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RESEARCH MEMORANDUM

PERFORMANCE OF AN EXPERIMENTAL ANNULAR TURBOJET COMBUSTOR WITH METHANE AND PROPANE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

PERFORMANCE OF AN EXPERIMENTAL ANNULAR TURBOJET COMBUSTOR WITH METHANE AND PROPANE

By Carl T. Norgren

SUMMARY

Combustion efficiencies obtained with two gaseous hydrocarbon fuels in an experimental turbojet combustor were compared. The fuels, methane and propane, are thermally stable and have low freezing points; when refrigerated, they can therefore be considered for supersonic flight applications where aerodynamic heating imposes a need for considerable heat rejection to the fuel. Methane was evaluated in an experimental combustor designed for operation with gaseous fuels. The annular combustor was designed to fit into a one-quarter sector of an annular housing with an outside diameter of 25.5 inches, an inside diameter of 10.6 inches, and a combustor length of approximately 23 inches. Combustion efficiencies were determined at simulated high-altitude flight conditions corresponding to operation in a 5.2-pressure-ratio engine at a flight Mach number of 0.6. Propane was previously evaluated in the same combustor at the same combustor operating conditions.

The combustion efficiencies obtained with methane were 98, 91, and 77 percent at simulated flight altitudes of 56,000, 70,000, and 80,000 feet, respectively. These flight altitudes correspond to combustor-inlet air pressures from 15 to 5 inches of mercury absolute. The combustion efficiency of propane was equivalent to that obtained with methane up to a simulated altitude of 70,000 feet; at 80,000 feet the combustion efficiency with propane was 10 percent higher than with methane. As the airflow was increased to 69 percent above a value representative of current practice at a combustor pressure of 15 inches of mercury absolute, both rich and lean blowout limits were observed with methane. The lower efficiencies and the reduced operational range obtained with methane are attributed, at least in part, to the lower fundamental flame speed of this fuel.

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INTRODUCTION

High temperatures encountered in high-speed, turbojet-powered aircraft necessitate the cooling of various engine and airframe components.

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The fuel represents a large potential heat sink for this cooling; however, thermal decomposition of current jet fuels limits the extent to which this heat sink can be utilized. Attempts are currently being made to provide a thermally stable, kerosene-type fuel for high-speed flight. Fuels which also offer a high thermal stability are the low-molecular-weight gaseous hydrocarbons. By liquefying these hydrocarbons the heat release per unit volume of fuel can be increased, and the heat of vaporization can be utilized for cooling. In reference 1 it is shown that, although, the liquefied low-molecular-weight hydrocarbons have much lower densities than conventional jet fuels, aircraft performance will not necessarily be penalized. The low-molecular-weight fuels would, however, present operating problems on the ground and in the air. Refrigeration and tank insulation would be required, and new problems in refueling, pumping, and engine control would be encountered.

It is shown in reference 2 that the high-altitude performance of an annular experimental combustor was better with one low-molecular-weight gaseous hydrocarbon, propane, than with a liquid hydrocarbon fuel. Another readily available, low-molecular-weight hydrocarbon that can be considered for high-speed flight is methane. The heat-absorption capacity of methane is considerably higher than that of propane because of its higher specific heat and latent heat of vaporization, and because it can be heated to higher temperatures without appreciable decomposition (ref. 1). The flame speed and flammability limits of methane are somewhat inferior to propane, however, and from the studies reported in reference 3 poorer combustion performance may be expected from methane.

The investigation reported herein was conducted in a full-scale one-quarter sector duct system. The combustion performance of methane was evaluated in an experimental low-pressure-loss combustor designed for operation with vapor fuel, and this performance was compared with that obtained with propane and prevaporized JP-4 fuel (ref. 4). Since variations in combustion efficiency are most pronounced at low air pressures and high air velocities in the combustor, the test conditions previously selected (ref. 4) as representative of high-altitude flight were also used in this investigation. Data were obtained for a simulated flight Mach number of 0.6 in a 5.2-pressure-ratio engine operating at 85-percent rated rotor speed at altitudes of 56,000, 70,000, and 80,000 feet. In addition, one condition representing 69 percent increased airflow at 56,000 feet was investigated. Data including combustion efficiency, outlet radial-temperature profile, and combustor pressure losses are presented.

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APPARATUS

Installation

The combustor installation (fig. 1) was similar to that of reference 4. The combustor-inlet and -outlet ducts were connected to the laboratory-air-supply and low-pressure-exhaust systems, respectively. Airflow rates and combustor pressures were regulated by remote-controlled valves located upstream and downstream of the combustor. Gaseous methane was supplied from high pressure cylinders with suitable pressure-reducing valves to supply low-pressure fuel to the system. The desired combustor-inlet air temperatures were obtained by means of electric preheaters.

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Instrumentation

Airflow was metered by a sharp-edged orifice (fig. 1) installed according to ASME specifications. The gaseous fuel-flow rate was metered with a calibrated sharp-edged orifice. Thermocouples and pressure tubes were located at the combustor-inlet and -outlet instrument stations indicated in figure 1. The number, type, and position of these instruments at each of the three stations are indicated in figures 2(a) to (c). The combustor-outlet thermocouples (station 2) and pressure probes (station 3) were located at centers of equal areas in the duct. The designs of the individual probes and the rakes are shown in figures 2(d) to (h). Manifolded upstream total-pressure probes (station 1) and downstream static-pressure probes (station 3) were connected to absolute manometers; individual downstream total- and static-pressure probes were connected to banks of differential manometers. The chromel-alumel thermocouples (station 2) were connected to a self-balancing, recording potentiometer.

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Combustor

The prevaporizing, low-pressure-loss combustor described in reference 4 (experimental combustor model 47) was used in this investigation. The prevaporizer in model 47 was removed, and the combustor was designated as model 48. The combustor geometry incorporated a streamlined combustor-inlet section, scoops for primary-air admission, and longitudinal U-shaped channels for secondary-air admission. The combustor was designed to fit into a one-quarter sector of an annular housing with an outside diameter of 25.5 inches, an inside diameter of 10.6 inches, and a combustor length of approximately 23 inches. A phantom view of the combustor assembled in the housing is shown in figure 3. The construction details of combustor model 48 are shown in figure 4; the combustor hole pattern is shown in figure 4(a), and the combustor profile geometry, in figure 4(b). The ratio of the accumulated hole area along the combustor length to the total hole area is shown as a function of combustor length in figure 4(c).

