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COMPARISON OF ASTM-A1 AND NATURAL GAS FUELS IN AN ANNULAR TURBOJET COMBUSTOR

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Cleveland, Ohio
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ABSTRACT

A preliminary study was made to determine possible problem areas in the use of natural gas fuel in aircraft turbojet combustors. A combustor designed for Mach 3.0 cruise operation with liquid ASTM-A1 fuel was operated with natural gas. The only change made to the combustor was in the fuel nozzle itself. Only one natural gas fuel nozzle design was used for these tests. Combustion efficiency, outlet temperature profiles, blowout and relight characteristics, flame radiation and smoke emission data were obtained. A comparison was made with data obtained from the same combustor using liquid ASTM-A1 fuel. The major problems encountered with natural gas were poor ignition and blowout characteristics.

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SUMMARY

A preliminary study was made to determine possible problem areas in the use of natural gas fuel in aircraft turbojet combustors. A combustor designed for Mach 3.0 cruise operation with liquid ASTM-A1 fuel was operated with natural gas. The only change made to the combustor was in the fuel nozzle itself. Only one natural gas fuel nozzle design was used for these tests.

Combustion efficiency, outlet temperature profiles, blowout and relight characteristics, flame radiation and smoke emission data were obtained. A comparison was made with data obtained from the same combustor using liquid ASTM-A1 fuel. Combustion efficiency was 100 percent with both fuels at all conditions for which the inlet total pressure exceeded 30 psia (20.7 N/cm^2), the inlet air temperature exceeded 600° F (589 K) and the fuel-air ratio exceeded 0.01. As inlet air temperature was reduced below 600° F (589 K), the combustion efficiency with natural gas fell off more rapidly than with ASTM-A1. Some improvement in radial average outlet temperature profile was obtained with natural gas over ASTM-A1; however, local maximum temperatures were higher with natural gas than with ASTM-A1. Relight characteristics were poorer with natural gas than with ASTM-A1 fuel.

INTRODUCTION

Recent studies have shown that liquified natural gas (LNG) fuel offers significant advantages in some turbojet engine applications (refs. 1 to 3). Compared with ASTM-A1 fuels, LNG has a higher heat of combustion and therefore a lower specific fuel consumption. In addition, the much greater heat sink capacity of the LNG can be important. For example, operation at higher turbine inlet temperatures may be made possible when fuel-cooled air is used for turbine blade cooling. In this manner a 31 percent payload improvement over ASTM-A1 fuel was calculated for a Mach 3 supersonic transport under certain conditions (ref. 2). An alternative to higher turbine inlet temperatures would be to use the additional heat sink provided by the LNG to maintain lower turbine metal temperatures, thereby increasing reliability and life.

The potential that LNG possesses as an aircraft fuel warrants further study of the problems involved in its use. Although stored on the aircraft in a liquid state, this cryogenic fuel would enter the combustor as a gas. Experience with gaseous fuels of any kind in turbojet combustors for flight conditions is quite limited.

Therefore, to make a preliminary determination of potential problems, the following approach was taken. An advanced design annular combustor was selected which had been extensively tested and evaluated at Lewis Research Center using ASTM-A1 fuel (refs. 4). A simple change in fuel nozzle design was made to permit testing with natural gas. No attempt was made in the course of testing to improve the fuel nozzle design.

Efficiency and exit temperature profile data were obtained over a range of operating conditions. Blowout and ignition data were obtained at low pressures. Flame radiation and combustor metal temperatures were also measured. All data were compared to data obtained with ASTM-A1 fuel in the same combustor.

FACILITY AND INSTRUMENTATION

The ASTM-A1 and natural gas comparison investigation was conducted in a closed-duct test facility of the Engine Components Research Laboratory of the Lewis Research Center. A block diagram of this facility is shown in figure 1. Airflows for combustion could be heated to 1200° F (922 K) without vitiation before entering the combustor.

Airflow rates and combustor pressures were regulated by remotely controlled valves upstream and downstream of the test section. Flow straighteners were used to evenly distribute the airflow entering the combustor. Further details of the facility and instrumentaion can be found in figure 1.

TEST COMBUSTOR

The combustor tested was designed using the ram-induction approach described in reference 5. With this approach the compressor discharge air is diffused less than it is in conventional combustors. The relatively high velocity air is then captured by scoops in the combustor liner and turned into the combustion and mixing zones. Vanes are used in the scoops to reduce pressure loss caused by the high velocity turns. The high velocity and steep angel of the entering air jets promote rapid mixing of the fuel and air in the combustion zone and of the burned gases and air in the dilution zone. The potential result of the rapid mixing is a shorter combustor or, alternatively, a better exit temperature profile in the same length.

A cross-section of the combustor is shown in figure 2. The outer diameter is almost 42 inches (1.07 m) and the length from compressor exit to turbine inlet is approximately 30 inches (0.76 m). A forward snout (fig. 2), on the combustor divides the diffuser into three concentric annular passages. The central passage conducts air to the combustor headplate and the inner and outer passages supply air to the combustor liner. There are five rows of scoops on each of the inner and outer liners to turn the air into the combustion and dilution zones.

Photographs of the snout and the combustor liner are shown in figure 3. Figure 3(a) is a view looking upstream into the combustor liner. The scoops in the inner and outer liners can be seen and the openings in the headplate for the fuel nozzles and swirlers. Figure 3(b) is a view of the snout and the upstream end of the combustor liner. The V-shaped cutouts in the snout fit around struts in the diffuser. The circular holes through the snout walls are for the fuel nozzle struts. Figure 3(c) gives a closer view of the liner and headplate showing the fuel nozzles (there are a total of 24) and swirlers in place. Further details of the combustor design are given in reference 4.

FUEL NOZZLES

Figure 4 shows the fuel nozzle assemblies used for liquid and gaseous fuels. Figure 4(a) shows the detail of the fuel nozzles used in the tests with ASTM-A1 fuel. These were simplex nozzles with the flow characteristics shown in figure 5.

Shown in figure 4(b) is the fuel nozzle used for the natural gas tests. Fuel flow characteristics for these nozzles are given in table II. The nozzles were designed to inject the fuel at low velocity for proper fuel-air mixing. The resulting low fuel nozzle differential pressure necessitated a primary flow restriction just upstream of the fuel nozzle to equalize fuel flow to all fuel nozzles. This function was served by the fuel nozzle strut flow passages (fig. 4) which had been sized for liquid fuel. A pintle design was selected to provide enough open area to keep the pressure drop across the nozzle low, and to cause some spreading of the fuel.

The natural gas nozzle was required to be interchangeable with the ASTM-A1 nozzle shown in figure 4(a). Because of this, the maximum length and diameter of the pintle were fixed by the air swirler. Due to the nozzle installation procedure, the pintle could not extend downstream beyond the air swirler. Furthermore, since the air swirler screwed on over the fuel nozzle strut, the pintle diameter was limited by the hole in the air swirler. A larger pintle would have been desirable.

RESULTS AND DISCUSSION

<u>Average radial exit temperature profile</u>. - Combustor outlet total temperature was measured at 3° increments around the exit circumference with five-point temperature rakes using high recovery aspirating platinum plus 13 percent rhodium-platinum thermocouples. The thermocouples were located at centers of equal areas across the annulus.

Figure 6 compares the average and peak exit temperature radial profiles for natural gas and ASTM-A1 fuels. The average radial temperatures were normalized to a 2200° F (1478 K) average exit temperature for comparison.

In the case of natural gas, the actual average exit temperature was only 2150° F (1450 K). The average temperature profile is slightly better with natural gas fuel than with ASTM-A1. However, the peak temperatures are considerably higher with natural gas.

Blowout and relight tests. - To obtain blowout data, the combustor was first operated at conditions that insured ignition. Then the pressure was lowered in steps, while the inlet air temperature and reference Mach number were held constant. At each pressure level a burst test (rapid increase in fuel/air ratio) was made to determine whether or not the combustor would produce a corresponding temperature rise. The pressure would then be reduced a further step and the process repeated until, finally, the combustor would blowout. A relight was then attempted at successively increased pressure levels. If relight occurred, another burst test was conducted at that condition.

Testing was limited by the facility to a minimum pressure of 4.5 psia (3.1 N/cm^2) and a minimum inlet air temperature of 65° F (292 K). All relight tests were conducted at a reference Mach number of 0.1 and a fuel-air ratio of 0.01. These conditions resulted in a temperature rise of about 700° F (389 K) for ASTM-A1 fuel and about 800° F (444 K) for natural gas fuel. Table I compares the lower heat of combustion and the hydrogen-carbon ratio of the two fuels. The burst tests increased the fuel/air ratio sufficiently to give a temperature rise of 1000° F (555 K) for both fuels.

As can be seen on figure 7, the best relight characteristics were obtained with liquid fuel. All data points are for natural gas fuel. The curve for ASTM-A1 fuel is from prior data. Limit lines of successful combustor relight and temperature rise are shown on this figure. The area to the right and above these limit lines represents the area where successful combustor relight can be expected. In the area between the relight limit line and the blowout points, relight and combustor acceleration may occur occasionally. In the area to the left and below the blowout points, ignition is very unlikely. Only one blowout point was obtained using liquid fuel. This occurred at 5.0 psia (3.4 N/cm^2) and 75° F (297 K). Several blowout points occurred using natural gas. Ignition was unsuccessful with natural gas below 125° F (325 K). No data with natural gas was taken between

125^{o} and 240^{o} F and (325 and 389 K) due to facility limitations at time of testing. Optimization of the natural gas fuel nozzle design may improve the natural gas relight performance.

