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COMPARISON OF COMBUSTION CHARACTERISTICS OF ASTM A-1, PROPANE, AND NATURAL-GAS FUELS IN AN ANNULAR TURBOJET COMBUSTOR

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16. Abstract

This report compares the performance of an annular turbojet combustor using natural-gas fuel with that obtained using ASTM A-1 and propane fuels. Propane gas was used to simulate operation with vaporized kerosene fuels. The results obtained at severe operating conditions and altitude relight conditions show that natural gas is inferior to both ASTM A-1 and propane fuels. Combustion efficiencies were significantly lower and combustor pressures for relight were higher with natural-gas fuel than with the other fuels. The inferior performance of natural gas is shown to be caused by the chemical stability of the methane molecule.

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SUMMARY

This report compares the performance of an annular turbojet combustor using natural-gas fuel with that obtained using ASTM A-1 and propane fuels. Propane gas was used to simulate operation with vaporized kerosene fuel. The combustion efficiency data obtained with these fuels is compared at several simulated off-design engine operating points. These points were chosen to illustrate the differences in performance obtainable with the three fuels. In addition, both altitude relight and combustor blowout data are compared for the three fuels.

These investigations show that the use of natural-gas fuel results is significantly lower values of combustion efficiency at severe operating conditions, higher values of combustor pressure (lower flight altitude) for altitude ignition and blowout, and a stronger tendency for combustion instability than either ASTM A-1 or propane fuel. The inferior performance obtained with natural-gas fuel is explained in terms of the chemical stability of the methane molecule. Physical and chemical properties of the three fuels are tabulated and compared to illustrate the relative chemical stability of each fuel.

INTRODUCTION

This report compares the combustion performance of ASTM A-1 fuel and natural-gas fuels in a combustor designed for an advanced supersonic flight engine. Propane fuel is also compared as a gaseous fuel representative of vaporized kerosene fuels. The comparisons are made on the basis of combustion performance at off-design and altitude relight conditions, and this performance is related to fundamental combustion properties of each fuel.

The use of liquefied natural gas as the fuel for engines powering a supersonic transport has been shown to have many potential advantages over the conventional kerosene fuels (refs. 1 to 4). The more important of these potential advantages are the increased heat-sink capability of liquefied natural gas, higher heating value on a weight basis, low flame radiation and low smoke levels in engine exhaust. As a result of this interest in natural-gas fuel, many combustor programs were conducted to document the performance attainable with natural-gas fuel (refs. 5 to 11). These programs included combustors designed specifically for natural-gas fuel as well as combustors designed for use with kerosene fuel (ASTM A-1). As expected, combustor performance with natural-gas fuel was equal to that obtained with ASTM A-1 fuel at combustor conditions simulating takeoff and cruise operation. However, combustor performance at off-design conditions was considerably poorer with natural-gas fuel. Combustion efficiency decreased markedly with decreasing pressure and was particularly sensitive to a decrease in the inlet-air temperature. Of particular importance were the very poor altitude blowout and relight limits obtained with natural-gas fuel. For every operating condition, the measured blowout and relight pressures were significantly higher than those obtained with ASTM A-1 fuel (ref. 5).

A recent investigation (ref. 12) was conducted to determine if combustor performance with natural-gas fuel could be significantly improved by determining the optimum method of fuel injection. This study was deemed necessary because many previous investigations (e.g., refs. 13 to 16) had indicated that the method of gaseous fuel injection was of primary importance in determining combustor performance. The best injector design for natural-gas fuel (ref. 12) was one that injected the fuel in discrete jets at a shallow angle relative to the combustor centerline. This injector also gave very good performance with propane fuel.

This report extends the effort of reference 12 by comparing the combustor performance with natural gas, propane, and ASTM A-1 liquid fuel. Propane fuel was used to simulate vaporized kerosene fuel injected as a gas instead of as a liquid. Three different configurations of gaseous fuel nozzles were used for the comparisons.

Nominal test conditions used for combustion efficiency determinations were as follows: inlet pressure, 13.8 and 17.2 newtons per square centimeter (20 and 25 psia); combustor reference velocity, 32.3 and 40.5 meters per second (106 and 133 ft/sec); and inlet-air temperature, 422 K (300° F).

The altitude relight and blowout test conditions included two combustor reference Mach numbers, 0.08 and 0.10, and two inlet-air temperatures, 300 and 425 K (80° and 305° F).

The U.S. customary system of units was used for primary measurements and calculations. Conversion to SI units (Systems International d'Unites) is done for reporting purposes only. In making the conversion, consideration is given to implied accuracy and may result in rounding off the values expressed in SI units.

APPARATUS

The combustor used in these tests was an advanced annular combustor described in references 17 and 18. This combustor was designed for use with liquid fuel and a modification to the fuel injectors was necessary for use with natural gas and propane fuels. Figure 1 is a cross-sectional sketch of the combustor test section showing inlet and outlet ducting and instrumentation planes. Pertinent dimensions are included.

Figure 2 is a cross-sectional sketch of the combustor headplate showing the liquid fuel dual-orifice fuel nozzle. The air swirler screws onto the fuel strut and acts as a retainer for the fuel nozzle. A photograph of the fuel nozzle installed in the fuel strut is also shown. Figure 3 shows the various gaseous fuel nozzles used in this study, two of which were used in tests reported in reference 12. To provide the increased injection area required for the gaseous fuels, the injection plane of the nozzle was located farther downstream than the injection plane of the liquid fuel dual-orifice nozzle.

Nozzle 2 (fig. 3(a)) provided angled injection of the fuel through six holes with a total injection area of 1.068 square centimeters (0.1656 in.^{2}). This nozzle was tested with gaseous propane (data reported herein) and with natural gas (data reported in ref. 12).

Nozzle 9A is shown in figure 3(b). The injection plane is farther downstream and the physical size of the nozzle has been substantially increased compared with nozzle 2. Angle injection through six holes with a total injection area of 1.254 square centimeters (0.1944 in.^{2}) is provided by nozzle 9A.

Nozzle 8 (fig. 3(c)) was tested with natural-gas fuel; these data are reported in reference 12. There are 10 angled injection holes per nozzle with a total injection area of 3.576 square centimeters (0.5542 in.^{2}). This nozzle is similar in physical size to 9A; however, nozzle 8 has a larger injection area than does nozzle 9A.

The capabilities of the facility used in this investigation are given in detail in references 17 to 19.

Fuels

Chemical and physical properties of the natural gas, propane, and ASTM A-1 fuels are presented in table I. The natural-gas composition reported is representative of that used during the test program, which was obtained from the natural gas supplied to the Lewis Research Center for general use. The gas composition varied slightly and was dependent on the seasonal demand and gas field from which it was obtained. The propane fuel was obtained from a commercial supplier. The ASTM A-1 was obtained from a source that is used by commercial airlines.

Instrumentation

Combustion air flow rates were measured by square-edge orifice plates installed according to ASME specifications. Liquid fuel flow was measured by turbine flow meters using frequency-to-voltage converters for readout and recording.

Combustor inlet-air total and static pressures were measured at the plane of the diffuser inlet (station 3, fig. 1). Combustor exhaust or outlet total and static pressures and total temperatures were measured at the turbine inlet plane (station 5, fig. 1). Combustor exhaust total pressures and temperatures were measured at 3^{o} increments around the exhaust circumference. At each point, five temperature and pressure readings were obtained across the radius.