These curves represent the proportioning of the hole area but not necessarily the proportioning of the air admitted along the combustor. The total air-admission hole area for this combustor was 95.9 square inches.

Performance data were obtained with fuel nozzle configuration L (from ref. 4) to enable direct comparison. The fuel nozzles were modified commercial hollow-cone nozzles having a sharp-edged orifice 1/8 inch in diameter with a simple swirl generator. Five fuel nozzles, symmetrically spaced, were used in this investigation. Since gaseous methane and propane have such different densities, the jet velocity would be considerably different at any given mass-flow rate; therefore, one additional set of fuel nozzles was tested. The fuel-nozzle orifices were enlarged to a 5/32-inch diameter. With these fuel nozzles (nozzle R) methane fuel was admitted into the combustor at approximately the same velocity as was propane using a fuel nozzle of configuration L.

Fuels

Fundamental properties of methane and propane fuels are shown in table I. For comparison, corresponding data for a representative MIL-F-5624C, grade JP-4, fuel are included in this table.

PROCEDURE

The test conditions investigated are as follows:

Condition	Combustor-inlet total pressure, in. Hg abs	Combustor-inlet total temperature, °F	Airflow rate per unit area[a], lb/(sec)(sq ft)	Simulated flight altitude in reference engine at cruise speed, ft
A	15	268	2.14	56,000
B	8	268	1.14	70,000
C	5	268	0.714	80,000
E	15	268	3.62	56,000

[a] Based on maximum combustor cross-sectional area of 0.73 sq ft.

Test conditions A, B, and C represent three simulated flight conditions for a reference turbojet engine with a 5.2-pressure-ratio compressor. A cruise speed of 85 percent of the rated rotor speed and a flight Mach number of 0.6 were assumed. One additional condition, E, was selected to represent an airflow rate 69 percent above that required in the reference engine at a flight altitude of 56,000 feet. At each test condition, combustion efficiencies and pressure-loss data were recorded for a range of fuel-air ratios with methane fuel. Similar data for propane fuel were obtained from reference 4.

Combustion efficiency was computed as the percentage ratio of the actual to the theoretical increase in enthalpy from the combustor-inlet to the combustor-outlet instrumentation plane (ref. 5). The arithmetic mean of the 30 outlet thermocouple indications was used to obtain the value of the combustor-outlet enthalpy for the experimental combustor configuration.

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The radial-temperature distribution at the combustor outlet (station 2) was determined for a temperature rise across the combustor of approximately 1180° F, which would correspond to the temperature required at 100 percent of rated engine speed in the reference turbojet engine at altitudes above the tropopause. The radial-temperature indications were obtained from the six thermocouple rakes (fig. 2(a)). The total-pressure loss was computed as the dimensionless ratio of the total-pressure loss to the combustor-inlet total pressure. Thirty individual total-pressure readings were averaged to obtain the total pressure at the combustor outlet. Combustor reference velocities were computed from the air mass-flow rate, the combustor-inlet density, and the maximum combustor cross-sectional area.

RESULTS AND DISCUSSION

The data obtained with experimental combustor models 48L and 48R using methane fuel are presented in table II. The data for propane operation in the experimental combustor model 47L, without prevaporizer, (from ref. 4) are included in table II. Combustor model 47L, without prevaporizer, is identical to combustor model 48L described herein.

Combustion Efficiency

The combustion efficiencies obtained with propane in combustor model 47L, without prevaporizer, are presented in figure 5 for a range of fuel-air ratios. In figure 5(a) combustion efficiencies are presented for test conditions A, B, and C (reference velocity, 80 ft/sec). In figure 5(b) the effect of increasing the reference velocity to 140 feet per second is shown for a constant burner pressure of 15 inches of mercury absolute. Two curves representing a constant temperature rise of 680° F (required for operation at 85 percent of rated speed) and 1180° F (required for operation at rated speed) are included in figure 5. At a temperature rise of 1180° F combustion efficiencies of 98, 93, and 86 percent were obtained for test conditions A, B, and C, respectively, (fig. 5(a)). Combustion efficiencies did not vary appreciably over the range of fuel-air ratios investigated and were relatively unaffected by the increased reference velocity (fig. 5(b)).

The combustion efficiencies of combustor model 48L with methane fuel are presented in figure 6. Two curves representing a constant temperature rise of 680° and 1180° F for methane are included in figure 6. As shown in figure 6(a) combustion efficiencies of 98, 91, and 77 were obtained at a temperature rise of 1180° F for test conditions A, B, and C, respectively, (reference velocity, 80 ft/sec). The combustion efficiencies at test condition A exceeded 100 percent at some fuel-air ratios; however, it is believed that burning was essentially complete and the 100-percent excess was due to experimental error. Errors involved in efficiency measurements with this combustor installation are discussed in reference 4. Combustion was not stable at low fuel-air ratios as indicated by the sharp drop in efficiency in this region. Comparison of the data from figures 5(a) and 6(a) shows that combustion with propane and methane at test conditions A and B (simulated altitudes of 56,000 and 70,000 ft, respectively) was approximately the same. However, at the very low pressure condition C (80,000 ft altitude), the range of efficient operation with methane decreased markedly, and efficiencies of 80 to 85 percent were obtained with this fuel over only a narrow range of fuel-air ratios (fig. 6(a)).

In figure 6(b) the effect of increasing the reference velocity to 140 feet per second at a constant burner pressure of 15 inches mercury absolute is shown. At the high velocity (condition E) methane operated over a very narrow range of fuel-air ratios, and both lean and rich blowout limits were observed. As shown in figure 5(b) no blowout limits were observed with propane fuel at this same condition.

The performance data presented in figures 5 and 6 for propane and methane were obtained in combustor models 47L, without prevaporizer, and 48L, respectively, with an identical fuel injector. Since gaseous methane has a much lower density than gaseous propane, methane was introduced into the combustion zone at a higher velocity than propane. It is shown in reference 4 that fuel-injection characteristics affect combustor performance markedly. Additional tests were therefore conducted with methane using an injector nozzle having a larger orifice diameter so that the fuel-exit velocity with methane would be the same as with propane. For any given fuel-air ratio, the momentum of the jet would also be the same for both fuels and similar penetration characteristics would be expected. The nozzle swirl generators were not modified for these tests. Combustion efficiencies of combustor model 48R, which incorporated the larger nozzle, with methane fuel are presented in figure 7. Only a sufficient number of fuel-air ratios at test conditions A, B, and C were investigated to indicate performance trends. Combustion efficiencies obtained with the smaller fuel nozzle (combustor model 48L) are included in figure 7 for comparison. Combustion efficiencies at low fuel-air ratios were improved considerably with the larger nozzle (combustor model 48R), particularly at conditions

A and B. No improvement was observed at the higher fuel-air ratios. At test conditions C, a lean blowout limit was obtained with the larger nozzle.