Combustion efficiency. - Efficiency was determined by dividing the measured temperature rise across the combustor by the theoretical temperature rise. The exit temperatures were measured with five-point traversing aspirated thermocouple probes and were mass-weighted for the efficiency calculation. Five hundred eighty-five individual exit temperatures were used in each mass-weighted average.

The combustion efficiency with natural gas was 100 percent at all conditions in which the inlet total pressure exceeded 30 psia (20.7 N/cm^2), the inlet air temperature exceeded 600^{o} F (589 K), and the fuel-air ratio was greater than 0.01. The combustion efficiency with natural gas fuel matched the performance of ASTM-A1 at these conditions (ref. 4). As inlet air temperature was reduced below 600^{o} F (589 K), the combustion efficiency with natural gas dropped off very rapidly. Figure 8 shows a combustion efficiency of only 30 percent at an inlet air temperature of 250^{o} F (394 K). The low combustion efficiency at low inlet air temperatures is consistant with the poor altitude relight capability at these conditions. Also shown is the combustion efficiency with ASTM-A1 fuel for comparision.

Combustor response to rapid increase in fuel flow. - Fast response thermocouple data were taken to see how well the combustor would react to a rapid increase in fuel/air ratio. For these tests a 0.005 inch (0.127 mm) diameter, platinum plus 13 percent rhodium-platinum wire-thermocouple with a 0.0333 second time constant was mounted in the combustor exhaust plane. The test conditions were 30 psia (20.7 N/cm^2) combustor inlet total pressure, 150 feet per second (45.7 m/sec) reference velocity and 250^{o} and 600^{o} F (394 and 589 K) inlet air temperature. The tests were conducted by first operating the combustor at a given fuel/air ratio. Then the fuel flow was rapidly increased to simulate a step change in fuel flow.

The results of these tests, shown in figures 9 and 10, are presented in terms of the ratios of instantaneous temperature rise to initial temperature rise $(\Delta T_t/\Delta T_o)$, and of instantaneous fuel flow to initial fuel flow $\dot{w}_t/\dot{w}_o$.

For conditions of constant combustion efficiency and stable exhaust temperature pattern, the ratio $\Delta T_t/\Delta T_o$ will very nearly equal $\dot{w}_t/\dot{w}_o$ at any one measuring point.

Figure 9 is typical of the combustor response with ASTM-A1 fuel over the range of inlet-air temperatures of 250^o to 600^o F (394 to 589 K).

Figure 10(a) shows the temperature response of natural gas fuel at 600^o F (589 K). This is much better than the 250^o F (394 K) data of figure 10(b), but is is short of the ASTM-A1 fuel response shown in figure 9. At 250^o F (394 K) inlet-air temperature (fig. 10(b)), the combustor temperature actually decreased momentarily as natural gas fuel flow increased. At this condition a 36 percent fuel-flow increase resulted in only a 2 percent temperature increase.

Flame radiation and headplate temperature. - Total flame radiation data were obtained at a single point in the combustor primary zone using a Leeds and Northrop radiometer. The location of the radiometer is shown in figure 2. The radiation data were taken at 1050^o F (839 K) inlet-air temperature and a combustor pressure of 60 psia (41.4 N/cm^2). With natural gas fuel the radiation heat flux was approximately 30 000 Btu per square feet per hour (9.4 $watts/cm^2$) independent of the reference velocity or fuel/air ratio over the range of test conditions shown in figure 11. With ASTM-A1 fuel in contrast, the radiation heat flux increased with decreasing reference velocity and fuel/air ratio as shown on figure 11. This is believed due to the flame front moving downstream as the air velocity increases, thus moving away from the radiometer viewing port. The flame front likely moves with ASTM-A1 for it takes a finite time for the liquid fuel to vaporize; this time would be a function of the amount of fuel and the heat transfer rate.

The headplate temperatures shown on figure 12 were measured with thermocouples mounted on the headplate. With ASTM-A1 fuel these temperatures increased slightly with increasing fuel-air ratio and decreasing reference velocity. With natural gas fuel there appeared to be little change in headplate temperature with either fuel-air ratio or reference velocity. However, the temperatures were about 50^o F (28 K) lower with natural gas fuel than with ASTM-A1 fuel at a fuel-air ratio of 0.016 and a reference velocity of 150 feet per second (45.7 m/sec). Lower headplate temperatures were expected with natural gas fuel as natural gas flames are generally less luminous than liquid fuel flames.

Smoke. - A VonBrand Smokemeter and Welsh Densichron and Reflection Unit (3832A) were used to obtain smoke data. A Welsh Gray Scale (Cat. no. 3827T) was used as a calibration reference. A gas sample flowrate of 0.3 standard cubic feet per minute per square inch ($2.19\times10^{-5} m^3/sec\text{-}cm^2$) of filter paper was maintained with a 2 psig ($1.38 N/cm^2$ above atmospheric) pressure above the moving filter paper tape and a 5 inch (12.7 cm) mercury vacuum below the filter paper tape. Clean filter paper readings were taken for reference.

Both natural gas and ASTM-A1 fuels gave very low smoke numbers. At 600° F (589 K) or 1050° F (839 K) inlet-air temperature, 60 psia ($41.4 N/cm^2$) combustor total pressure and reference velocities from 100 to 200 feet per second (30.5 to 61.0 m/sec) both fuels usually gave smoke numbers less than one. Natural gas smoke numbers ranged from 0 to 2.6 while ASTM-A1 smoke numbers ranged from 0 to 6.0.

The threshold of visible smoke is 20 to 30 using this method of measuring smoke number. These low values obtained in these tests are partly accounted for by the relatively low pressures at which the tests were conducted. At more realistic sea level take-off combustor pressures, the smoke numbers would be higher.

CONCLUDING REMARKS

Tests were made using natural gas fuel in an advanced turbojet combustor designed and developed for ASTM A-1 jet-type liquid fuel. A single fuel nozzle design was used. The following results were obtained with the gaseous fuel.

1. Combustion efficiency was a 100 percent at all conditions for which the inlet total pressure exceeded 30 psia ($20.7 N/cm^2$), the inlet air temperature exceeded 600° F (589 K) and the fuel-air ratio exceeded 0.01. As inlet air temperature was reduced below 600° F (589 K) the combustion efficiency with natural gas, unlike that of ASTM-A1, fell off rapidly. At a temperature of 250° F (395 K) the efficiency was only 30 percent.

2. The radial average outlet temperature profiles were slightly improved using natural gas over the profiles obtained using liquid fuel. The local maximum temperatures that occurred were higher, however, with natural gas.

3. Blowout occurred at much higher pressures and temperatures with natural gas. Relight characteristics were also much poorer than with liquid fuel.

4. Flame radiation, combustor headplate temperatures and smoke emission were lower for natural gas than for ASTM A-1 fuel.

It cannot be concluded from these preliminary tests that the above trends are general. The tests can only be taken to show possible areas of difficulty in the use of natural gas as a turbojet combustor fuel. More complete and systematic studies are required to determine whether or not these potential problem areas are of real importance.

REFERENCES

1. Weber, Richard J.; Dugan, James F., Jr.; and Luidens, Roger W.: Methane-Fueled Propulsion Systems. Paper 66-685, AIAA, June 1966.

2. Whitlow, John B., Jr.; Eisenberg, Joseph D.; and Shovlin, Michael D.: Potential of Liquid-Methane Fuel for Mach-3 Commercial Supersonic Transports. NASA TN D-3471, 1966.

3. Joslin, C. L.: The Potential of Methane as a Fuel for Advanced Aircraft. Aviation and Space: Progress and Prospects. ASME, 1968, pp. 351-355.

4. Rusnak, J. P.; and Shadowen, J. H.: Development of an Advanced Annular Combustor. Rep. PWA-FR-2832, Pratt & Whitney Aircraft (NASA CR-72453), May 30, 1969.

5. Chamberlain, John: Ram Induction Combustor Concept. Presented at the AIAA Third Propulsion Joint Specialist Conference, Washington, D.C., July 17-21, 1967.

TABLE I. - COMPARISON OF ASTM - A1 AND NATURAL GAS FUELS

	ASTM - A1	Natural Gas
Lower heat of combustion	18 600 Btu/lb 43 300 J/g	20 530 Btu/lb 47 720 J/g
Hydrogen-Carbon ratio	0.161	0.3276

TABLE II. - NATURAL GAS FUEL NOZZLE CHARACTERISTICS

	Combustor conditions inlet air		Combustor headplate downstream static pressure, psia (N/cm^2)	Reference velocity, ft/sec (m/sec)	Total fuel flow rate, lb/sec (kg/sec)	Fuel-air ratio	Combustion efficiency	Fuel temperature, $^{\circ}$R (K)	Calculated* fuel nozzle inlet hole conditions (fig. 4(b)) pressure velocity		Calculated* swirler annulus inlet conditions (fig. 4(b)) pressure velocity	
	Total pressure, psia (N/cm^2)	Temperature, $^{\circ}$R (K)							psia (N/cm^2)	ft/sec (m/sec)	psia (N/cm^2)	ft/sec (m/sec)
A	60.0 (4.14)	1046 (837)	57.3 (39.5)	126 (38.4)	0.625	0.0092	105.7	546 (559)	65.6 (45.2)	521 (158.9)	59.0 (40.7)	209 (63.7)
B	60.0 (41.4)	1045 (836)	53.2 (36.7)	192 (58.5)	1.526	0.0145	105.3	557 (565)	100.0 (69.9)	866 (264.0)	61.0 (42.1)	492 (150.0)
C	25.0 (17.2)	242 (390)	22.0 (15.2)	129 (39.3)	0.63	0.0104	-----	524 (547)	43.0 (29.6)	766 (233.5)	25.9 (17.9)	450 (137.2)
D	16.0 (11.0)	300 (422)	14.5 (10.0)	136 (41.4)	0.39	0.0104	-----	520 (544)	25.5 (17.6)	787 (240.0)	16.8 (11.6)	425 (129.5)
E	12.0 (8.3)	394 (474)	10.5 (7.2)	142 (43.3)	0.27	0.0104	-----	517 (543)	17.9 (12.3)	777 (236.8)	12.0 (8.3)	408 (124.4)

Conditions A and B represent maximum and minimum fuel flow conditions with 60 psia (41.2 N/cm^2) inlet air total pressure.