Exhaust thermocouples were platinum - 13-percent-rhodium/platinum and were of the high-recovery aspirating type. The indicated readings of all thermocouples were taken as true values of the total temperatures. More detail of the instrumentation construction, dimensions, and readout capability are given in references 17 to 19.

PROCEDURE

Combustion Efficiency Tests

Table II presents the three operating conditions used for combustion efficiency comparisons of the nozzles. The table includes inlet pressures, inlet temperatures, mass flows, reference velocities, and values of a correlating parameter PT/V. The PT/V parameter is calculated from inlet total pressure, inlet total temperature, and combustor reference velocity. The different operating conditions are designated as conditions 1, 2, and 3. The severity of the combustor inlet conditions in terms of PT/V increases from condition 1 to 3.

Conditions 1 and 2: change in reference velocity at the same inlet pressure.

Conditions 2 and 3: variation in inlet pressure at the same reference velocity.

Conditions 1 and 3: constant air flow with variation in inlet pressure and reference velocity.

The procedure followed at each condition was that after ignition the inlet conditions of pressure, temperature, and air flow were adjusted to desired values. Data were taken at several fuel-air ratio values with 0.008 and 0.020 being arbitrarily selected as the lean and rich fuel-air ratio limits, respectively.

Altitude Limit Tests

Altitude limit data were taken to determine the combustor pressures where the combustor flame blew out and where ignition occurred. These tests were conducted as follows: after ignition at a pressure considerably higher than the possible blowout pressure, values of inlet-air temperature and reference Mach number were held constant while decreasing the inlet total pressure. Fuel-air ratio was held at about 0.010 during the change in inlet-air pressure. At each inlet condition fuel flow was then increased to a value intended to give an approximate 556 K (1000° F) theoretical temperature rise. The fuel-flow increase was over a time period of 6 to 8 seconds. If the monitored exhaust temperatures showed an increase during the fuel-flow increase, the fuel-air ratio was reduced back to about 0.010, and the series of steps was repeated at successively lower pressure levels. This procedure was repeated until combustor blowout was encountered during the increase in fuel flow.

Pressure values for relight were determined as follows: at the desired inlet conditions, the fuel-air ratio was slowly varied up and down from about 0.005 to 0.015 (during a maximum time period of 60 sec). If ignition occurred and combustion was stable at this fuel-air ratio, the inlet pressure was recorded as an ignition pressure.

CALCULATIONS

Combustion Efficiency

Efficiency was determined by dividing the measured temperature rise across the combustor by the theoretical temperature rise. Exit temperatures were measured with five-point, traversing, aspirated thermocouple probes and were mass-weighted for the efficiency calculation. The inlet temperature was the arithmetic average of readings of eight single-point thermocouples around the inlet circumference. The theoretical temperature rise was computed as a function of fuel (heat of formation and hydrogen-carbon weight ratio), inlet-air pressure, inlet-air temperature, and fuel-air ratio.

The composition of the natural gas as shown in table I indicated about 97 to 98 percent hydrocarbons. The heating value and fuel-air ratios used for theoretical temperature rise and other calculations and figures were based on actual hydrocarbons in the gas. The nonhydrocarbons were considered to be air.

Inlet-Air Total Pressure

The average inlet-air total pressure was obtained by mass-weighting values from eight five-point pressure rakes around the diffuser inlet. Static pressures, used in the mass weighting calculations, were measured around the circumference on both the inner and outer wall of the inlet annulus.

Combustor Reference Mach Number and Velocity

The combustor reference Mach number was computed from the total air flow, inlet total pressure and temperature, and reference area (maximum cross-sectional area between inner and outer shrouds, 4484 square centimeter (695 in.^{2})).

Reference velocity for the combustor was computed from combustor reference Mach number and sonic velocity at the particular inlet condition.

RESULTS AND DISCUSSION

Combustion Efficiency Tests

A summary of combustion efficiency test data with ASTM A-1 and propane is tabulated in table III. Figure 4 compares the combustion efficiency measurements obtained with the three fuels. The combustion efficiency with propane and natural gas fuels is slightly better than that obtained with ASTM A-1 fuel at the milder operating conditions of figure 4(a). Also shown is the efficiency of natural-gas fuel with nozzle 8. Unstable combustion occurred at a fuel-air ratio in excess of 0.019 with this nozzle, and combustion efficiency was considerably below that obtained with nozzle 2 with natural-gas fuel. The comparison in combustion efficiency between propane in nozzle 9A and natural gas in nozzle 8 reflects differences in the combustion properties of the two fuels. These nozzles were designed so that the gaseous fuels were injected at the same velocity for similar weight flow rates. Therefore, injection velocity effects cannot account for the large differences in efficiency. Injection velocity effects may contribute to the combustion efficiency differences between propane and natural gas obtained with nozzle 2. Figures 4(b) and (c) show the effects of increasingly severe operating conditions on combustion efficiency. In each case the efficiency with propane fuel exceeds that of ASTM A-1 fuel. Natural-gas fuel combustion efficiency decreases markedly with unstable combustion frequently occurring.

The data are replotted in figure 5 with combustion efficiency shown against the combustion parameter PT/V for three values of heat content per unit weight of air. For each fuel the fuel-air ratio, which provides the desired heat content per unit weight of air, was calculated (see table IV). The corresponding values of combustion efficiency were then obtained from figure 4. The combustion efficiency of natural-gas fuel rapidly decreases with increasing test condition severity. Only at the mildest operating condition does natural-gas efficiency equal or exceed that of ASTM A-1 fuel. As before, the efficiency of propane fuel is better than that of ASTM A-1 fuel.

Effect of fuel injector design. - Reference 12 covers work on a wide variety of fuel injectors for use with natural-gas fuel. The best injector of that work (injector 2) was used in this program. Comparing the combustion efficiency obtained with this injector indicates that natural-gas fuel is inferior to propane as a fuel. There has been a large body of work done on gaseous fuel injectors, and the results of those tests confirm the conclusion that no method of injecting natural-gas fuel yet tested will give combustion efficiency as good as that obtained with propane fuel in the same injector. Many injectors have given good efficiency but none have given combustion efficiency equal to that obtained with propane fuel or JP-type kerosene fuel at these severe operating conditions.

Effect of common injection velocity. - The data shown in figure 4 also compare the combustion efficiency for natural gas and propane fuels at the same injection velocity. At the same fuel weight flow rate, fuel nozzle 8 with natural gas and fuel nozzle 9A with propane inject the fuel at the same velocity. Propane fuel again gives clearly superior combustion efficiency at every fuel-air ratio. The differences seem not to be relevant to the nozzle design, but rather to the fuel itself.

