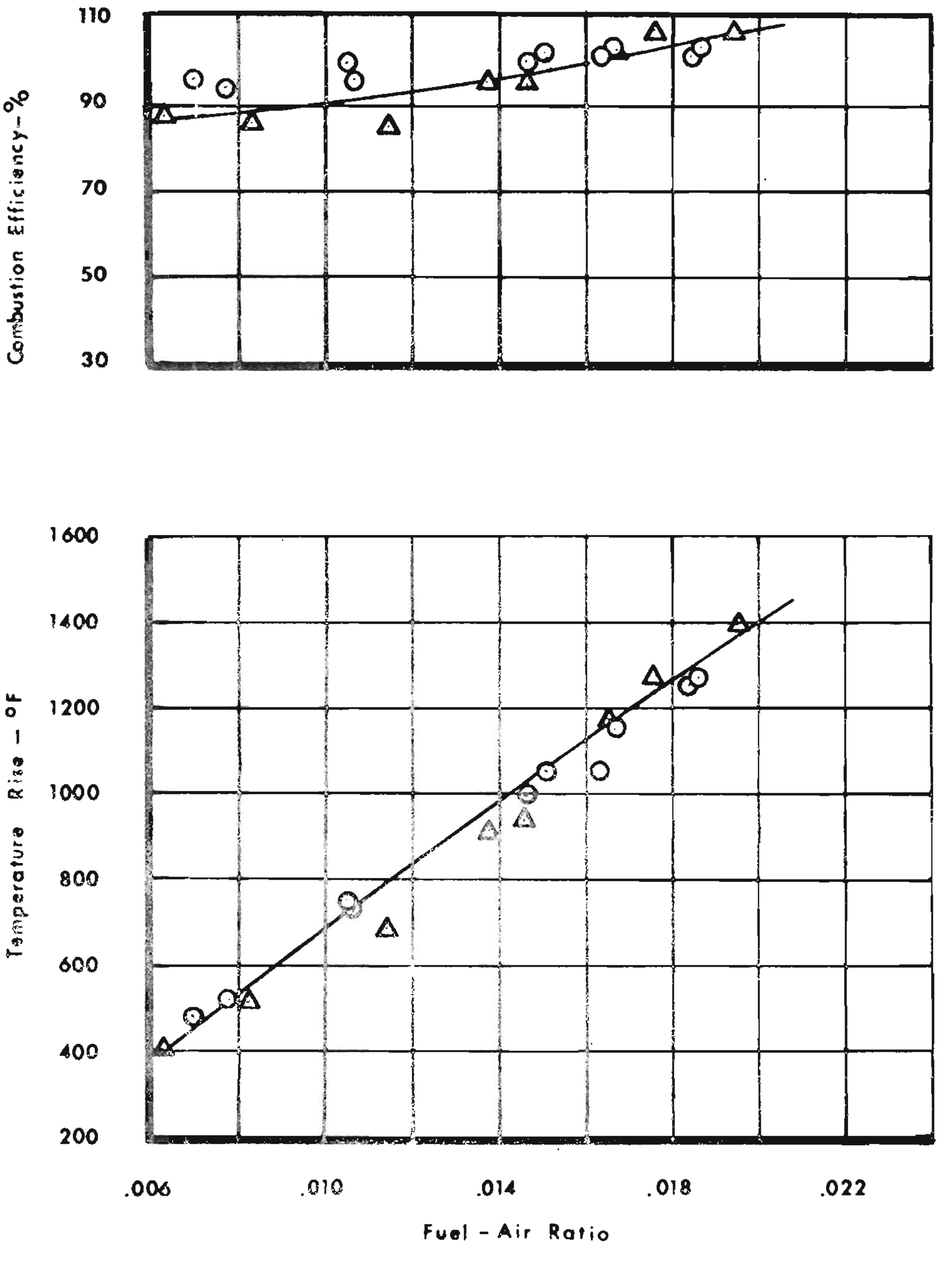


FIGURE 10

Variation of Flame Radiation Reading with Fuel-Air Ratio for Conventional and Gelled Fuel X