Conditions A, C, D, and E represent ignition points.

*The fuel nozzle inlet hole and swirler annulus inlet conditions were calculated from the combustor static pressure, fuel flow, and test section inlet fuel temperature.

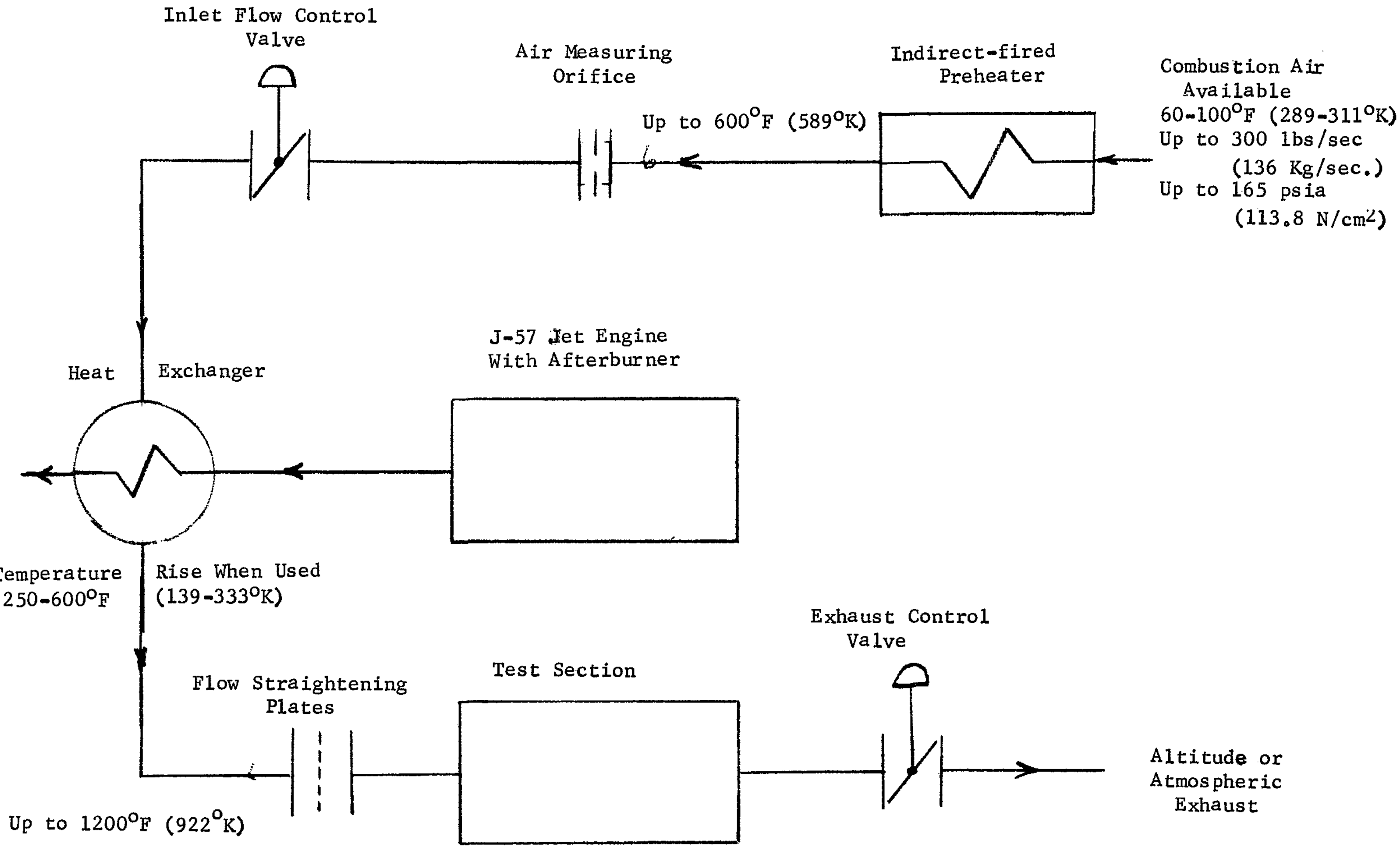

Figure 1. - Test Facility Combustion Air Schematic

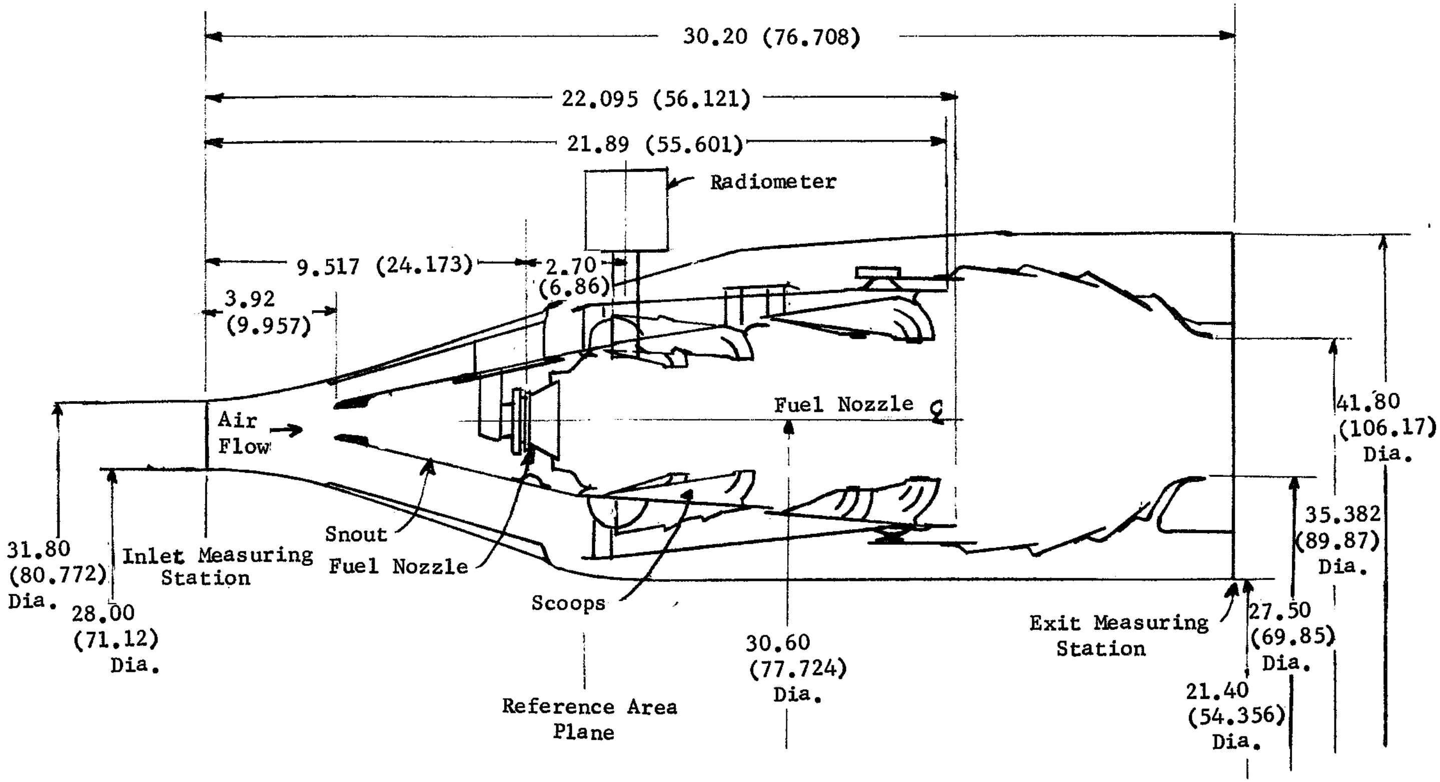

Figure 2. - Combustor Cross-Section (Dimensions are in inches (cm))