Correlation of Combustion Efficiency

Combustion efficiency is presented in figure 8 as a function of the combustion parameter V_r/P_iT_i (ref. 6), where V_r is the combustor reference velocity based on the maximum cross-sectional area (105 sq in.); P_i is the inlet total pressure; and T_i is the inlet air temperature. The efficiency data of figure 8(a) are for a combustor temperature rise of 680° F, the value required in the reference engine at cruise speed. Figure 8(b) presents similar data for a temperature rise of 1180° F, the value required for rated-speed operation. The combustion efficiencies for propane and methane were obtained from the faired curves of figures 5 and 6. Combustion-efficiency data obtained with JP-4 fuel in the prevaporizing combustor model 47L (ref. 3) are included in figure 8 for comparison. Methane and propane operated with comparable efficiencies at test conditions A and B (simulated altitudes of 56,000 and 70,000 ft), and at both temperature rise values (680° and 1180° F). At the low-pressure test condition C (80,000 ft), however, the efficiencies with methane were approximately 10 percent lower than with propane. Combustion efficiencies with prevaporized JP-4 fuel compared favorably with the efficiencies obtained with the vapor fuels.

Differences in the combustion efficiencies among a variety of fuels are frequently attributed to differences in fundamental combustion properties such as flame speed, flammability limits, spontaneous-ignition temperatures, and minimum spark-ignition energy. It was shown in reference 3 that, of a number of fundamental combustion properties considered, flame speed provided the best correlation with combustion efficiency. An empirical attempt was made to combine the effects of operating conditions (V_r, P_i, T_i) and flame speed in a single correlating parameter

$$\eta_b = (V_r/P_iT_i)(1/U_f)^a$$

where η_b is the combustion efficiency; U_f, the fundamental flame speed; and a, the constant. The term V_r/P_iT_i was used to correlate the effect of operating conditions in figure 8. Values of U_f relative to the flame speed of propane (table I), that is, $U_f = U_{f,fuel}/U_{f,propane}$, were used in the correlation attempt. The necessity of exponent a applied to the U_f term was indicated by the correlations presented in reference 3. A reasonable correlation of the data reported herein with these empirical functions is shown in figure 9 using a value of a of 2.75. Since a is undoubtedly a function of the individual combustion chamber, it cannot be considered applicable to other combustor data. For example, the data of reference 3 show that, for given operating conditions, $\eta_b = (1/U_f)^{1.87}$. Many attempts have been made to correlate combustion efficiencies with fundamental fuel properties and operating parameters. It is shown in reference 7 that no single correlating parameter can be expected to be adequate for all combustors or for the entire range of operating conditions because of a probable shift from one rate-controlling step to another as operating conditions are varied. 4252

Temperature Profiles

The radial-temperature profiles at the outlet of combustor model 48L, together with the desired temperature profile, are shown in figure 10 for a temperature rise of 1180° F (required for rated-speed operation of the reference engine). The desired temperature profile represents an approximate average of profiles required or desired in a number of current turbojet engines. In figure 10(a), the profiles obtained with gaseous propane are presented for test conditions A, B, and C. In figure 10(b), similar data obtained with gaseous methane are presented. The average radial-temperature profile obtained with the gaseous fuels followed the desired profile reasonably well. In figure 11, the isothermal contour patterns at the combustor outlet are shown for methane operation at test condition B at an average outlet temperature of 1440° F. Considerable circumferential asymmetry in temperature pattern is noted. At least a part of the asymmetry may be attributed to the side walls of the combustor, which would not be present in a full-annulus unit.

Pressure Losses

The combustor pressure losses obtained in combustor model 48L are shown in figure 12. The pressure losses are presented as the ratio of the total-pressure loss to the combustor-inlet total pressure. Pressure losses of 2 to 4 percent were obtained as compared with losses of 4 to 6 percent in most current production-model combustors. The study from which this combustor design evolved (ref. 4) was concerned primarily with achieving a low-pressure-loss design.

SUMMARY OF RESULTS

Performance characteristics of two gaseous hydrocarbon fuels in an annular combustor designed to operate with vapor fuel were compared. The following results were obtained for simulated high-altitude flight in a 5.2-pressure-ratio engine at a flight Mach number of 0.6.

1. The combustion efficiencies with gaseous methane were 98, 91, and 77 percent at 56,000, 70,000, and 80,000 feet, respectively, at a temperature rise of 1180° F and a combustor reference velocity of 80 feet per second. Corresponding combustion efficiencies with gaseous propane were 98, 93, and 86 percent at 56,000, 70,000, and 80,000 feet, respectively.

2. The combustor stability limits were narrower for methane operation than with propane operation. Both rich and lean blowout limits were observed with methane when the combustor reference velocity was increased to 140 feet per second.

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3. The lower combustion efficiencies obtained with methane at the more severe operating condition are attributed, at least in part, to the lower fundamental flame speed of this fuel.

4. The combustor-outlet temperature profiles were generally satisfactory with either propane or methane operation.

CONCLUDING REMARKS

In the experimental combustor model 48L, which was developed with propane fuel, methane did not burn as efficiently at the most severe operating conditions; and at an increased airflow rate only a limited operating range was possible due to flame blowout. Even though it appears that the poorer performance of methane, as compared with propane, is due to its lower flame speed, narrower flammability limits, etc., it may be possible to improve the performance by utilizing a combustor designed specifically for methane fuel operation. It would be expected, however, to be easier to obtain high performance with the higher flame speed fuel.

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Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 22, 1956

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TABLE I. - SELECTED PROPERTIES OF THREE HYDROCARBON FUELS

	Methane	Propane	MIL-F-5624C, grade JP-4
Freezing point, °F	-296	-306	-85
Boiling point, °F	-259	-44	---
Critical temperature, °F	-116	206	640
Net heat of combustion, Btu/lb	21,500	19,930	18,680
Lean flammability limit			
Percent by volume	4.4	2.0	0.8
Fuel-air ratio	0.027	0.033	0.035
Rich flammability limit			
Percent by volume	15.5	11.4	5.6
Fuel-air ratio	0.097	0.18	0.25
Spontaneous ignition temperature, °F	1170	940	484
Maximum fundamental flame velocity, cm/sec[a]	37	43	40
Comparative heat sink capacity potential, fraction of heat of combustion[b]	0.052	0.042	0.013

[a] Ref. 8.