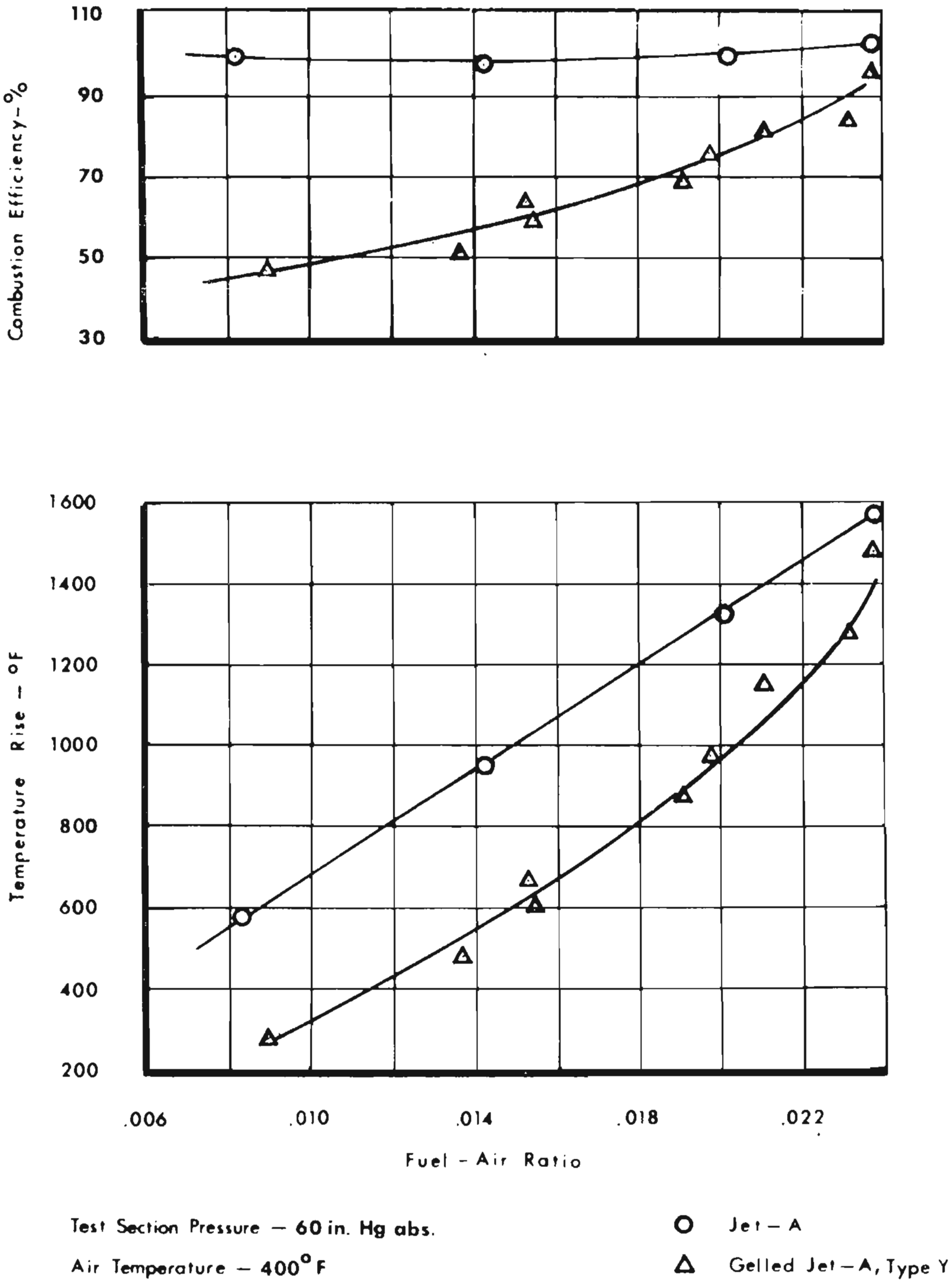


Test Section Pressure — 150 in. Hg abs.
Air Temperature — 540° F
Fuel Temperature — 60°F

○ Jet – A
△ Gelled Jet – A, Type Y

FIGURE 11

Variation of Combustion Efficiency and Temperature Rise with Fuel-Air Ratio for Conventional and Gelled Fuel Y at 150 in. Hg abs. Test Section Pressure, and 60°F Fuel Temperature



Test Section Pressure — 60 in. Hg abs.