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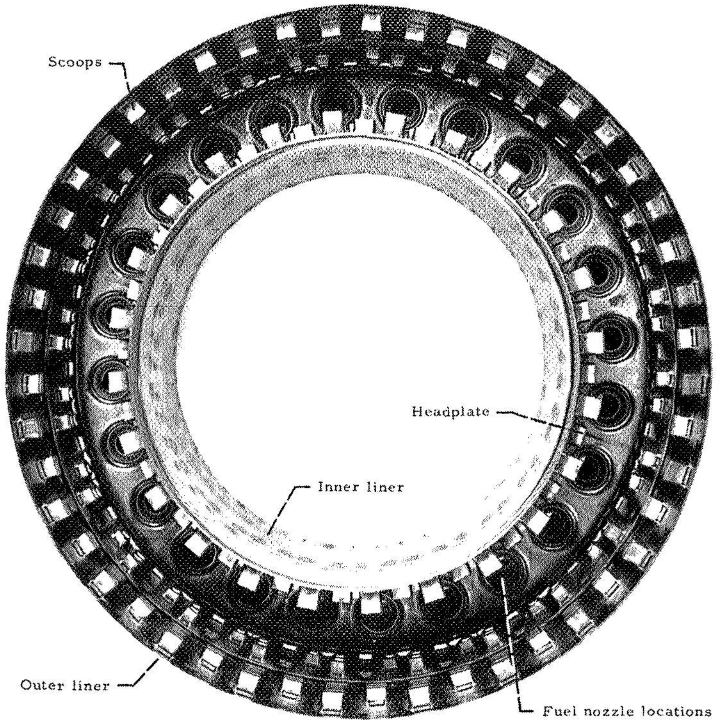
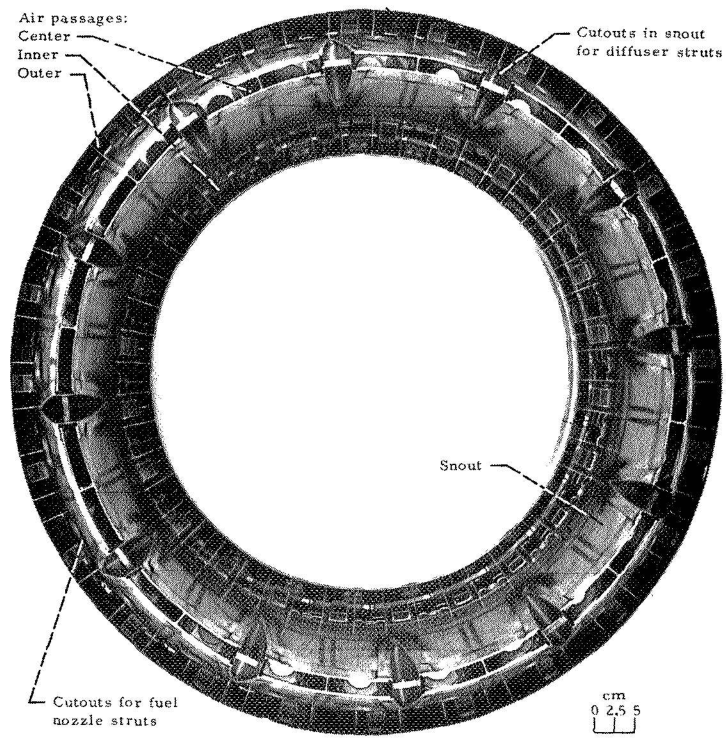
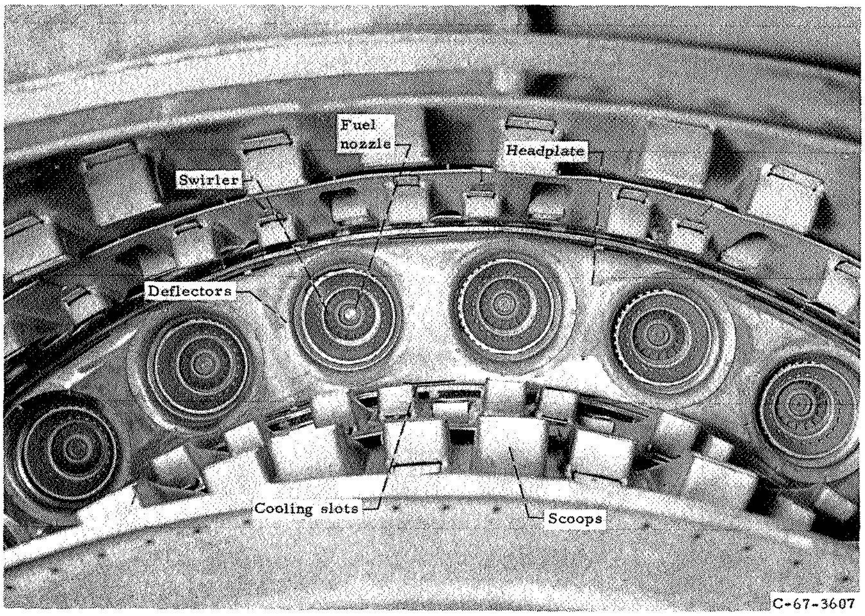


(a) Viewed from downstream end.



(b) Viewed from upstream end.

Figure 3. Ram induction combustor.



(c) Viewed from douwnstream end.

Figure 3. Concluded.

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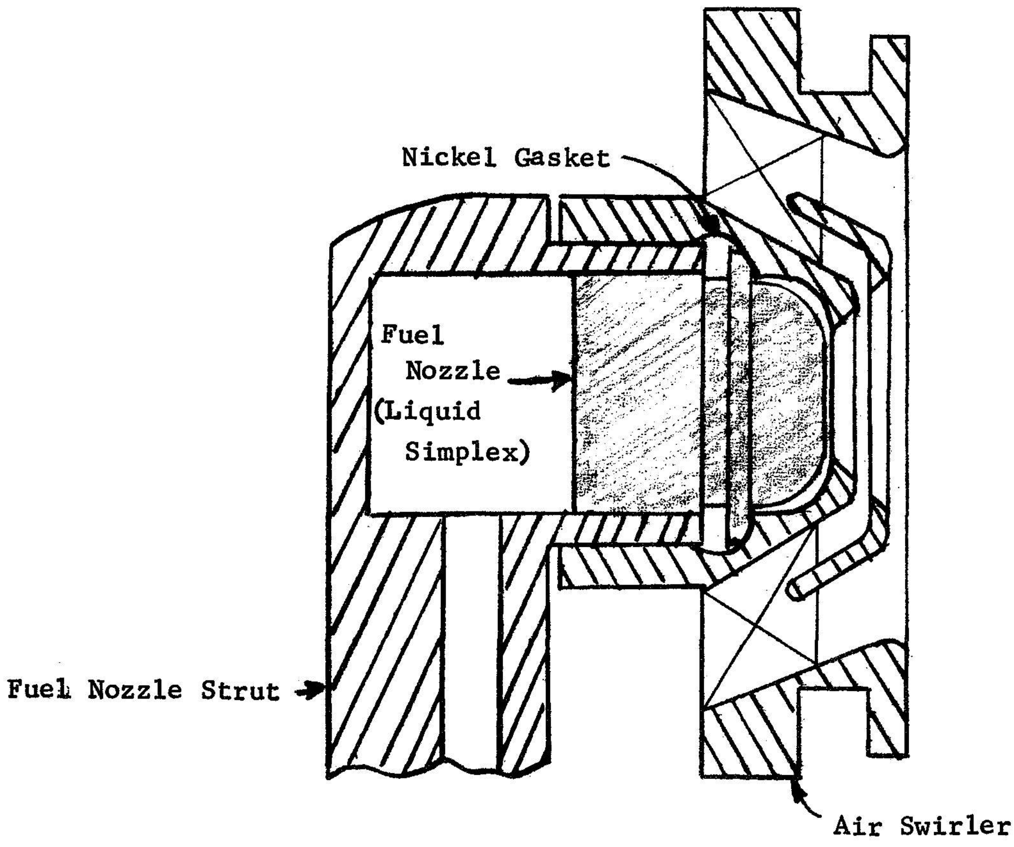