[b] Ref. 1.

TABLE II. - COMBUSTOR TEST DATA

Run	Combustor-inlet total pressure, in. Hg	Combustor-inlet total temperature, °F	Airflow rate, lb/sec	Airflow rate per unit area, lb/(sec)(sq ft)	Fuel flow rate, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Mean temperature rise through combustor, °F	Combustion efficiency, percent	Inlet fuel temperature, °F	Total pressure drop through combustor, percent	Combustion parameter (cu ft)/(lb)(sec)(°R)
Model 47L; Propane												
1	5.0	273	0.530	0.726	20.6	0.0108	1010	737	89.0	84	2.5	308
2	5.0	270	.527	.722	27.5	.0133	1160	890	89.2	82		306
3	5.0	271	.530	.726	30.3	.0160	1310	1039	88.2	82		306
4	5.0	272	.527	.722	32.3	.0187	1440	1168	86.2	81	3.0	306
5	5.0	272	.527	.722	34.0	.0211	1550	1278	84.6	82		306
6	5.0	280	.525	.719	19.4	.0093	880	600	84.0	92		309
7	5.0	272	.521	.714	22.7	.0112	1010	738	86.5	90		305
8	5.0	272	.521	.714	32.1	.0188	1430	1158	84.8	90		305
9	8.0	270	.822	1.13	25.3	.0086	930	660	100.0	91	2.7	188
10	8.0	269	.816	1.12	30.3	.0103	1025	756	95.6	93		187
11	8.0	269	.817	1.12	35.3	.0120	1140	871	96.5	94		187
12	8.0	269	.816	1.12	40.6	.0138	1250	981	99.2	95		187
13	8.0	270	.816	1.12	45.2	.0154	1345	1075	94.8	97		188
14	8.0	271	.815	1.12	50.4	.0172	1435	1164	92.7	98		188
15	8.0	271	.813	1.15	60.3	.0206	1580	1309	88.5	99		187
16	15.0	249	1.536	2.10	59.2	.0106	1070	821	102.1	98		96
17	15.0	268	1.546	2.12	67.0	.0120	1180	912	100.3	98		100
18	15.0	268	1.552	2.13	74.2	.0133	1270	1002	100.6	98		100
19	15.0	267	1.553	2.13	82.6	.0148	1350	1083	99.3	97		100
20	15.0	268	1.550	2.12	92.1	.0165	1450	1182	97.8	97	3.6	100
21	15.0	268	1.550	2.12	102.1	.0183	1550	1282	97.0	97		100
22	15.0	266	2.638	3.61	76.9	.0081	905	639	101.5	76		171
23	14.9	270	2.630	3.60	95.0	.0100	1040	770	101.0	76		172
24	15.0	263	2.645	3.63	111.1	.0117	1145	882	100.7	77		170
25	15.0	266	2.641	3.62	132.0	.0139	1280	1014	97.8	79		171
26	15.1	272	2.638	3.61	153.8	.0162	1410	1138	96.0	80		172
27	15.1	262	2.675	3.67	171.2	.0179	1475	1213	93.5	84	13.7	170
Model 48L; Methane												
28	5.0	273	0.533	0.730	23.2	.0121	1035	762	80.2	71		
29	5.0	264	.532	.729	24.6	.0128	1120	856	85.2	72		
30	5.0	272	.532	.729	25.9	.0135	1175	903	85.9	72		
31	5.0	271	.532	.729	27.4	.0143	1225	954	86.9	72		
32	5.0	268	.532	.729	29.5	.0154	1285	1017	86.2	74		
33	5.0	268	.535	.733	32.1	.0167	1340	1072	84.7	72		
34	5.0	267	.532	.729	33.5	.0175	1360	1093	82.2	71		
35	5.0	264	.532	.729	36.0	.0188	1410	1146	81.0	70		
36	5.0	265	.528	.724	38.0	.0200	1440	1175	78.9	70		
37	5.0	266	.529	.725	40.0	.0210	1455	1189	76.1	70		
38	5.0	266	.530	.730	43.9	.0230	1460	1194	70.2	70		
39	15.0	269	1.570	2.15	32.6	.0058	740	471	89.9	76		
40	15.0	276	1.560	2.14	38.1	.0068	835	559	101.1	74		
41	15.0	268	1.572	2.15	35.1	.0062	775	507	100.3	77		
42	15.0	266	1.575	2.16	41.3	.0073	865	599	101.4	75		
43	15.0	268	1.570	2.15	46.7	.0083	940	672	101.1	73		
44	15.0	267	1.574	2.16	53.2	.0094	1040	773	103.1	72		
45	15.0	269	1.572	2.15	56.4	.0100	1070	801	100.8	71		
46	15.0	268	1.572	2.15	64.7	.0114	1185	917	102.1	70		
47	15.0	270	1.572	2.15	77.0	.0136	1310	1040	101.1	69		
48	15.0	268	1.570	2.15	89.0	.0157	1440	1172	98.0	68		
49	15.0	272	1.570	2.15	99.0	.0175	1540	1268	96.8	68		
50	15.0	269	1.565	2.14	70.6	.0125	1260	991	101.3	70		