Effect of fuel properties. - Table V is a compilation of various physical and combustion properties for methane (natural gas), propane, and ASTM A-1 fuel. A comparison of the properties of propane and ASTM A-1 indicate that at least as far as the more important combustion properties are concerned, propane is a fair representation of vaporized ASTM A-1 fuel. An examination of the properties of methane (natural gas) indicate that it is a stable hydrocarbon with narrow combustible limits and high diffusivity in air. The following properties indicate why performance with natural gas is consistently inferior to the other fuels at severe operating conditions. The narrow combustible limits indicate that combustion can occur only over a limited range of fuel-air ratios in the primary zone. This in turn requires critical design to optimize combustion intensity over the wide ranges of fuel and air flows typical of turbine engine combustors. The low molecular weight and hence high diffusivity of methane mean that the fuel quickly disperses in the turbulent regions of the primary zone, and fuel-air ratios can quickly fall below the combustible limit. This observation is supported by results of unreported investigations of emission measurements, at low efficiency off-design operation, conducted at NASA. Carbon monoxide did not appear in the exhaust gas samples, which implies that virtually none of the inefficiency was caused by partial combustion or oxidation of the fuel. Other properties listed such as bond strength, and spontaneous ignition temperature, point to the basic chemical stability of the methane molecule.

These factors explain why poor combustion efficiency was obtained with natural-gas fuel at the severe operating conditions. As previously mentioned, the combustor used in these tests was designed for use with ASTM A-1 liquid fuel. In order to optimize combustor performance with natural gas, combustor modifications or redesign will be required. Design changes may include an increase in the number of fuel injection points, an increase in the capability to vary the primary air flow, and changes in combustor combustion volume.

Altitude Limit Tests

A summary of altitude limit test data with ASTM A-1 and propane is listed in table VI. The altitude limit test results with the three fuels are shown in figures 6 and 7. These results show the effects of fuel types, nozzle design, reference Mach number, and inlet-air temperature on the pressure where satisfactory ignition is obtained and where combustion blowout occurs. The ignition data are shown in figure 6. The ignition pressures of propane and ASTM A-1 fuel are markedly superior to (lower than) that of natural-gas fuel. Increasing the inlet-air temperature does improve the results with natural gas especially at the lower values of reference Mach number. The combustor pressures at blowout for the three fuels are shown in figure 7. At the lower inlet-air temperature, the blowout data with natural-gas fuel is again inferior to that of propane and ASTM A-1. At the higher inlet-air temperature of 425 K, the differences are relatively minor and decrease further as the reference Mach number decreases.

The poor performance of natural-gas fuel relative to that of propane and ASTM A-1 at altitude relight conditions is explainable in terms of the properties of natural gas mentioned previously. These are the narrow combustion limits, fuel stability, and high diffusivity. The high spontaneous ignition temperature of methane is a measure of the difficulty of igniting the fuel. The narrow combustible limits require that a near stoichiometric mixture of fuel exist in the area of the ignitor for a time sufficient to have combustion initiated. This requires a careful control of fuel-air mixture near the ignitor. Such careful control is not required with fuels having wider stability limits and lower ignition temperature.

Combustion Instability

Virtually every combustor tested using natural gas or methane fuel has encountered considerable combustion instability. References 6 and 12 describe these combustors and the difficulties encountered with combustion instability. Conversely, combustors tested using ASTM A-1 and propane have been almost entirely free of any form of combustion instability. This characteristic of natural-gas fuel is also explainable in terms of its narrow combustible limits. Natural-gas combustion will not be initiated until the fuel-air ratio is within the combustible range. Once there, the gaseous fuel mixture burns rapidly. A rapid increase in combustor temperature and bulk gas velocity then occurs virtually within a single axial plane of the combustor. This situation is ideal for the onset of combustion instability. Conversely, the wider limits of combustion of propane and ASTM A-1 fuels mean that combustion can be initiated while the fuel-air mixture is very rich. This spreads the combustion axially within the combustor, and combustion instability has rarely been encountered.

CONCLUDING REMARKS

Tests were conducted to compare the performance of an annular turbojet combustor using natural-gas fuel with that obtained using ASTM A-1 and propane fuels. The combustor was designed for use with kerosene fuels.

Physical properties that make the use of natural-gas fuel attractive as a heat sink for future high-speed aircraft also make natural gas a poor choice as the fuel. The high thermal stability of the methane molecule so necessary when used as a heat sink make the combustion performance with this fuel poor at severe operating conditions. Normal ground starting, takeoff, and cruise conditions are relatively mild operating conditions, and performance with natural-gas fuel is comparable with kerosene fuel. However, at off-design and severe operating conditions the performance with natural-gas fuel will be considerably poorer than that with kerosene-type fuels. This is particularly true of the altitude blowout and ignition limits. The tendency for combustion instability is also considerably greater with natural-gas fuel than with kerosene fuels.

The design of a combustor for exclusive use of natural-gas fuel must be concerned primarily with maintaining good combustion efficiency and stability at severe operating conditions. Attaining altitude blowout and relight limits comparable with those of kerosene fueled combustors will require a considerable effort.

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Cleveland, Ohio, October 11, 1972,
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TABLE I. - CHEMICAL AND PHYSICAL PROPERTIES OF FUELS

(a) Natural gas and gaseous propane

	Natural gas	Gaseous propane
Density,[a] kg/m^3 (lb/ft^3)	0.7320 (0.0457)	1.8646 (0.1164)
Net heat of combustion (calculated) J/kg (Btu/lb)	$49\ 770\times10^3$ (21 397)	$46\ 315\times10^3$ (19 925)
Normalized chromatographic analysis, vol. %:		
Methane	93.50	0.15
Ethane	3.53	0.17
Propane	0.53	99.61
C_4, C_5, and C_6 hydrocarbons	0.32	0.03
Nitrogen	1.05	0.03
Carbon dioxide	1.07	----
Oxygen	trace	0.01

(b) ASTM A-1

Gravity, ^{o}API (D287)	43.1
ASTM distillation (D86), K (^{o}F):	
Initial boiling point	433 (320)
5 Percent evaporated	444 (340)
10 Percent evaporated	455 (360)
30 Percent evaporated	472 (390)
50 Percent evaporated	483 (410)
70 Percent evaporated	495 (431)
90 Percent evaporated	519 (474)
95 Percent evaporated	533 (500)
Final boiling point	547 (525)
Residue, percent	1.1
Loss, percent	0.9
Flash point (D56), K (^{o}F)	324 (124)
Pour point (D97), K (^{o}F)	233 (-58)
Viscosity at 239 K (-30^{o} F)(D445), m^2/sec (cS)	9.2×10^{-6} (9.2)
Aromatics (D1319), vol. %	15.51
Net heat of combustion (D1405), J/kg (Btu/lb)	$43\ 270\times10^3$ (18 615)

[a]At 289 K (60^{o} F) and 10.159 N/cm^2 (30.00 in. Hg at 32^{o} F).

TABLE II. - COMBUSTOR NOMINAL OPERATING CONDITIONS

[Temperature, 422 K (300^{o} F).]