Figure 4. - Fuel Nozzle Assembly
(a) ASTM-A1 Fuel Nozzle Assembly

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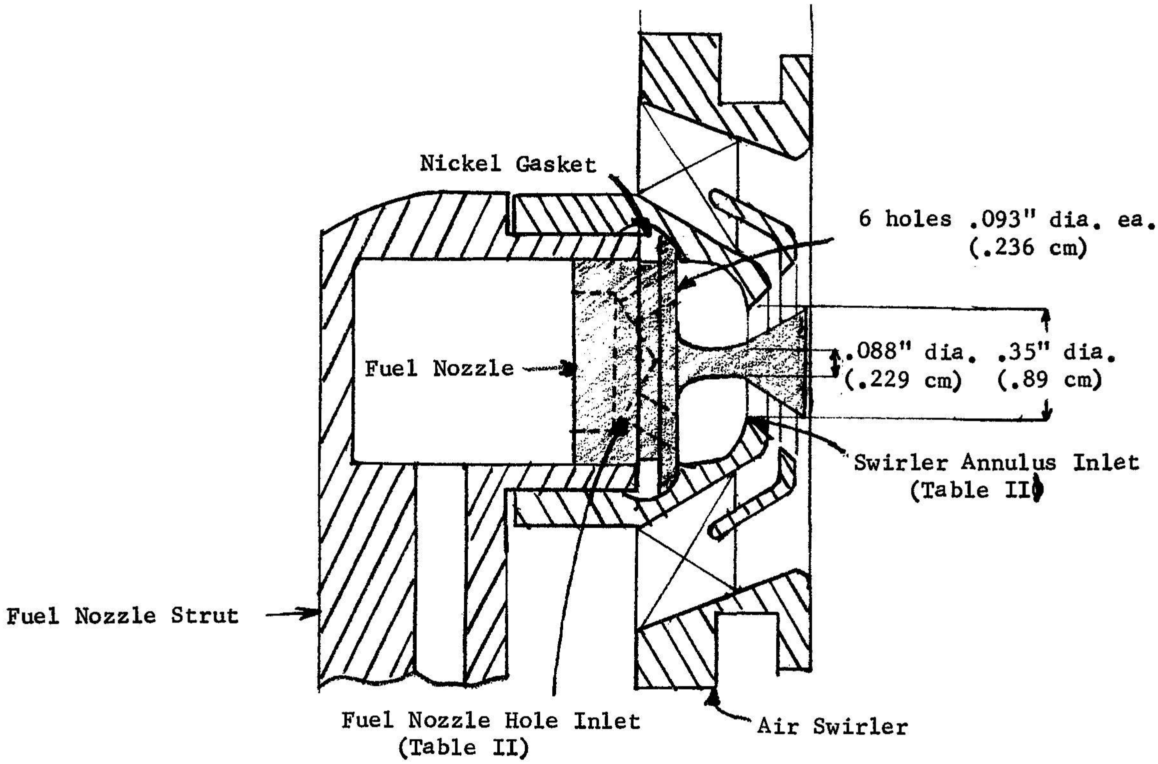
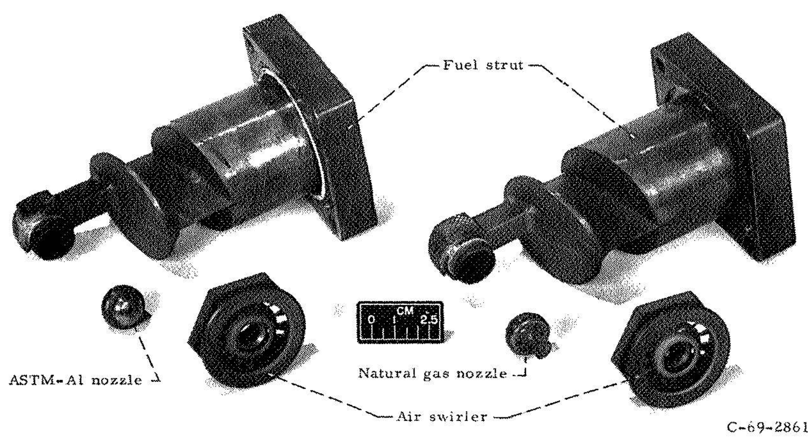


Figure 4. - Fuel Nozzle Assembly
(b) Natural Gas Fuel Nozzle Assembly



(c) ASTM-Al and natural gas fuel struts, nozzles and air swirlers.

Figure 4. - Concluded.

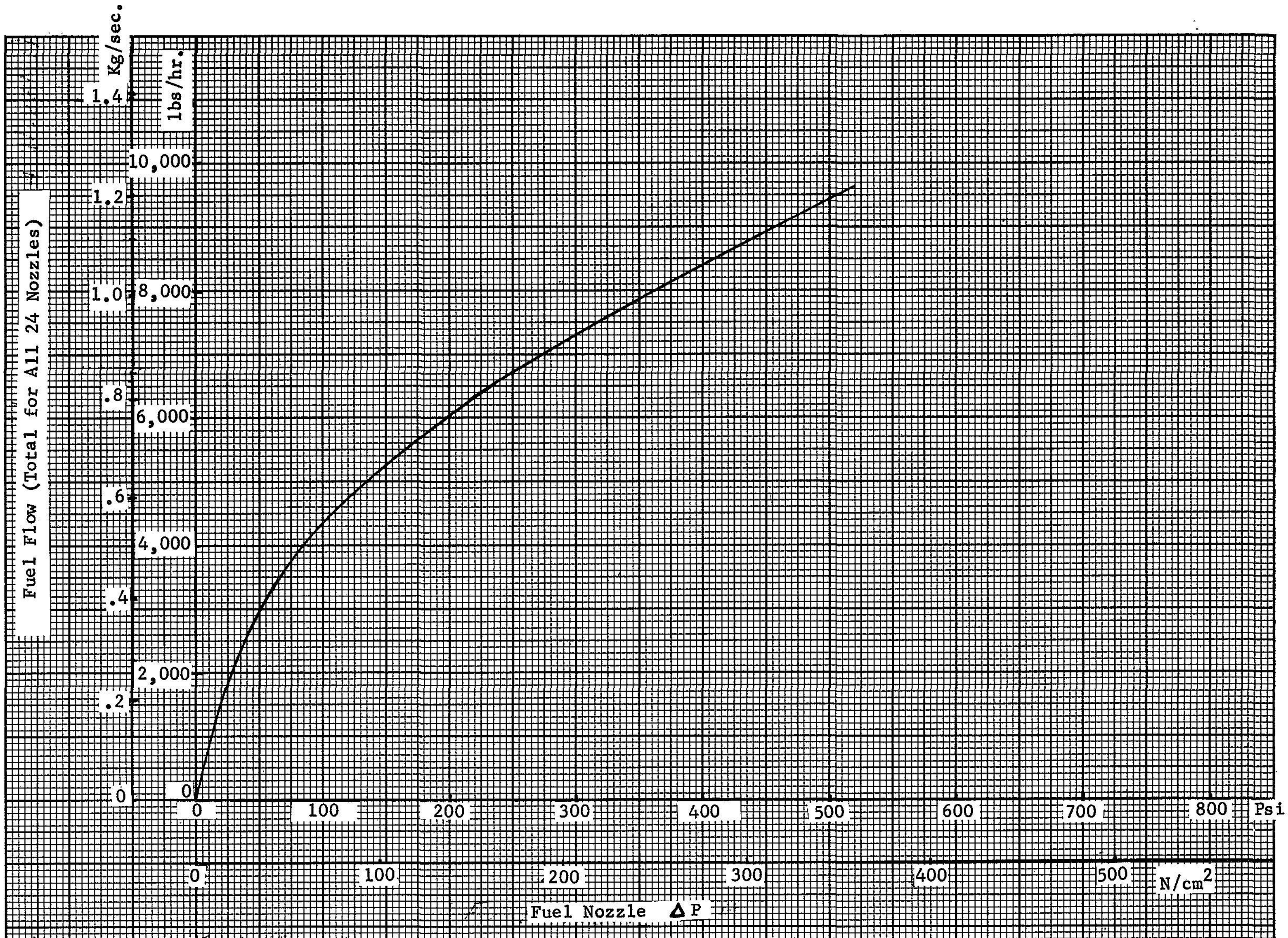


Figure 5. - Fuel Flow Characteristics for the ASTM-A1 Simplex Nozzles.

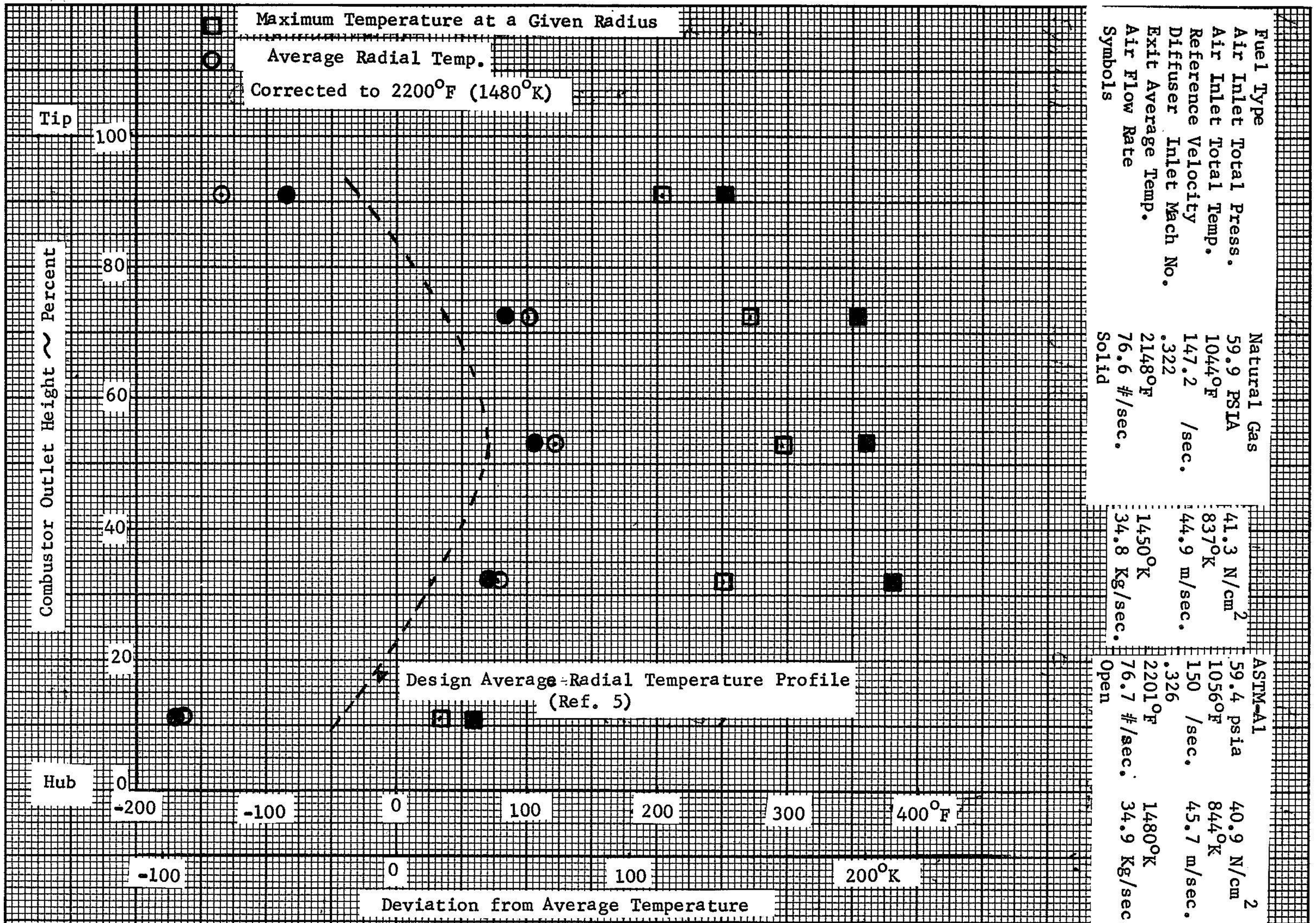


Figure 6. - Comparison of Combustor Average Radial Exit Temperature Profiles.