TABLE II. - Concluded. COMBUSTOR TEST DATA

Run	Combustor-inlet total pressure, in. Hg	Combustor-inlet total temperature, °F	Airflow rate, lb/sec	Airflow rate per unit area, lb/(sec)(sq ft)	Fuel flow rate, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Mean temperature rise through combustor, °F	Combustion efficiency, percent	Inlet fuel temperature, °F
Model 48L; Methane										
51	16.5	253	2.64	3.62	72.8	0.0077	835	582	94.0	79
52	16.4	277	2.64	3.62	80.0	.0084	945	668	99.0	77
53	16.2	273	2.63	3.61	88.2	.0093	1030	757	101.8	77
54	16.2	278	2.63	3.61	95.0	.0101	1090	812	101.7	77
55	15.2	268	2.61	3.58	95.0	.0101	1080	812	101.0	77
56	15.2	268	2.64	3.62	104.0	.0109	1140	872	101.4	77
57	15.2	269	2.64	3.62	115.7	.0122	1230	961	100.1	76
58	15.1	252	2.63	3.61	99.0	.0105	1100	848	102.0	79
59	15.0	272	2.63	3.61	123.0	.0130	1270	998	98.7	79
60	15.1	272	2.63	3.61	135.2	.0143	1330	1068	96.6	78
61	15.5	268	2.63	3.61	147.5	.0156	1380	1112	93.6	80
62	15.7	266	2.63	3.61	155.0	.0164	1420	1154	92.6	79
63	15.1	268	2.63	3.61	99.2	.0105	1080	812	101.5	79
64	7.9	268	0.833	1.14	23.3	.0078	780	512	80.5	79
65	8.0	272	.830	1.14	26.1	.0088	920	648	93.1	79
66	8.0	266	.833	1.14	28.9	.0097	1000	734	95.0	79
67	8.0	271	.833	1.14	31.7	.0106	1070	799	95.0	79
68	8.0	269	.833	1.14	35.3	.0118	1160	891	97.2	78
69	8.0	266	.840	1.15	38.7	.0128	1220	954	95.5	78
70	8.0	272	.840	1.15	42.0	.0139	1275	1003	94.2	77
71	8.0	264	.840	1.15	48.3	.0160	1380	1116	91.0	76
72	8.1	272	.840	1.15	51.9	.0172	1440	1168	90.2	76
73	8.0	272	.840	1.15	56.0	.0186	1510	1238	89.1	76
74	5.0	267	.525	.720	22.8	.0120	1070	803	85.1	83
75	5.0	262	.525	.720	20.0	.0106	870	608	67.7	83
Model 48R; Methane										
76	5.0	276	0.525	0.720	21.4	0.0113	1040	764	85.5	83
77	5.0	278	.525	.720	22.9	.0121	1090	812	86.3	84
78	5.0	278	.524	.718	24.5	.0130	1150	872	86.3	84
79	5.0	262	.523	.717	27.6	.0144	1225	963	86.6	85
80	5.0	264	.523	.717	32.1	.0170	1330	1066	82.3	83
81	5.0	260	.521	.714	35.8	.0191	1410	1150	80.2	83
82	5.0	276	.525	.720	24.0	.0127	900	624	62.2	82
83	8.0	260	.833	1.14	20.0	.0067	790	530	97.3	81
84	8.0	262	.833	1.14	17.9	.0060	690	528	87.1	81
85	8.0	270	.833	1.14	22.5	.0076	880	610	99.6	81
86	8.0	272	.833	1.14	24.9	.0083	940	668	99.8	82
87	8.0	262	.833	1.14	51.4	.0172	1430	1168	90.0	79
88	8.0	262	.830	1.14	51.4	.0172	1435	1173	90.3	78
89	5.0	272	.525	.720	22.2	.0118	1085	813	88.2	83
90	8.0	273	.838	1.15	25.1	.0083	940	667	99.9	83
91	8.0	268	1.028	1.41	31.5	.0085	940	672	98.2	81
92	8.0	270	1.232	1.69	49.5	.0112	960	690	82.1	74
93	9.0	270	1.470	2.01	48.7	.0092	Blowout			74
94	15.0	270	1.555	2.13	33.2	.0060	760	490	101.3	73
95	15.0	268	1.555	2.13	28.8	.0052	695	427	100.5	76
96	15.0	268	1.550	2.12	25.1	.0050	620	352	95.5	76

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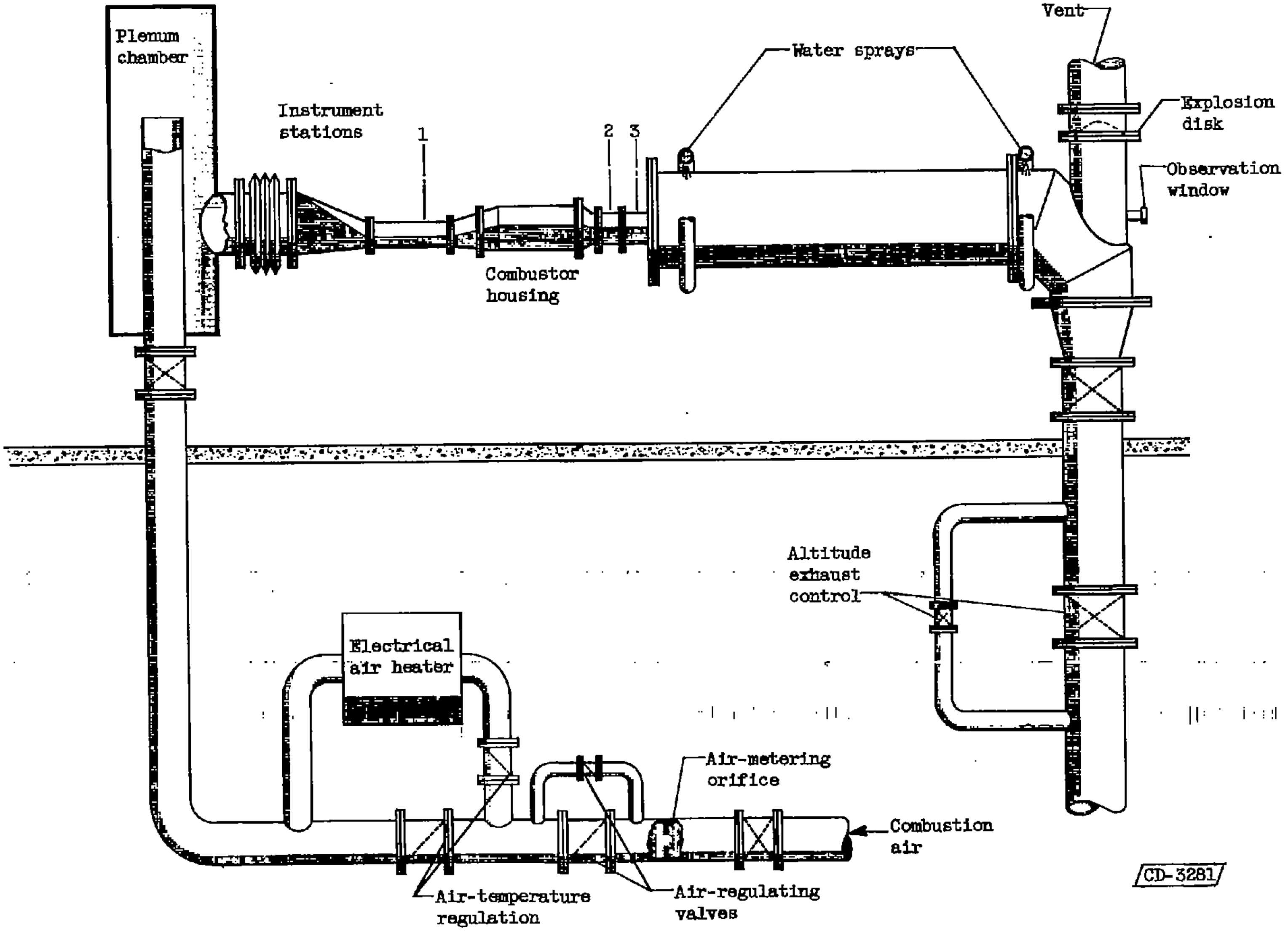
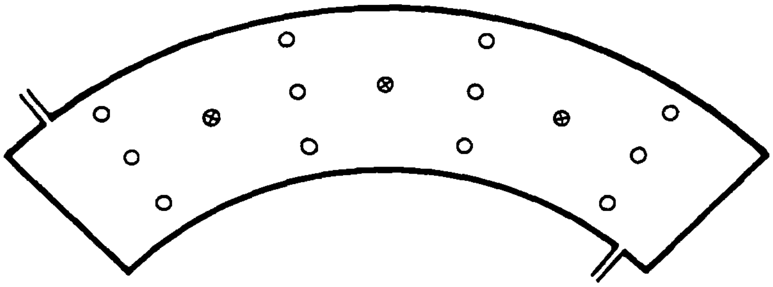
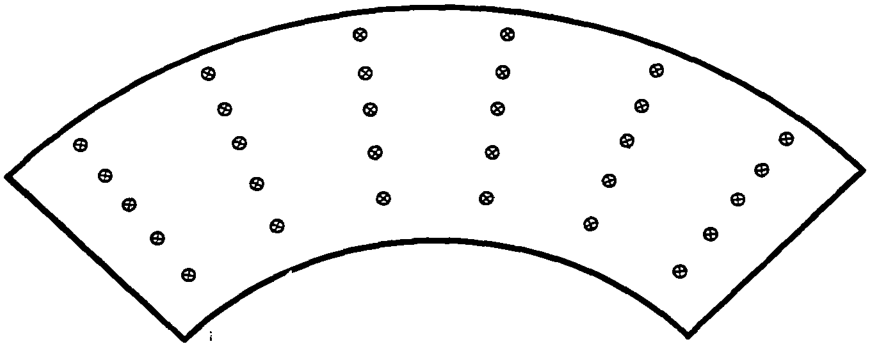