Operating condition	Pressure		Air flow rate		Reference velocity		$\frac{PT}{V}$ Parameter	
	N/cm^2	psia	kg/sec	lb/sec	m/sec	ft/sec	$\frac{N\text{-}K\text{-}sec}{m^3}$	$\frac{lb\text{-}^{o}R\text{-}sec}{ft^3}$
1	17.2	25.0	20.6	45.5	32.3	106	22.53×10^5	25.81×10^3
2	17.2	25.0	25.9	57.0	40.5	133	17.95	20.57
3	13.8	20.0	20.7	45.6	40.5	133	14.36	16.46

TABLE III. - COMBUSTOR EFFICIENCY DATA

(a) Fuel, ASTM A-1

Combustor inlet-air conditions: Pressure, total, N/cm^2	Pressure, total, psia	Temperature, total, K	Temperature, total, °F	Flow, kg/sec	Flow, lb/sec	Reference velocity, m/sec	Reference velocity, ft/sec	Parameter PT/V, N-K-sec/m^3	Parameter PT/V, lb-°R-sec/ft^3	Fuel temperature, K	Fuel temperature, °F	Manifold-combustor fuel pressure differential, N/cm^2	Manifold-combustor fuel pressure differential, psid	Calculated fuel injection velocity, m/sec	Calculated fuel injection velocity, ft/sec	Fuel-air ratio	Combustor average exhaust temperature, total, K	Combustor average exhaust temperature, total, °F	Combustor temperature rise, K	Combustor temperature rise, °F	Combustion efficiency, percent
Dual orifice fuel nozzle																					
17.2	25.0	424	304	19.9	43.9	31.4	103	23.35×10^5	26.76×10^3	303	85	79.3	115.0	----	---	0.0084	686	776	263	473	79.1
17.0	24.7	423	301	20.4	44.9	32.0	105	22.44	25.71	295	72	81.6	118.3	----	---	.0101	753	895	331	595	83.3
17.1	24.8	421	299	20.4	44.9	32.0	105	22.53	25.82	295	71	84.9	123.2	----	---	.0133	870	1106	448	807	88.2
17.1	24.8	423	301	20.4	45.0	32.0	105	22.54	25.83	296	74	87.9	127.6	----	---	.0162	981	1306	558	1005	91.4
17.2	24.9	421	299	20.4	45.0	32.0	105	22.70	26.01	296	73	91.2	132.3	----	---	.0193	1096	1513	674	1214	94.5
17.2	24.9	422	300	20.5	45.1	32.0	105	22.64	25.94	298	76	94.2	136.6	----	---	.0224	1206	1712	784	1412	96.2
17.1	24.8	421	298	20.4	44.9	32.0	105	22.49	25.77	297	75	94.9	137.7	----	---	.0234	1242	1776	821	1478	96.8
17.1	24.8	432	318	23.7	52.2	37.8	124	19.51	22.36	317	111	81.0	117.5	----	---	.0086	702	804	270	486	79.6
17.2	24.9	423	301	25.0	55.2	39.0	128	18.56	21.27	297	75	88.1	127.8	----	---	.0134	867	1101	444	800	86.6
17.1	24.8	421	299	25.1	55.4	39.3	129	18.35	21.03	299	78	92.6	134.3	----	---	.0165	971	1288	549	989	88.6
17.1	24.8	423	301	25.1	55.4	39.3	129	18.46	21.15	298	76	95.5	138.6	----	---	.0197	1087	1497	664	1196	91.6
17.0	24.7	423	301	25.1	55.3	39.3	129	18.32	20.99	298	76	99.4	144.1	----	---	.0229	1205	1709	783	1409	94.4
13.7	19.8	421	299	20.0	44.0	39.0	128	14.78	16.94	298	77	79.3	115.1	----	---	.0084	670	747	249	448	75.0
13.6	19.7	429	312	21.1	46.5	42.1	138	13.85	15.87	293	67	79.5	115.3	----	---	.0079	655	720	227	409	72.4
13.6	19.7	425	306	20.3	44.8	40.2	132	14.31	16.40	295	71	81.5	118.1	----	---	.0102	734	862	309	557	77.6
13.7	19.8	424	303	20.2	44.5	39.6	130	14.58	16.71	294	70	85.2	123.6	----	---	.0133	847	1065	423	762	83.3
13.7	19.9	425	305	20.2	44.5	39.6	130	14.68	16.82	294	70	88.4	128.2	----	---	.0165	954	1258	530	954	85.4
13.6	19.7	424	303	20.1	44.4	39.9	131	14.45	16.56	296	73	91.6	132.8	----	---	.0195	1055	1439	631	1136	87.7
13.8	20.0	419	295	20.5	45.3	39.6	130	14.58	16.71	291	65	81.5	118.2	----	---	.0101	725	846	306	551	77.4
13.7	19.9	420	296	20.5	45.2	39.6	130	14.58	16.71	294	70	85.2	123.6	----	---	.0132	839	1051	419	755	82.7
13.7	19.8	419	295	20.5	45.1	39.6	130	14.41	16.51	294	69	88.3	128.1	----	---	.0163	935	1224	516	929	84.3
13.7	19.8	421	298	20.4	45.0	39.9	131	14.40	16.50	295	72	91.5	132.7	----	---	.0194	1042	1416	621	1118	86.9
13.7	19.9	420	296	20.4	45.0	39.6	130	14.54	16.66	295	71	94.4	137.0	----	---	.0224	1161	1630	741	1333	91.0

(b) Fuel, gaseous propane

Pressure, total, N/cm^2	Pressure, total, psia	Temperature, total, K	Temperature, total, °F	Flow, kg/sec	Flow, lb/sec	Reference velocity, m/sec	Reference velocity, ft/sec	Parameter PT/V, N-K-sec/m^3	Parameter PT/V, lb-°R-sec/ft^3	Fuel temperature, K	Fuel temperature, °F	Fuel pressure differential, N/cm^2	Fuel pressure differential, psid	Fuel injection velocity, m/sec	Fuel injection velocity, ft/sec	Fuel-air ratio	Exhaust temperature, K	Exhaust temperature, °F	Temperature rise, K	Temperature rise, °F	Combustion efficiency, percent
Fuel nozzle 2																					
17.0	24.6	425	305	20.9	46.0	33.2	109	21.74×10^5	24.91×10^3	322	120	25.6	37.2	33.2	109	0.0117	877	1119	452	814	93.7
17.4	25.2	426	308	20.9	46.0	32.6	107	22.73	26.05	329	132	36.3	52.6	43.0	141	.0152	1016	1370	589	1061	95.8
17.2	24.9	419	295	22.3	49.1	34.7	114	20.76	23.79	309	96	14.2	20.5	23.5	77	.0079	705	809	286	514	84.8
17.0	24.7	426	308	24.9	55.0	39.6	130	18.34	21.02	303	85	16.0	23.1	26.8	88	.0080	713	823	286	514	83.7
16.9	24.5	433	319	25.1	55.3	40.5	133	18.05	20.68	294	69	27.2	39.4	33.2	109	.0102	818	1013	386	694	90.3
13.6	19.7	420	297	20.5	45.3	40.2	132	14.20	16.27	303	85	24.1	34.9	36.3	119	.0107	809	997	389	700	87.0
13.6	19.7	421	298	20.5	45.3	40.2	132	14.24	16.32	306	91	16.3	23.6	29.0	95	.0084	719	834	298	536	83.8
13.5	19.6	420	297	20.5	45.3	40.5	133	14.04	16.09	303	86	10.0	14.5	22.3	73	.0063	635	683	214	386	78.5
Fuel nozzle 9A																					
17.2	25.0	426	308	21.1	46.5	33.2	109	22.14×10^5	25.37×10^3	291	65	42.6	61.8	36.9	121	0.0180	1141	1595	715	1287	100.7
17.2	24.9	428	310	21.1	46.6	33.5	110	21.85	25.04	295	72	33.7	48.9	32.3	106	.0149	1016	1370	589	1060	98.4
17.2	24.9	432	318	21.3	46.9	34.1	112	21.73	24.90	308	95	20.0	29.0	23.2	76	.0098	806	991	374	673	91.7
17.1	24.8	434	322	21.5	47.3	34.7	114	21.38	24.50	302	84	27.2	39.5	28.3	93	.0122	906	1172	472	850	94.3
17.2	25.0	425	305	26.4	58.1	41.1	135	17.83	20.43	292	66	45.3	65.6	38.4	126	.0144	964	1275	539	970	92.9
17.2	24.9	431	316	26.3	58.8	41.8	137	17.76	20.35	301	82	27.2	39.4	29.0	95	.0099	783	950	352	634	85.1
17.2	24.9	434	322	26.2	57.8	42.1	138	17.78	20.37	319	114	36.1	52.4	37.5	123	.0125	890	1143	456	821	89.1
17.2	24.9	433	320	26.3	58.0	42.1	138	17.66	20.24	305	90	56.2	81.6	44.5	146	.0162	1065	1458	632	1138	97.6
13.7	19.8	426	307	21.1	46.5	41.8	137	13.96	16.00	291	64	37.0	53.7	39.6	130	.0145	938	1229	512	922	87.7
13.7	19.9	427	309	21.1	46.5	41.5	136	14.10	16.16	284	52	47.2	68.5	46.0	151	.0182	1100	1521	673	1212	94.4
13.7	19.9	433	320	21.5	47.3	42.7	140	13.94	15.97	324	124	23.5	34.1	31.7	104	.0097	762	912	329	592	81.2
13.8	20.0	435	323	21.5	47.3	42.7	140	14.05	16.10	326	127	32.5	47.1	37.8	124	.0121	859	1087	425	765	85.2