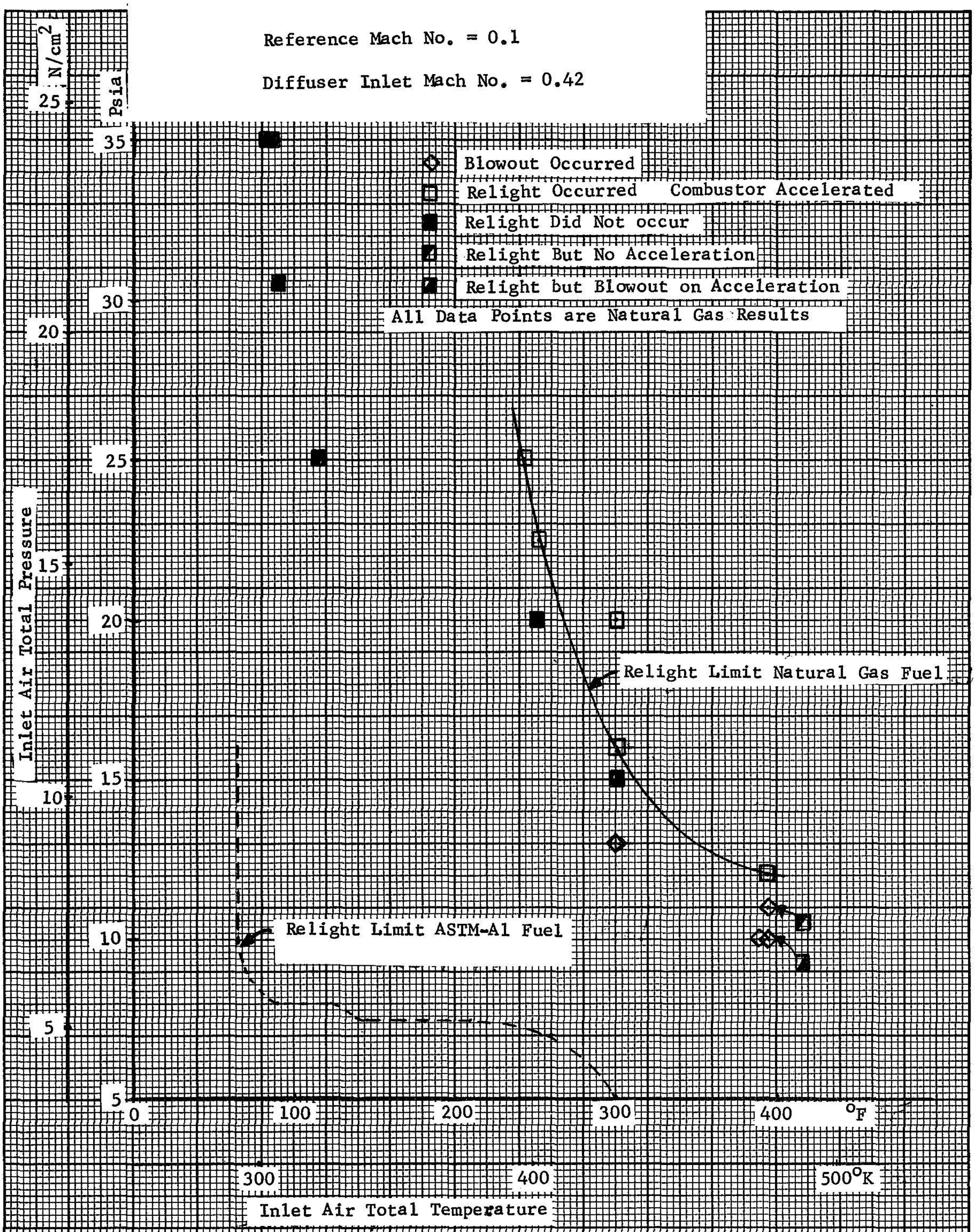


Figure 7. - Combustor Blowout and Altitude Relight Results

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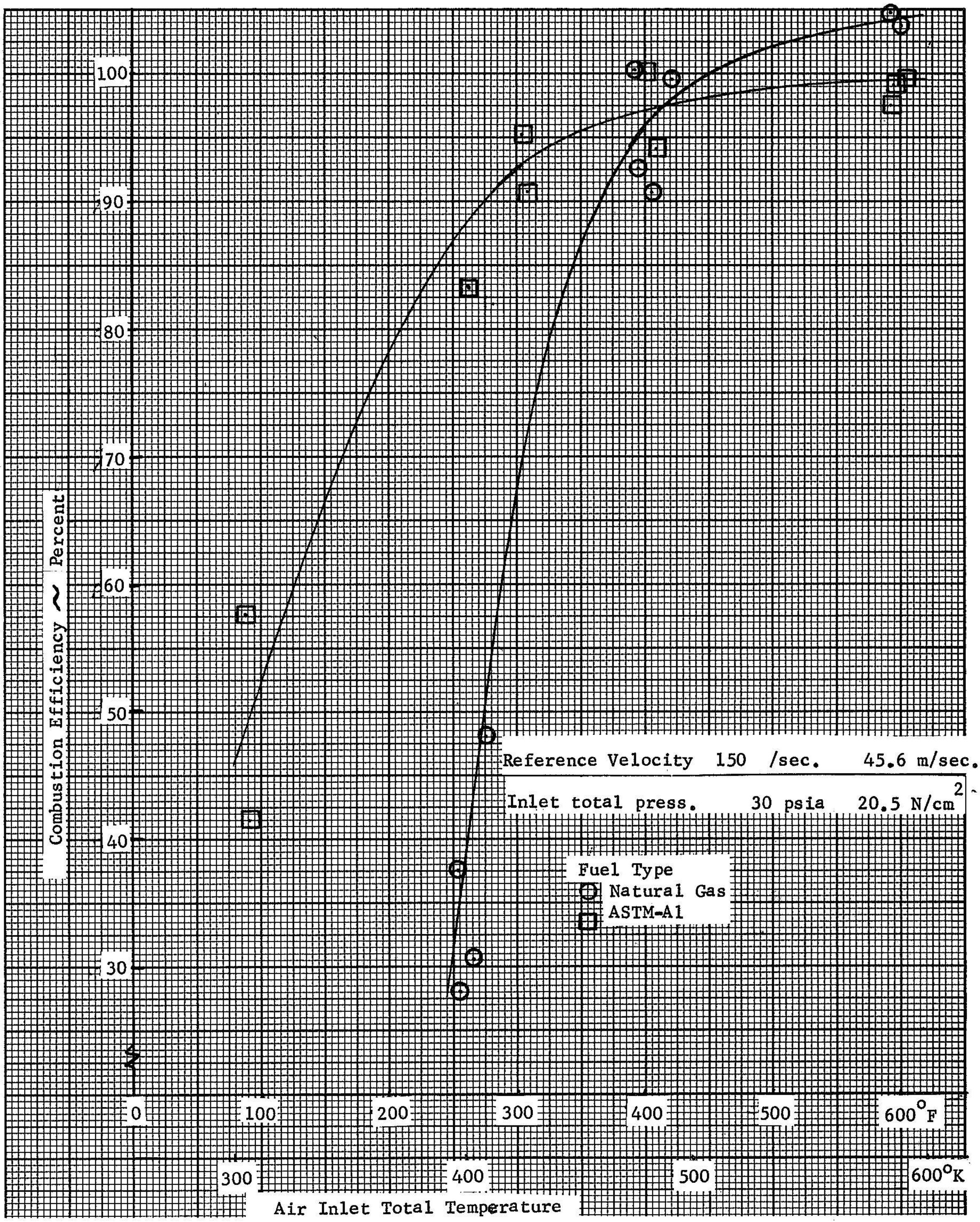

Figure 8. - Variation of Combustor Efficiency at Various Inlet Air Temperatures with Natural Gas and ASTM-A1 Fuels