Air Temperature — 400°F

Fuel Temperature — 60°F

FIGURE 12

Variation of Combustion Efficiency and Temperature Rise with Fuel-Air Ratio for Conventional and Gelled Fuel Y at 60 in. Hg abs. Test Section Pressure, and 60°F Fuel Temperature

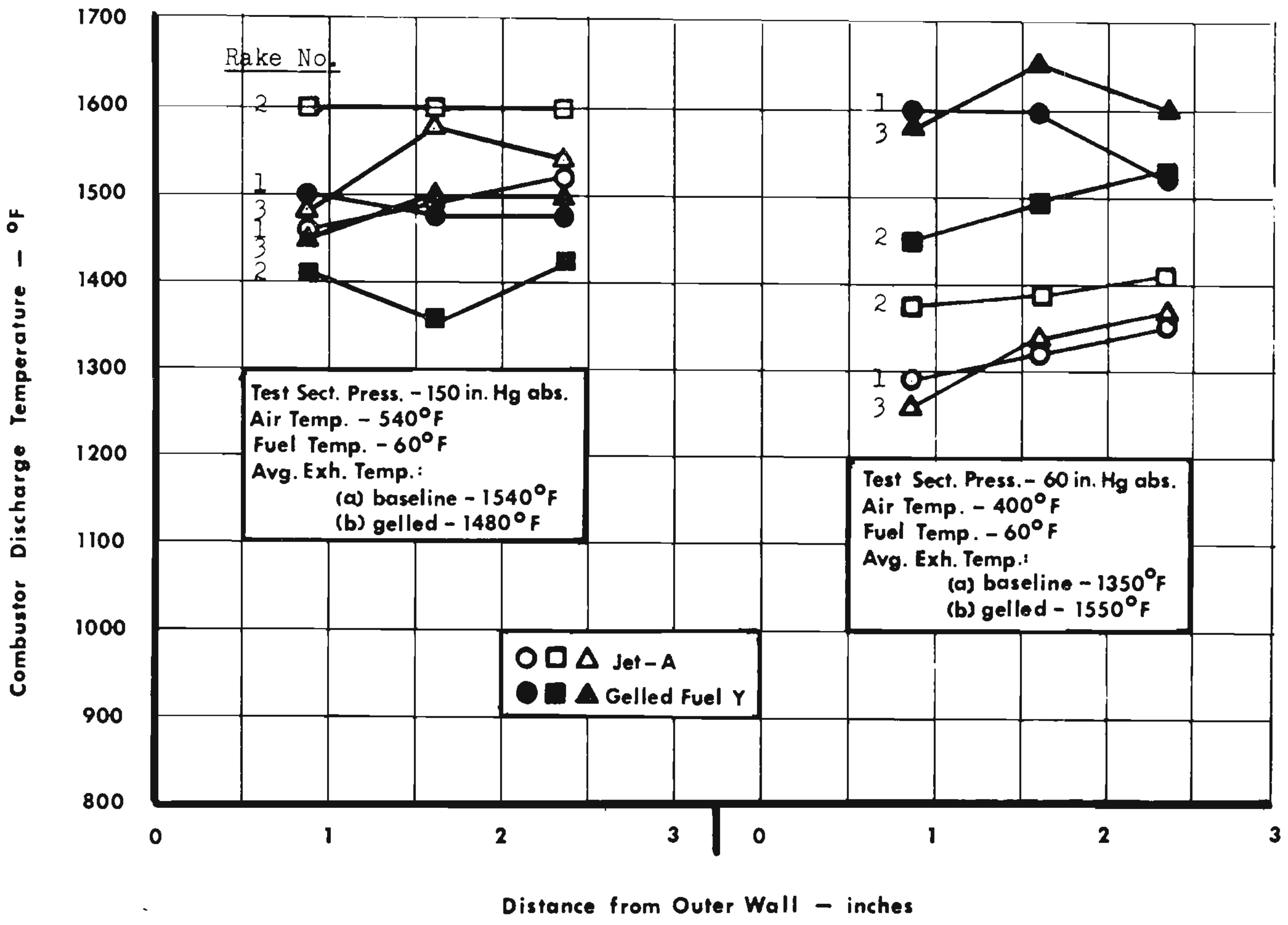


FIGURE 13

Exhaust Gas Temperature Profile for
Conventional and Gelled Fuel Y

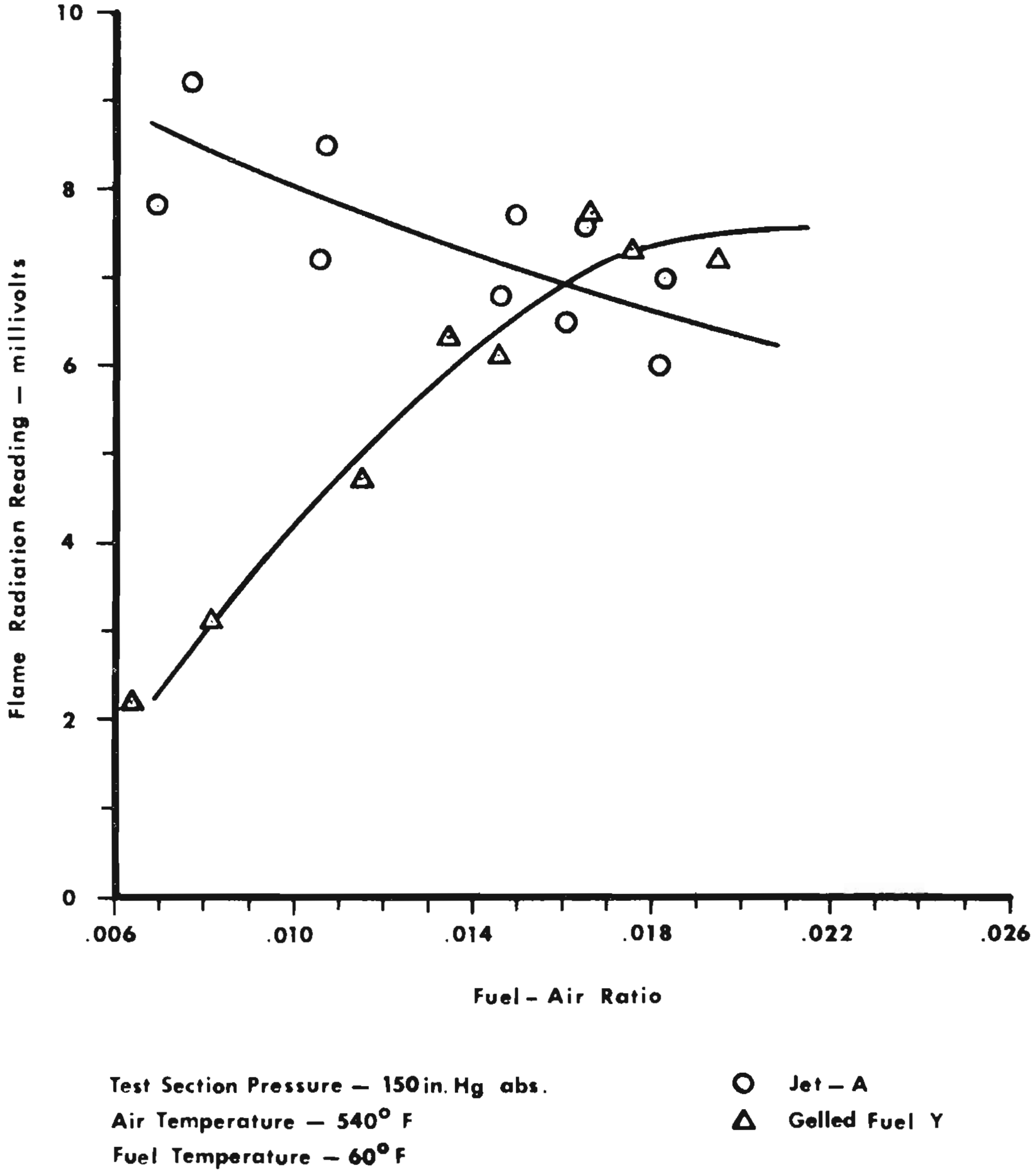


FIGURE 14

Variation of Flame Radiation Reading with Fuel-Air Ratio for Conventional and Gelled Fuel Y