TABLE IV. - HEAT CONTENT PER UNIT WEIGHT OF AIR FOR THREE FUELS AT VARIOUS FUEL-AIR RATIOS

Fuel	Fuel-air ratio	Heat content	
		J/g_{air}	Btu/lb_{air}
ASTM A-1	0.0090	389	168
	.0140	606	261
	.0200	865	372
Propane	.0084	389	168
	.0131	606	261
	.0187	865	372
Natural gas	.0078	389	168
	.0122	606	261
	.0174	865	372

TABLE V. - FUNDAMENTAL PHYSICAL AND COMBUSTION PROPERTIES OF METHANE, PROPANE, AND ASTM A-1 FUELS

	Methane	Propane	ASTM A-1
Flammability limits, percent stoichiometric:			
Lean	[a]46	[a]51	[b]51
Rich	[a]164	[a]283	[b]385
Maximum burning velocity, cm/sec	[c]33.8	[c]39.0	------
Spontaneous ignition temperature, K (^{o}F)	[a]905 (1170)	[a]778 (940)	[a, d]516 (468)
Diffusion coefficient, cm^2/sec	[e]0.181	[e]0.100	[e]0.050
Chemical bond strength, kJ/mole (kcal/mole)	[f]435 (104)	[g]410 (98)	------
Minimum ignition energy, J	[h]4.70×10^{-4}	[h]3.05×10^{-4}	------
Molecular weight	16.04	44.10	[i]164
Reaction rate at gas temperature of 750 K (890^{o} F), mole/sec	[j]7×10^{-9}	[j]4×10^{-5}	------

[a]Ref. 20, appendix table XXXII.
[b]Ref. 21, eqs., p. 29.
[c]Ref. 22.
[d]Jet fuel, grade, JP-5.
[e]Ref. 23.
[f]Ref. 24, H-CH_3.
[g]Ref. 24, H-n-C_3H_7.
[h]Ref. 25.
[i]Ref. 26.
[j]Ref. 27.

TABLE VI. - COMBUSTOR ALTITUDE LIMIT DATA

Combustor inlet-air conditions							Rating criteria	
Pressure, total		Temperature, total		Flow		Reference Mach number	Ignition; stable combustion at ignition fuel-air ratio	Combustion-blowout as fuel-air ratio increased above 0.01; stable combustion at fuel-air ratio of 0.010 or less
N/cm^2	psia	K	°F	kg/sec	lb/sec			
Fuel, gaseous propane; fuel nozzle 9A								
5.5	8.0	298	77	7.8	17.2	0.078	Yes	No
4.8	7.0	298	76	6.8	15.0	.078	Yes	No
4.1	6.0	300	80	5.9	12.9	.079	No	---
3.4	5.0	296	73	4.9	10.8	.078	---	No
3.1	4.5	297	75	3.9	8.6	.069	---	Yes
9.7	14.0	301	82	17.1	37.7	.099	Yes	No
8.3	12.0	298	76	14.7	32.3	.098	Yes	No
6.9	10.0	300	80	12.2	26.9	.098	Yes	No
6.2	9.0	298	77	11.0	24.2	.098	No	No
5.5	8.0	298	76	9.8	21.5	.098	No	No[a]
3.4	5.0	416	290	4.2	9.3	.080	Yes	No
2.8	4.0	416	290	3.4	7.5	.081	No	---
2.8	4.0	416	290	3.4	7.5	.081	---	Yes
5.5	8.0	414	285	8.4	18.5	.100	Yes	No
3.4	5.0	415	288	5.3	11.6	.100	Yes	No
2.8	4.0	416	290	4.3	9.4	.102	No	Yes
Fuel, gaseous propane; fuel nozzle 2								
9.7	14.0	422	300	14.5	32.0	0.100	---	No
9.0	13.0	422	300	13.6	30.0	.101	Yes	---
5.5	8.0	422	300	8.4	18.6	.101	Yes	---
4.1	6.0	422	300	6.4	14.0	.102	No	---
3.4	5.0	422	300	5.3	11.6	.101	No	No
2.8	4.0	422	300	4.2	9.3	.101	---	Yes
Fuel, ASTM A-1 dual orifice fuel nozzle								
9.7	14.0	305	90	17.1	37.8	0.100	---	No
7.6	11.0	303	85	13.4	29.6	.099	Yes	No
6.2	9.0	303	85	11.0	24.2	.099	Yes	No
5.5	8.0	303	86	9.8	21.5	.099	No	---
4.8	7.0	303	85	8.5	18.8	.099	No	---
4.1	6.0	305	90	7.3	16.0	.098	---	No
3.4	5.0	304	87	6.1	13.4	.099	---	No
3.3	4.8	304	87	5.9	13.0	.100	---	Yes
9.7	14.0	425	305	14.7	32.5	.102	Yes	No
6.9	10.0	425	305	10.5	23.2	.101	---	No
5.5	8.0	424	303	8.4	18.6	.102	---	No
4.1	6.0	415	288	6.3	13.8	.099	Yes	No
3.4	5.0	416	290	5.3	11.7	.101	No	No
2.8	4.0	419	295	4.2	9.3	.101	No	No
2.1	3.0	420	296	3.2	7.0	.101	---	Yes

[a]Facility limit.