Figure 1. - Installation of one-quarter sector of 25.5-inch-diameter annular combustor.

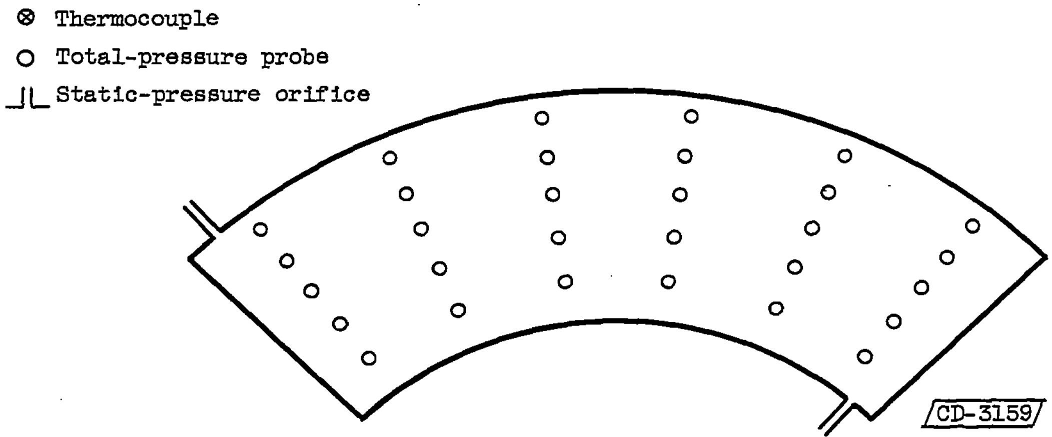
4252



(a) Inlet thermocouples (iron-constantan) and inlet total-pressure probes in plane at station 1.



(b) Outlet thermocouples (chromel-alumel) in plane at station 2.



(c) Outlet total-pressure probes in plane at station 3.

Figure 2. - Experimental combustor instrumentation.

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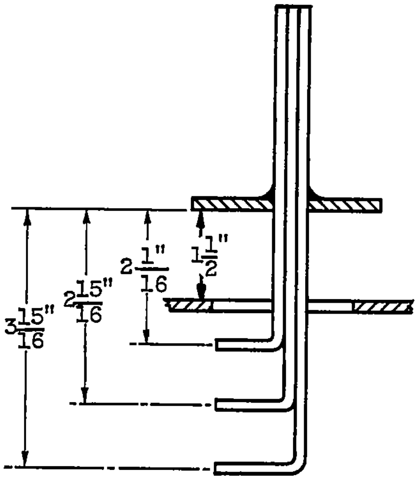
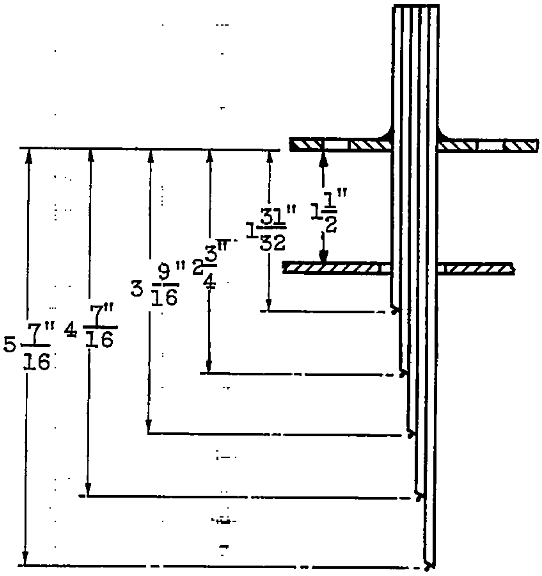
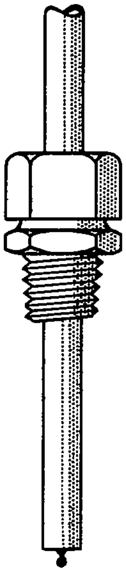


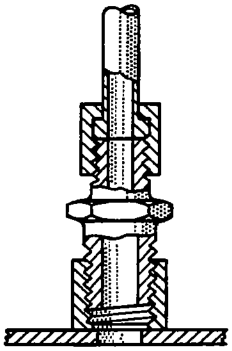
(d) Inlet total-pressure rake.