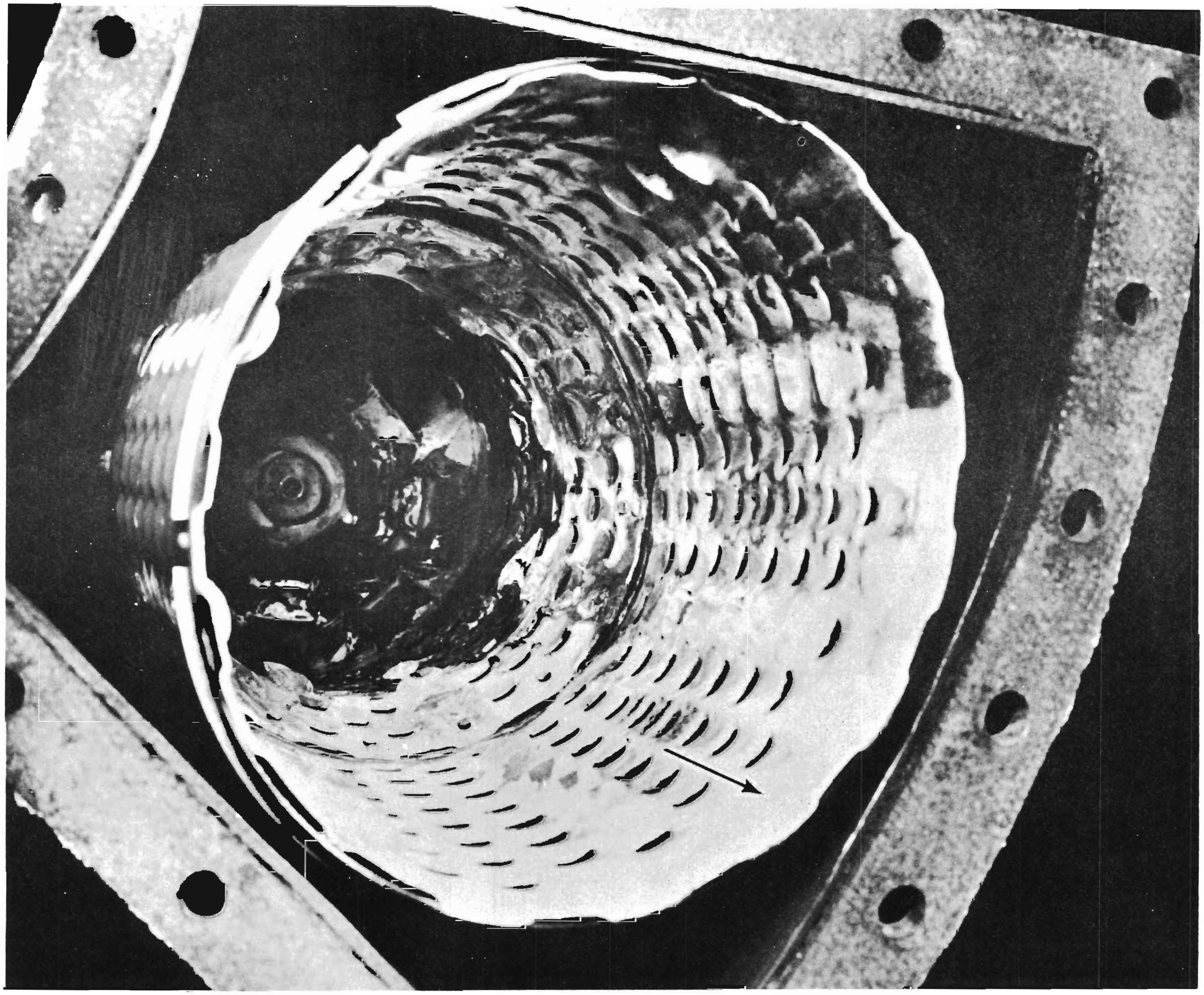


FIGURE 15 COMBUSTOR LINER DESPOSITION WITH THE USE OF GELLED FUEL Y

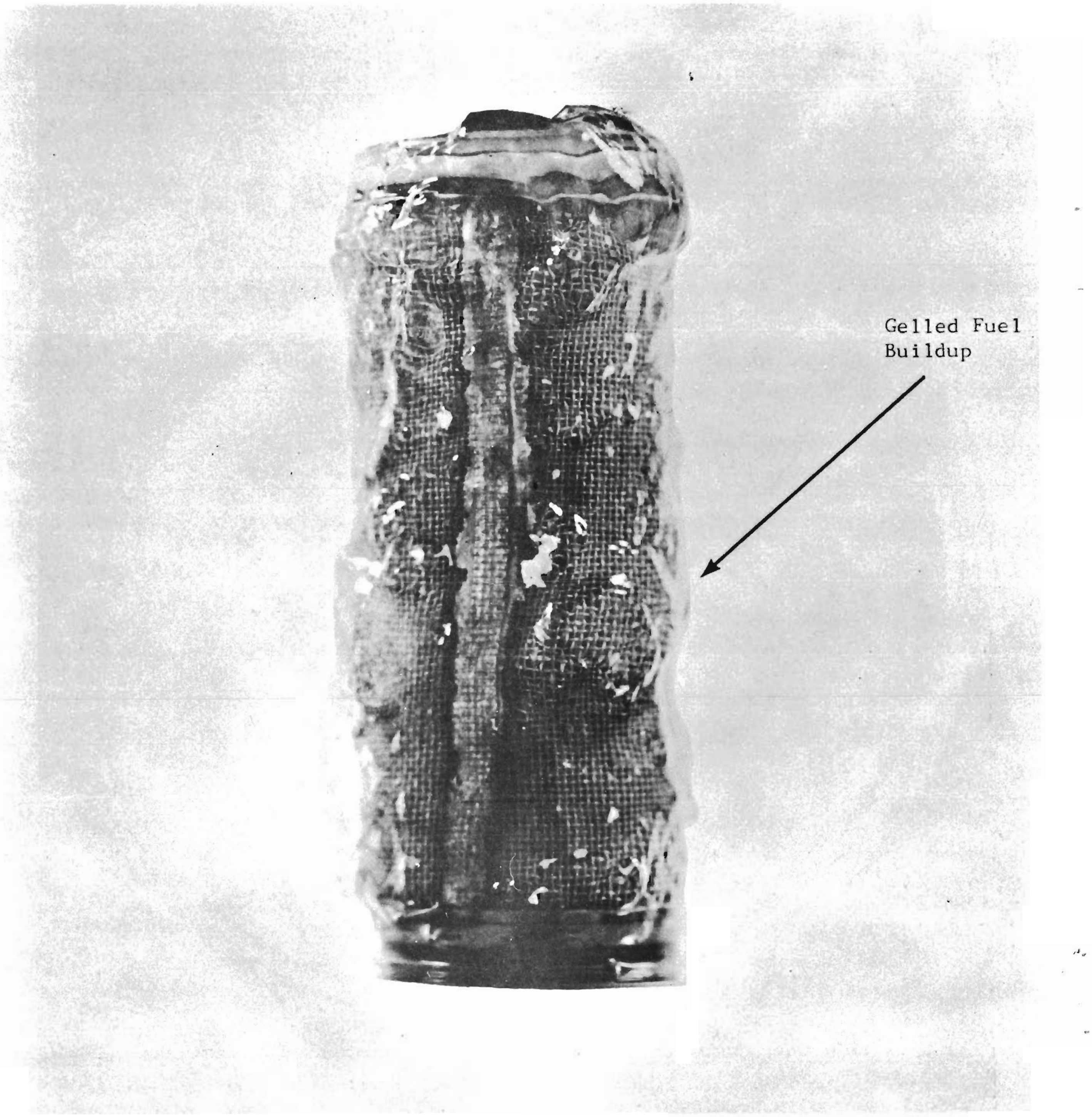


FIGURE 16 FORTY MESH SCREEN FILTERS AFTER GELLED FUEL RUN WITH GELLED FUEL X