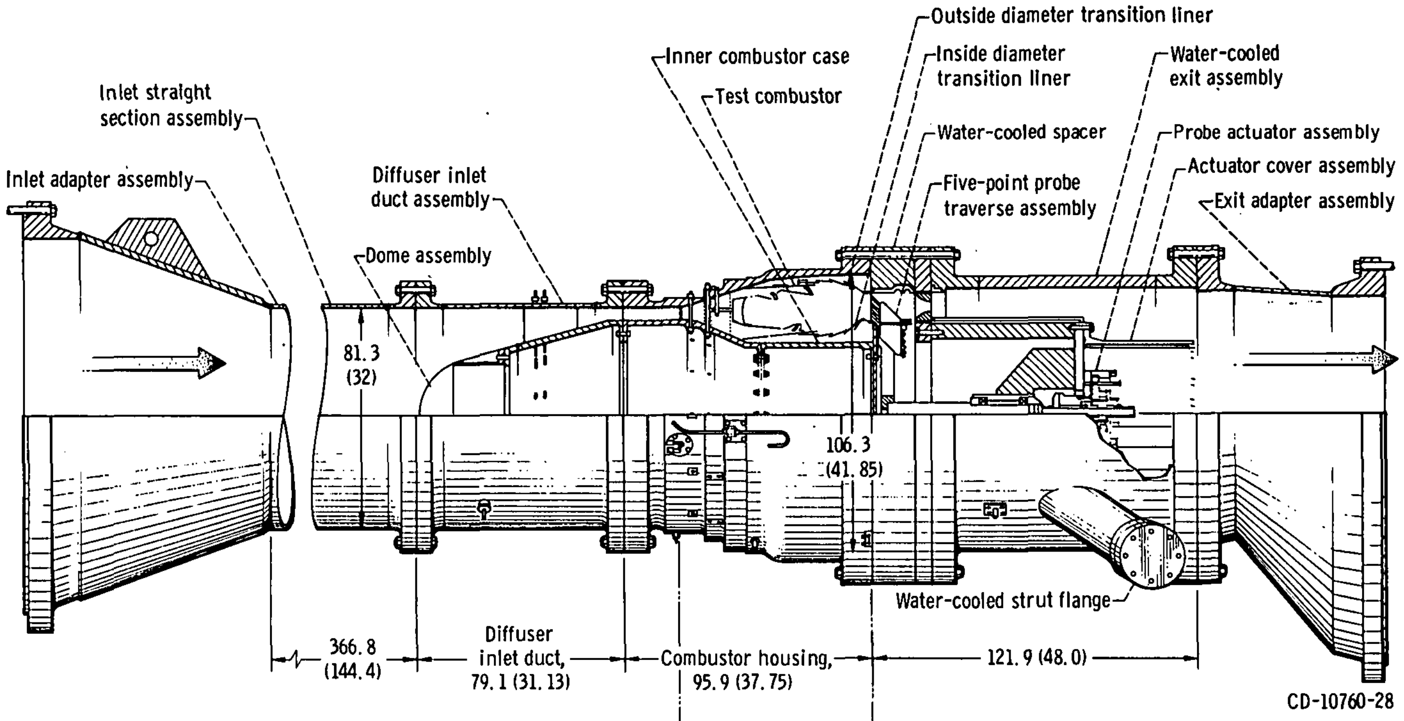
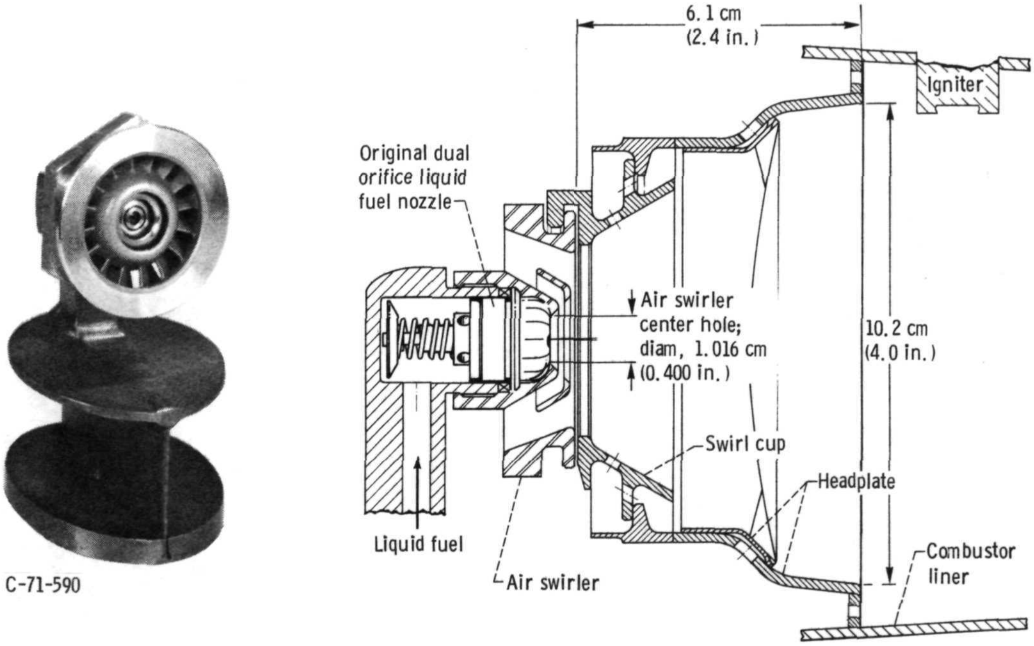
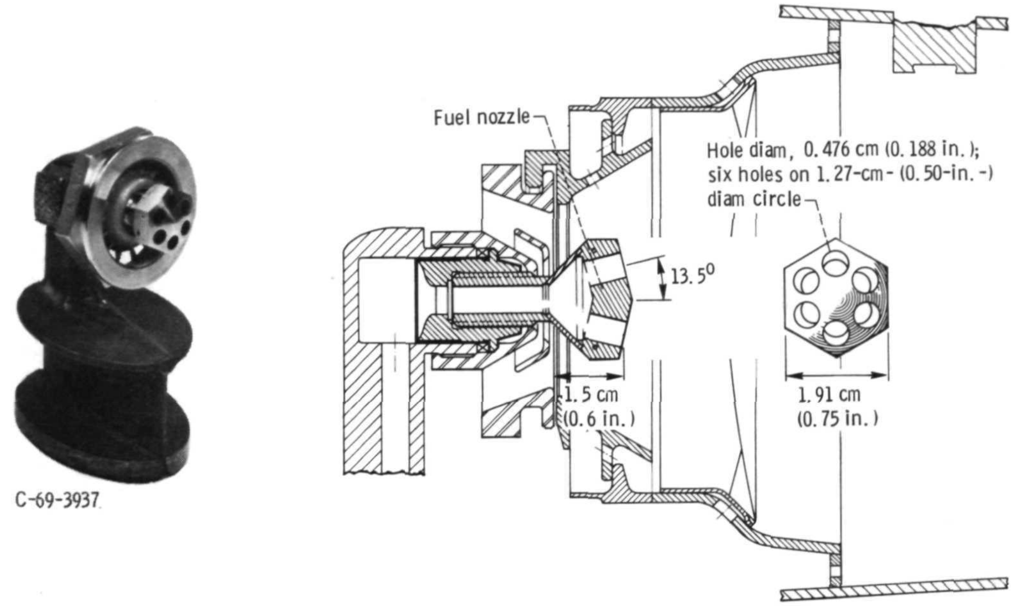


Figure 1. - Test section for full-scale annular combustor. (Dimensions are in centimeters (in.).)