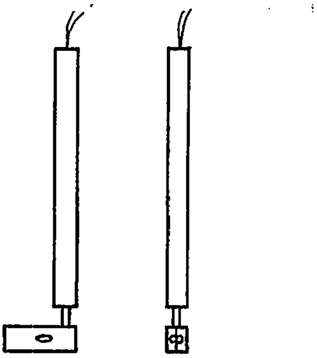
(e) Outlet thermocouple rake.



(f) Inlet thermocouple.



(g) Static-pressure orifice.



(h) Wedge stream-static probe.

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Figure 2. - Concluded. Experimental combustor instrumentation.

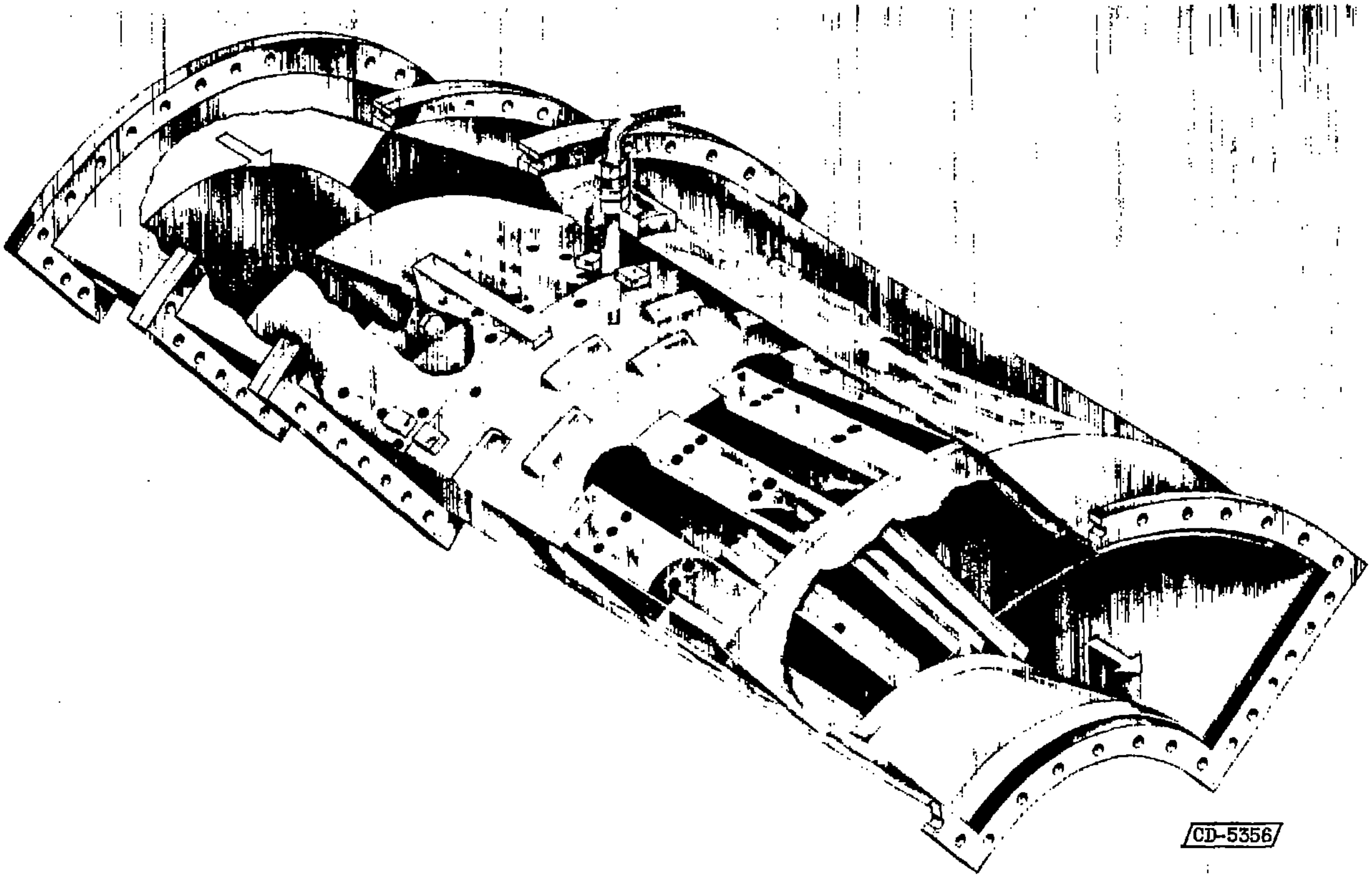
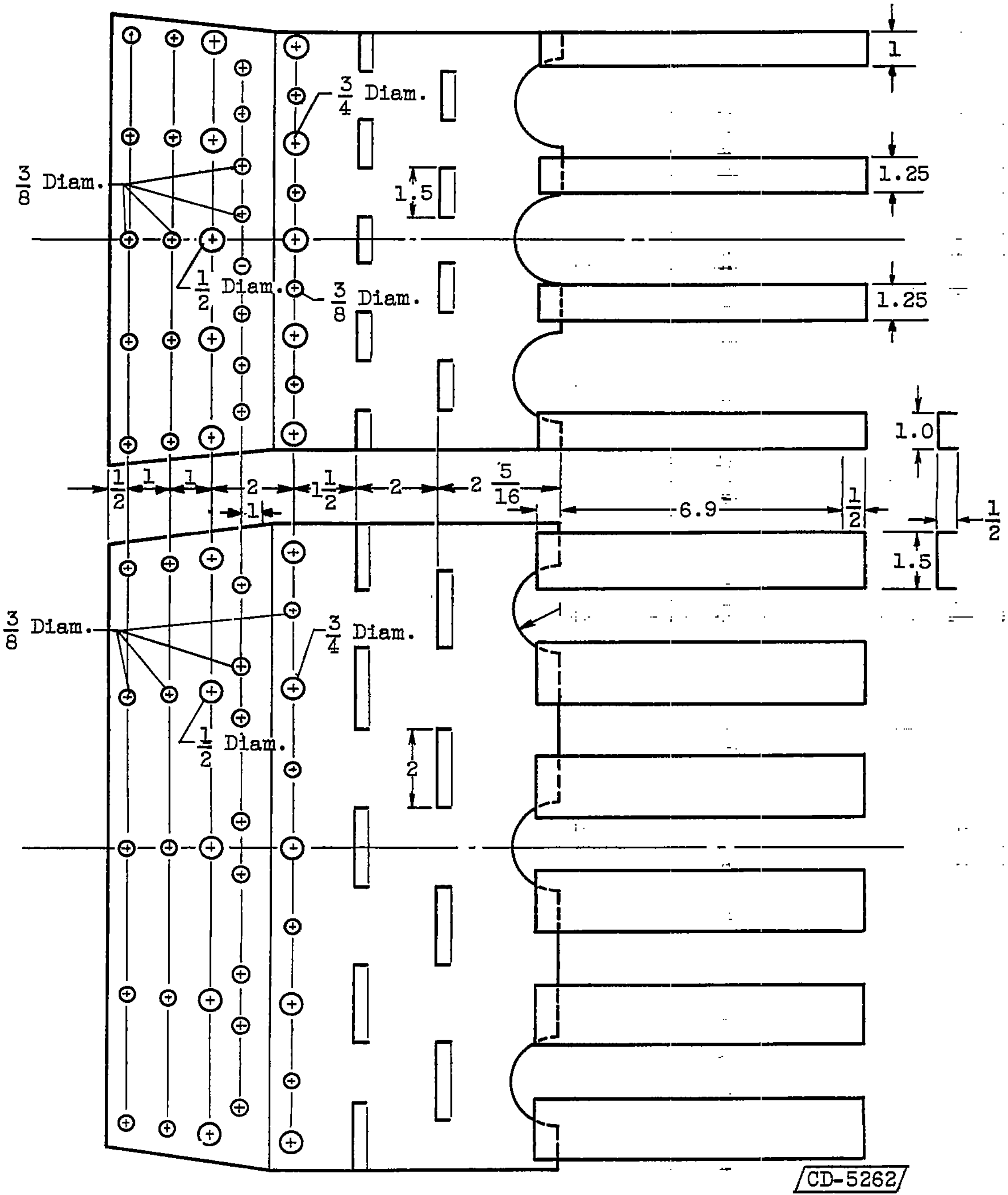