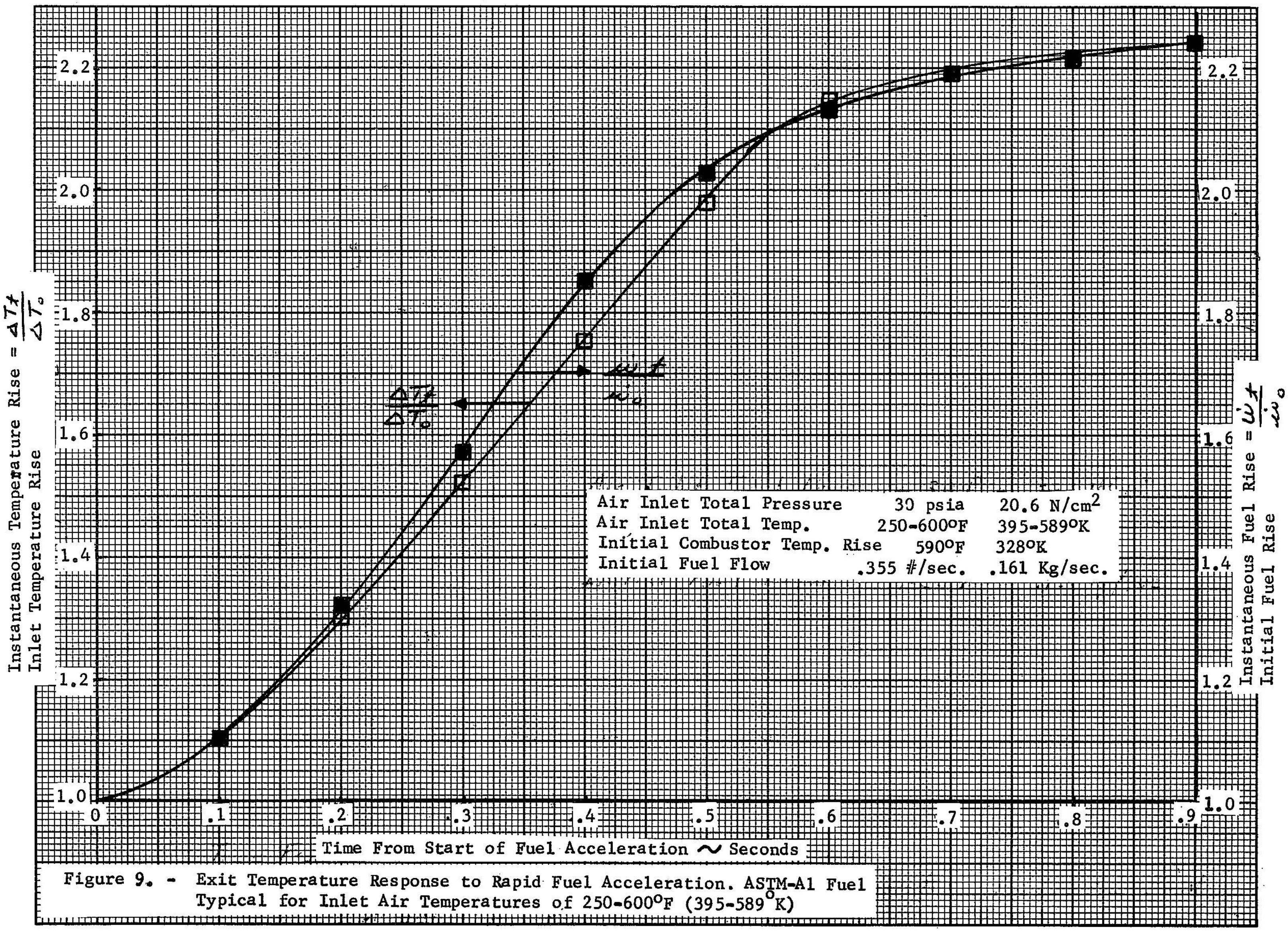

Figure 9. - Exit Temperature Response to Rapid Fuel Acceleration. ASTM-A1 Fuel Typical for Inlet Air Temperatures of 250-600°F (395-589°K)

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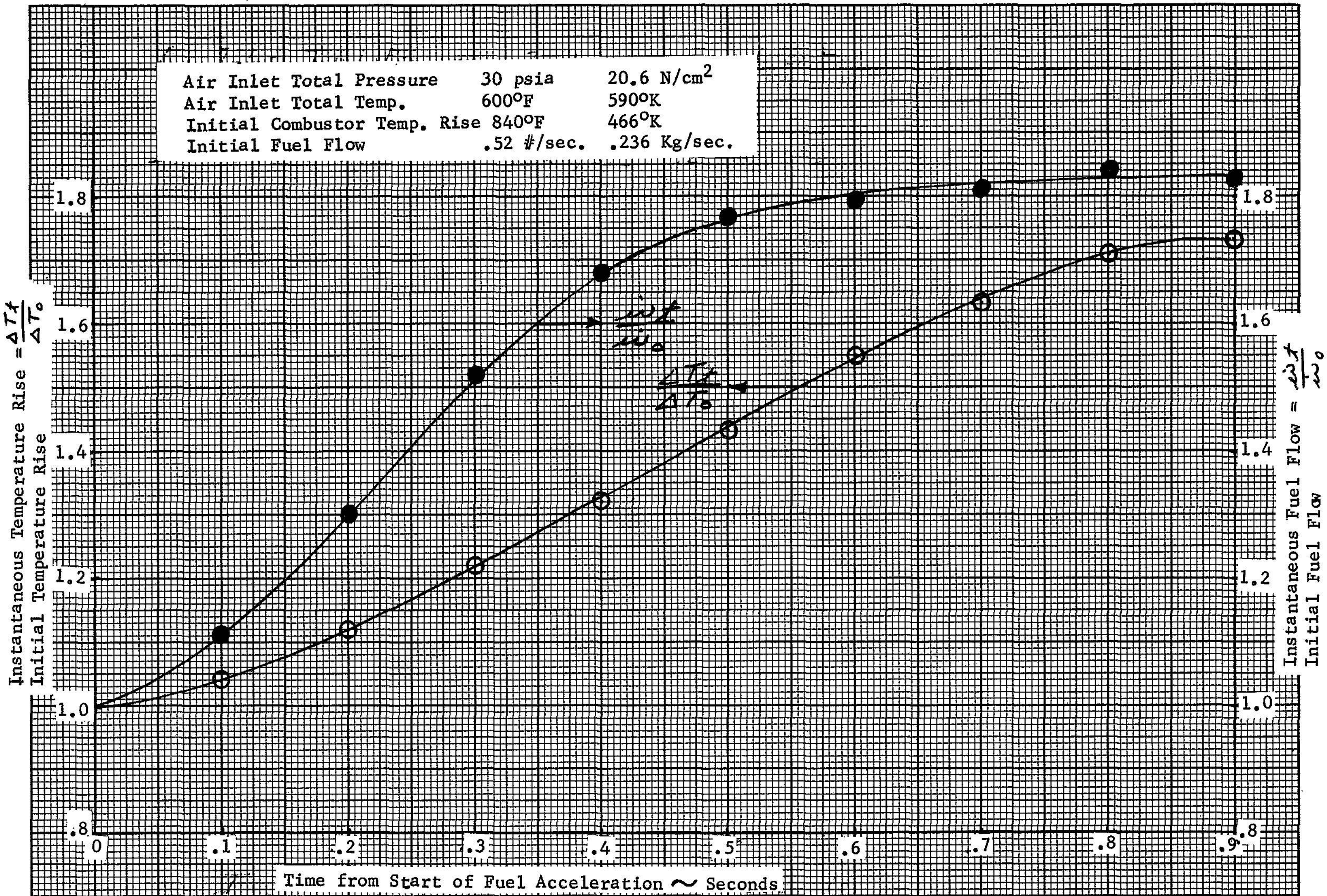

Figure 10. - Exit Temperature Response to Rapid Fuel Acceleration. Natural Gas Fuel
(a) High Inlet Air Temperature