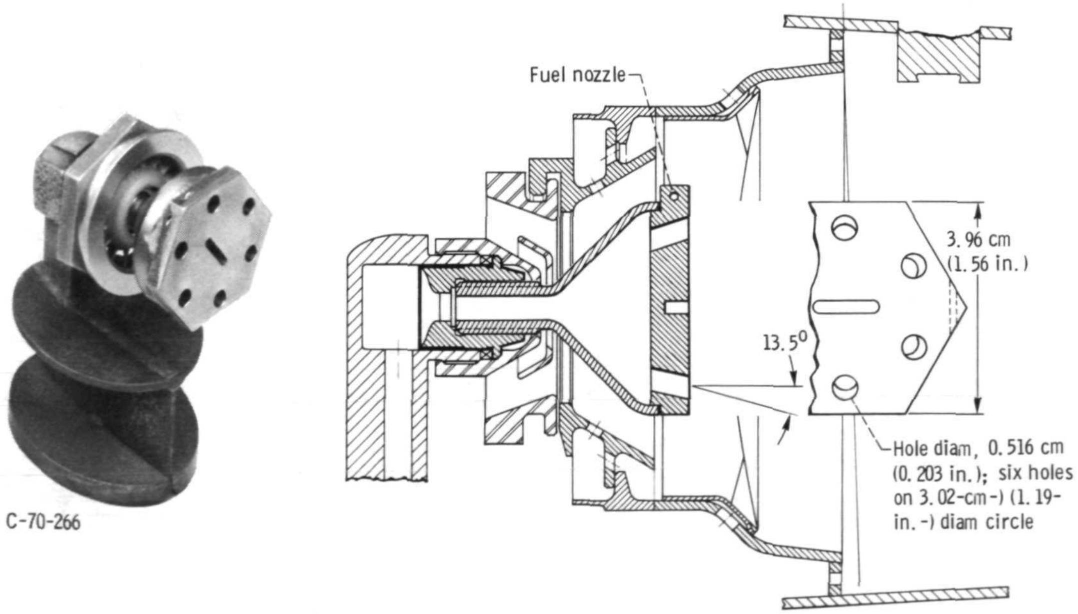


C-71-590

Figure 2. - Liquid fuel dual-orifice nozzle fuel strut installed in combustor head plate.

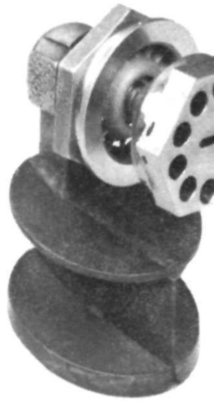


(a) Fuel nozzle 2; tested with gaseous propane and natural gas.

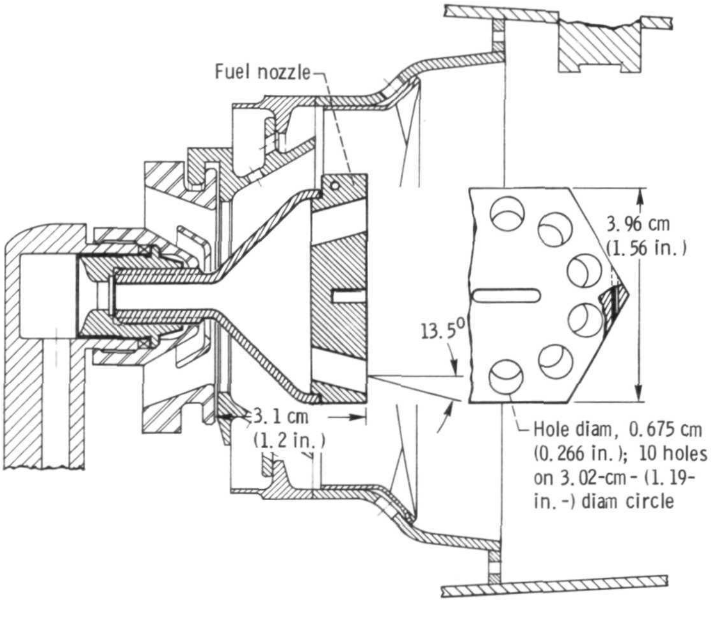


(b) Fuel nozzle 9A; tested with gaseous propane.

Figure 3. - Gaseous fuel nozzle installed in fuel strut.

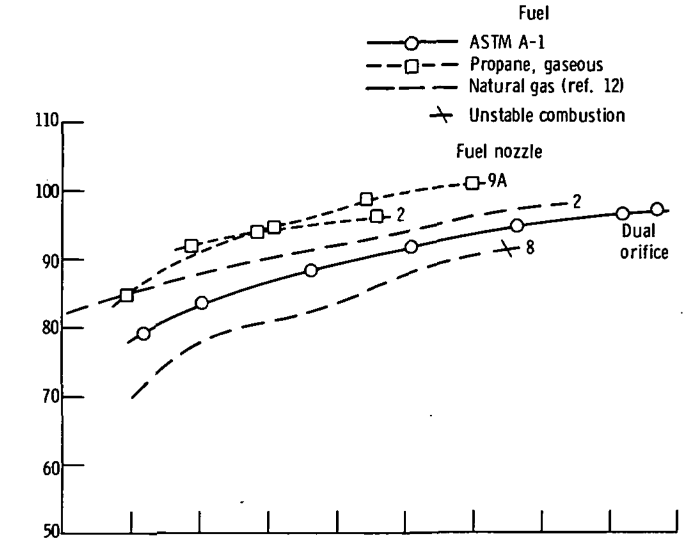


C-70-263

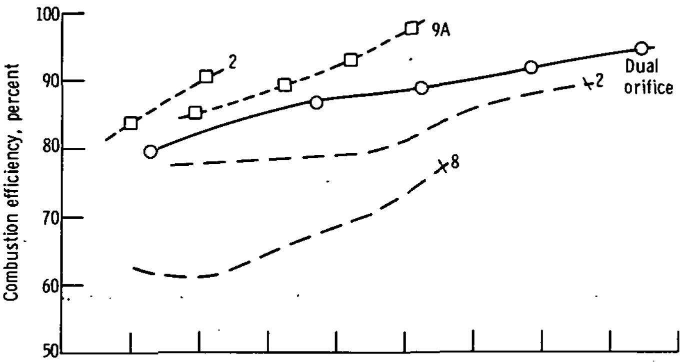


(c) Fuel nozzle 8; tested with natural gas.

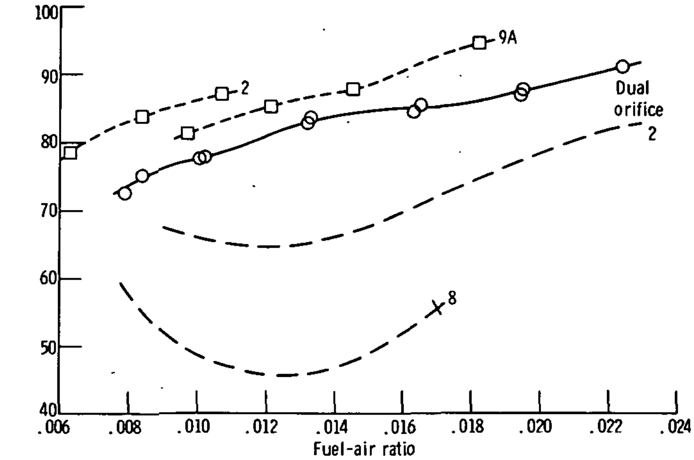
Figure 3. - Concluded.