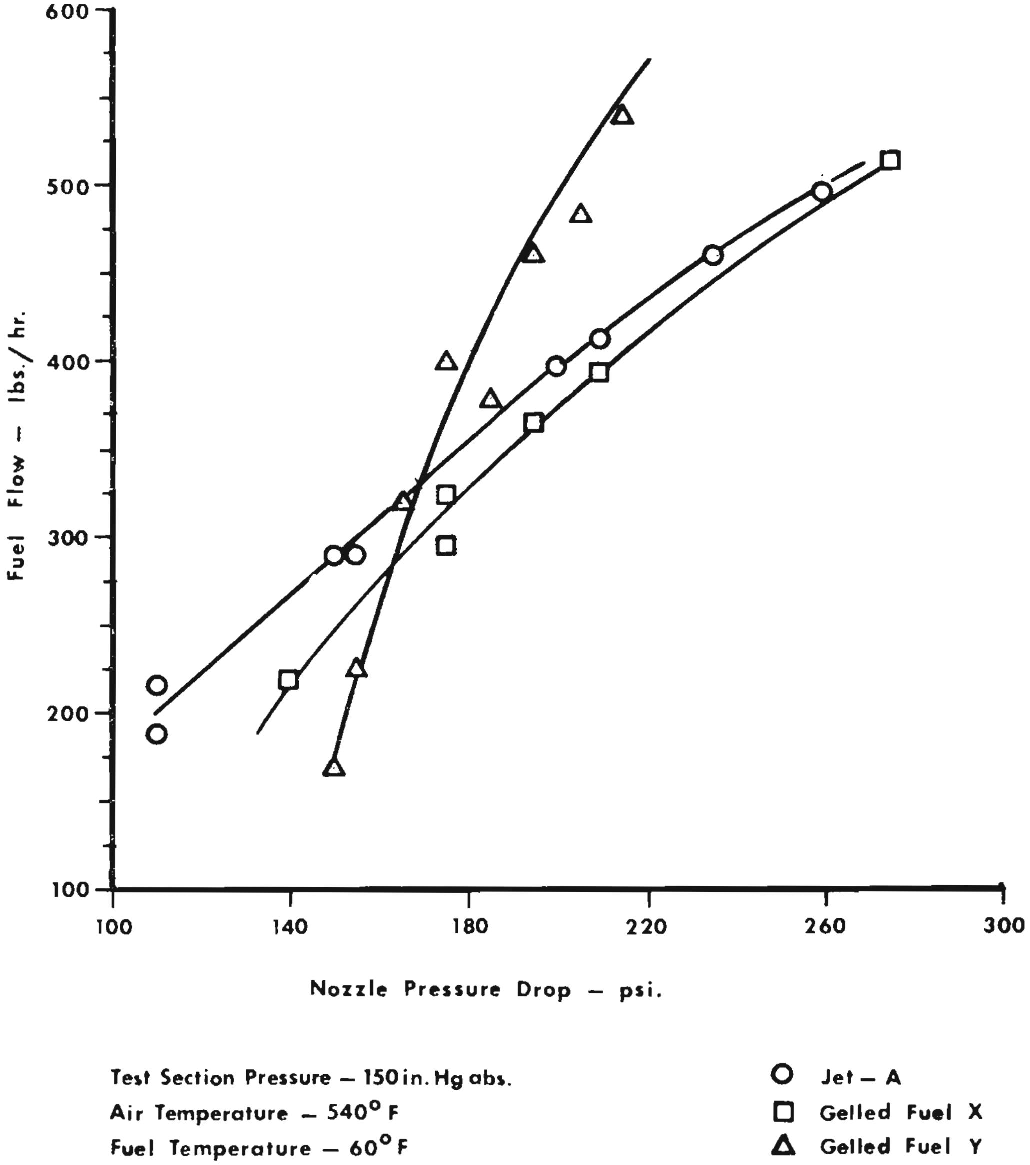


FIGURE 17

Fuel Flow Rate Versus Nozzle Pressure Drop for Jet A, Gelled Fuel X, and Gelled Fuel Y

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By: A. J. Atkinson, Final Report, April 1969
25 pp including figures
(Agreement No. FA67NF-AP-20 Project No. 520-005-02X Report No. FAA-NA-69-1 (DS-68-27)

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