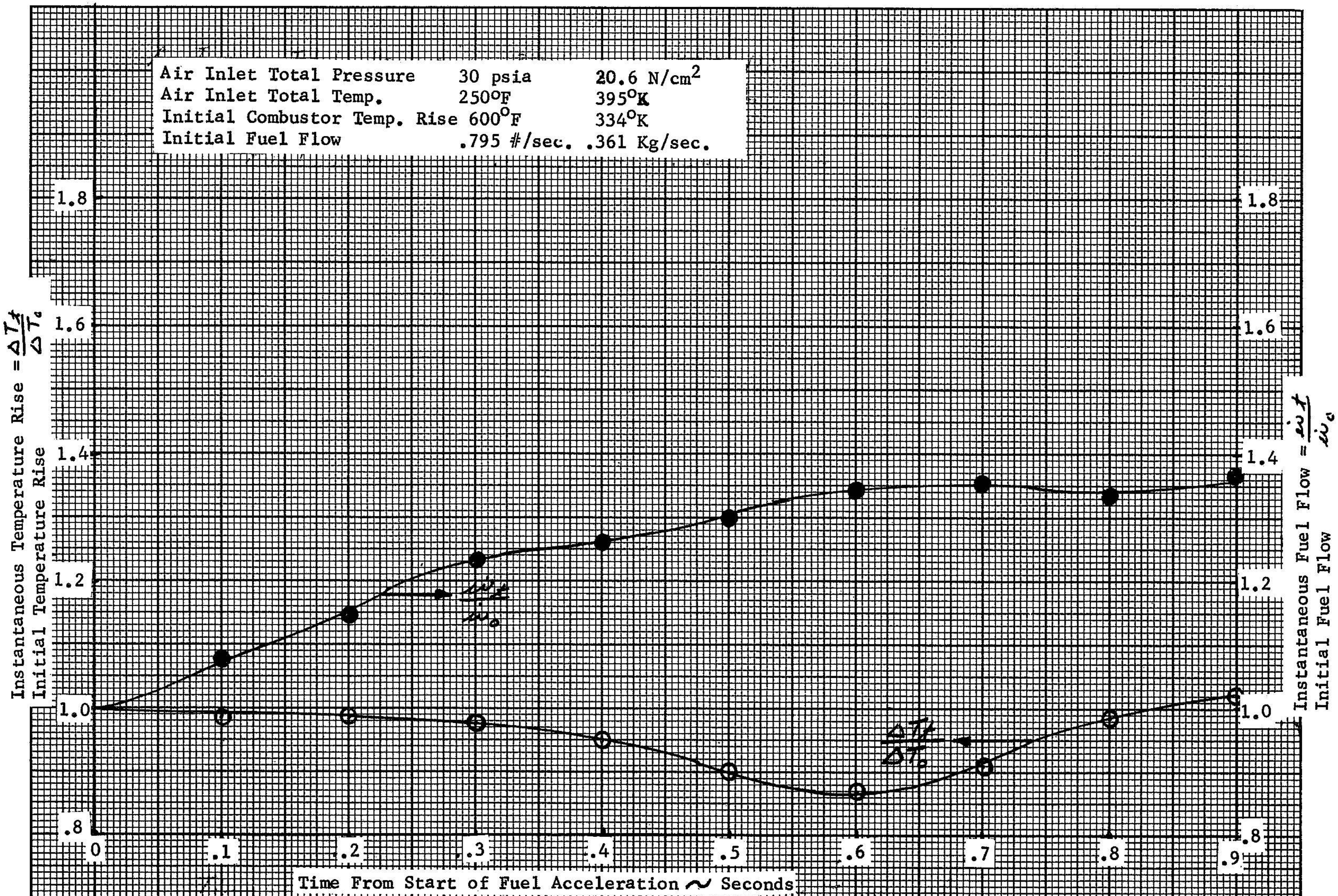

Figure 10. - Exit Temperature Response to Rapid Fuel Acceleration, Natural Gas Fuel
(b) Low Inlet Air Temperature

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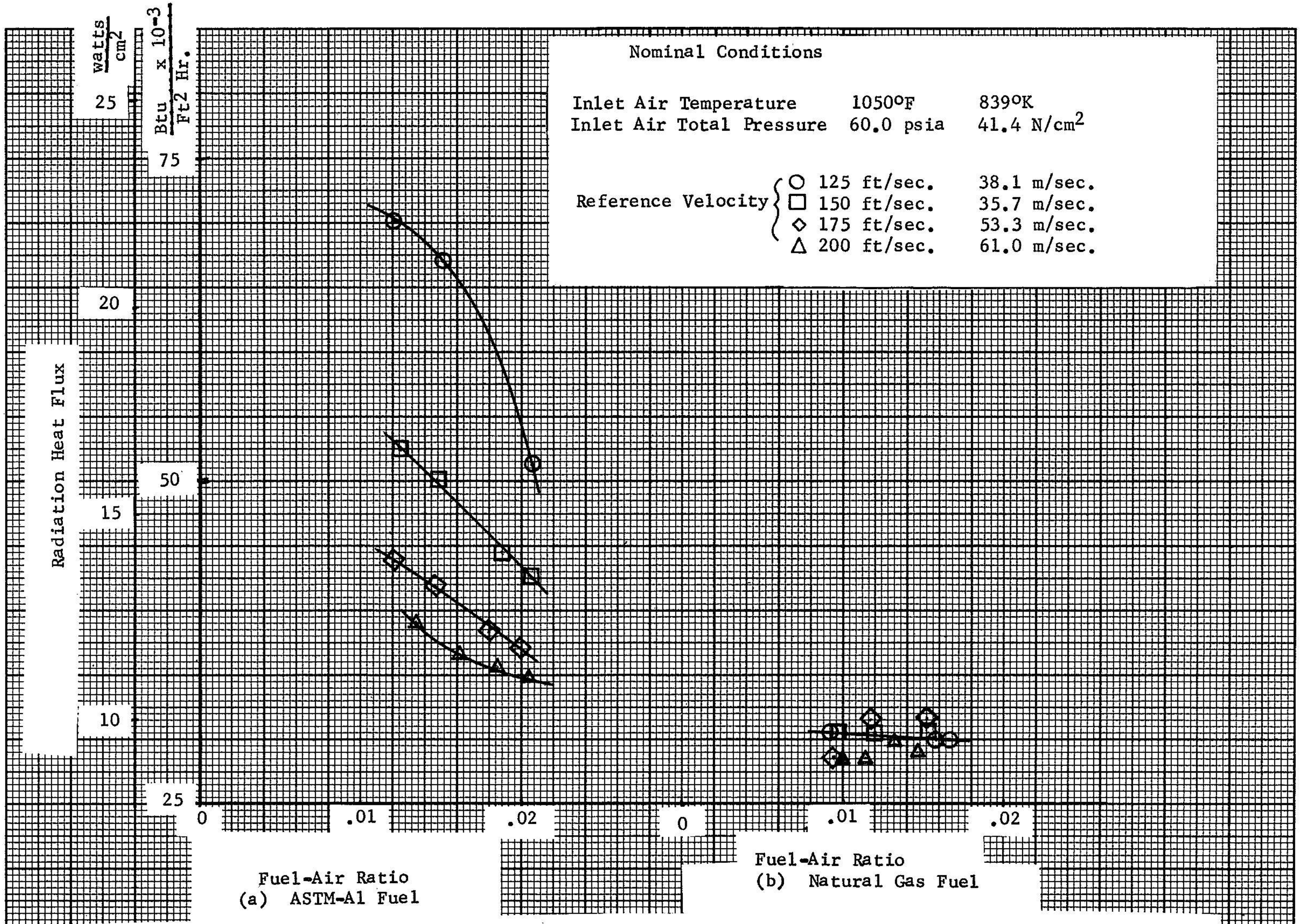

Figure 11. - Radiation Heat Flux with ASTM-A1 and Natural Gas Fuels

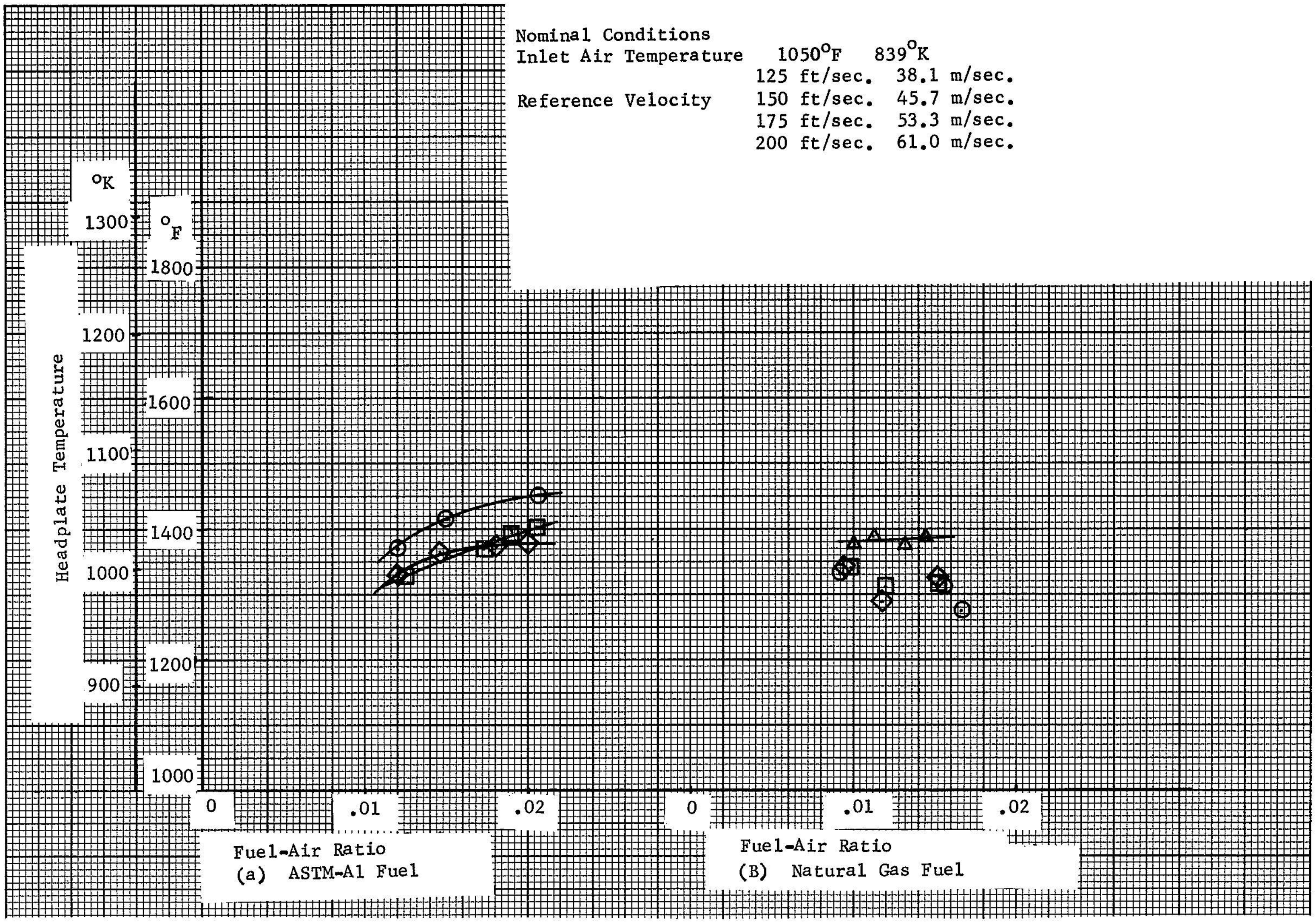

Figure 12. - Headplate Temperatures with ASTM-A1 and Natural Gas Fuels