(a) Nominal operating condition 1: Pressure, 17.2 newtons per square centimeter (25 psia); temperature, 422 K (300° F); reference velocity, 32.3 meters per second (106 ft/sec).

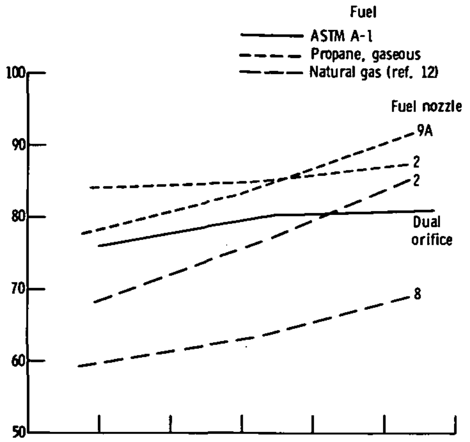


(b) Nominal operating condition 2: Pressure, 17.2 newtons per square centimeter (25 psia); temperature, 422 K (300° F); reference velocity, 40.5 meters per second (133 ft/sec).

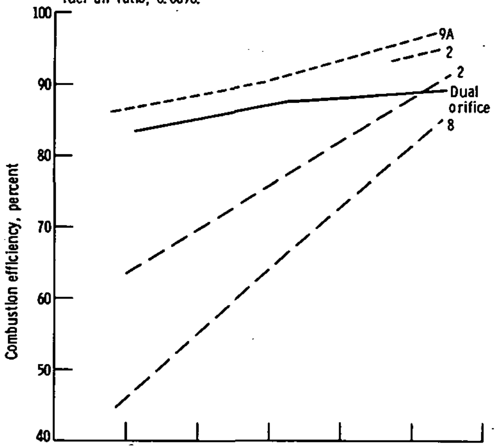


(c) Nominal operating condition 3: Pressure, 13.8 newtons per square centimeter (20 psia); temperature, 422 K (300° F); reference velocity, 40.5 meters per second (133 ft/sec).

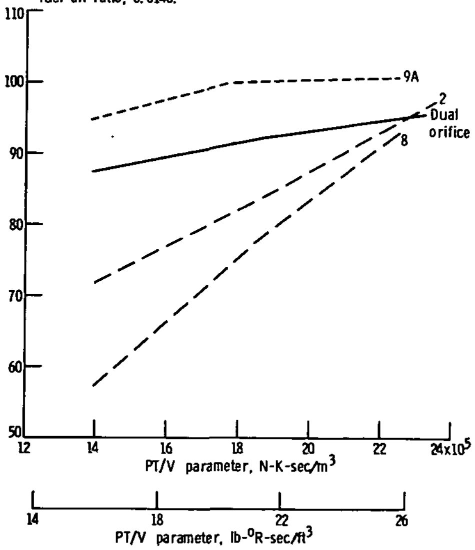
Figure 4. - Variation of combustion efficiency with fuel-air ratio for various fuel nozzles and fuels.



(a) Heat content, 389 joules per gram of air (168 Btu/lb_{air}); ASTM A-1 fuel-air ratio, 0.0090.



(b) Heat content, 606 joules per gram of air (261 Btu/lb_{air}); ASTM A-1 fuel-air ratio, 0.0140.



(c) Heat content, 865 joules per gram of air (372 Btu/lb_{air}); ASTM A-1 fuel-air ratio, 0.0200.

Figure 5. - Variation of combustion efficiency with combustion correlating parameter for various fuel nozzles and fuels.

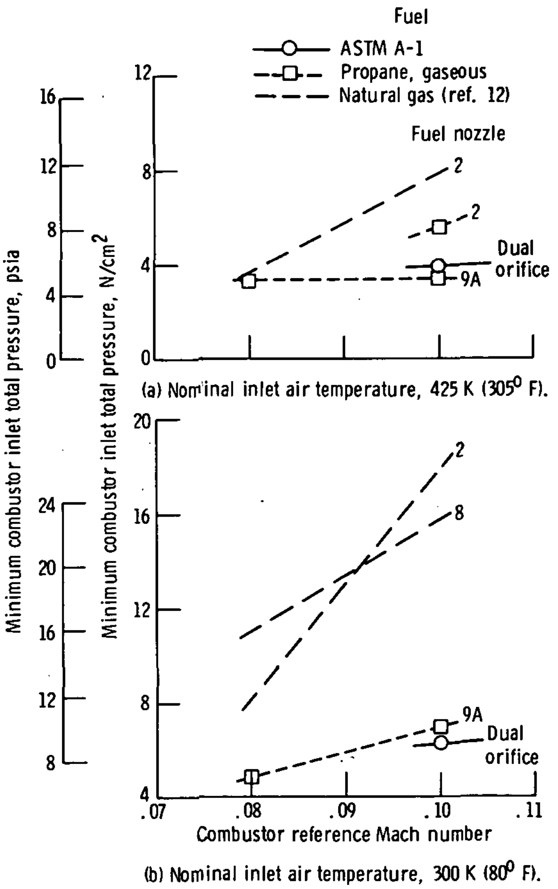


Figure 6. - Minimum combustor pressures for satisfactory ignition with various fuels.

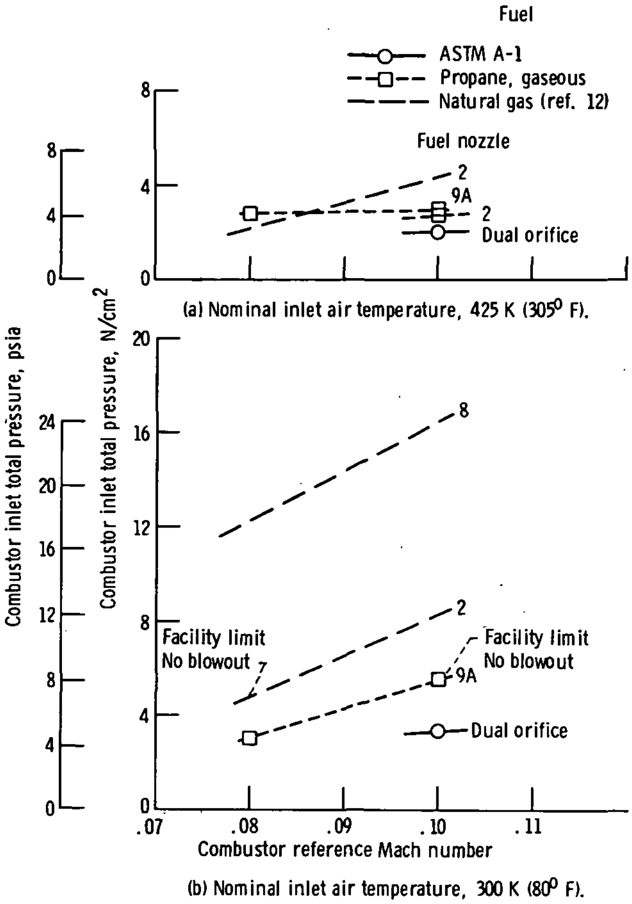


Figure 7. - Combustor blowout pressure for various fuels.

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