Figure 3. - Phantom view of combustor model 48 assembled in test ducting.



(a) Wall pattern.

Figure 4. - Liner details of combustor model 48. (Dimensions are in inches.)

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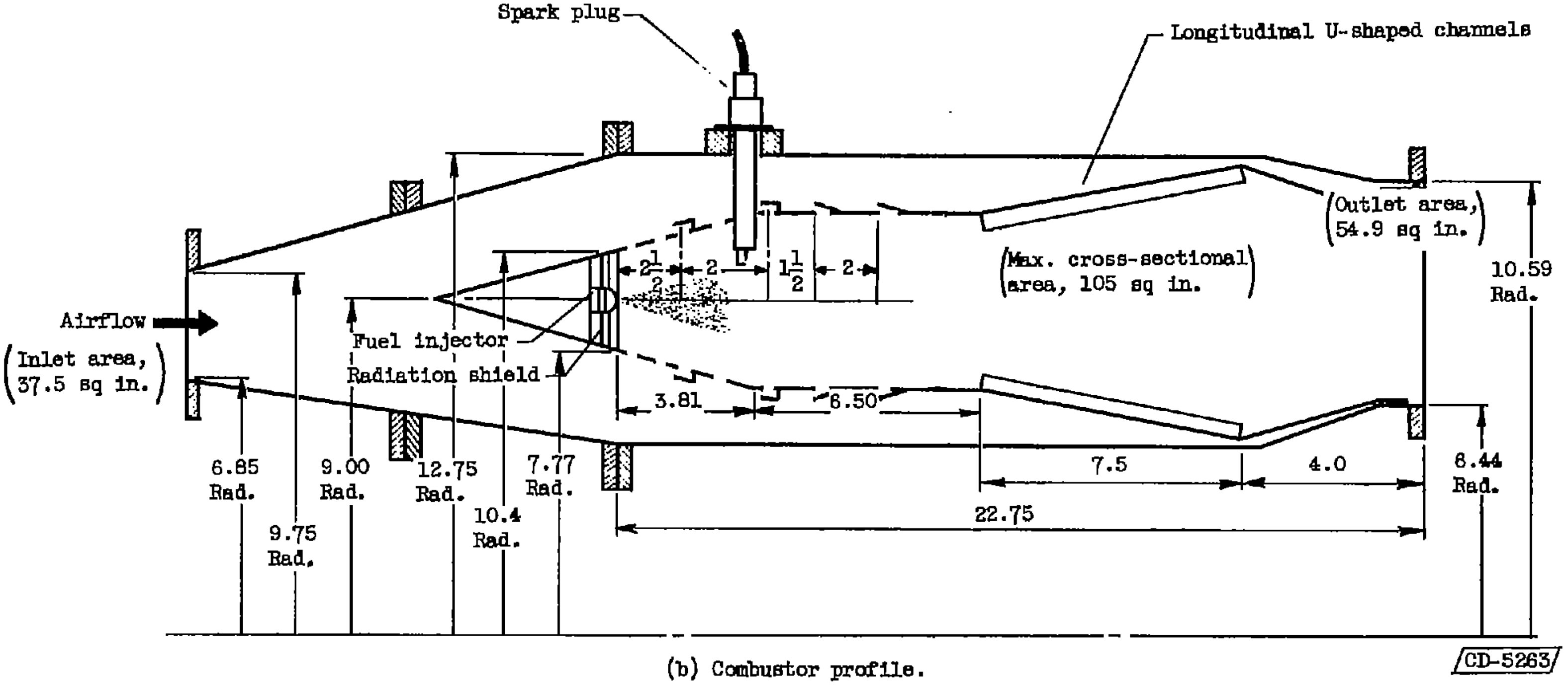
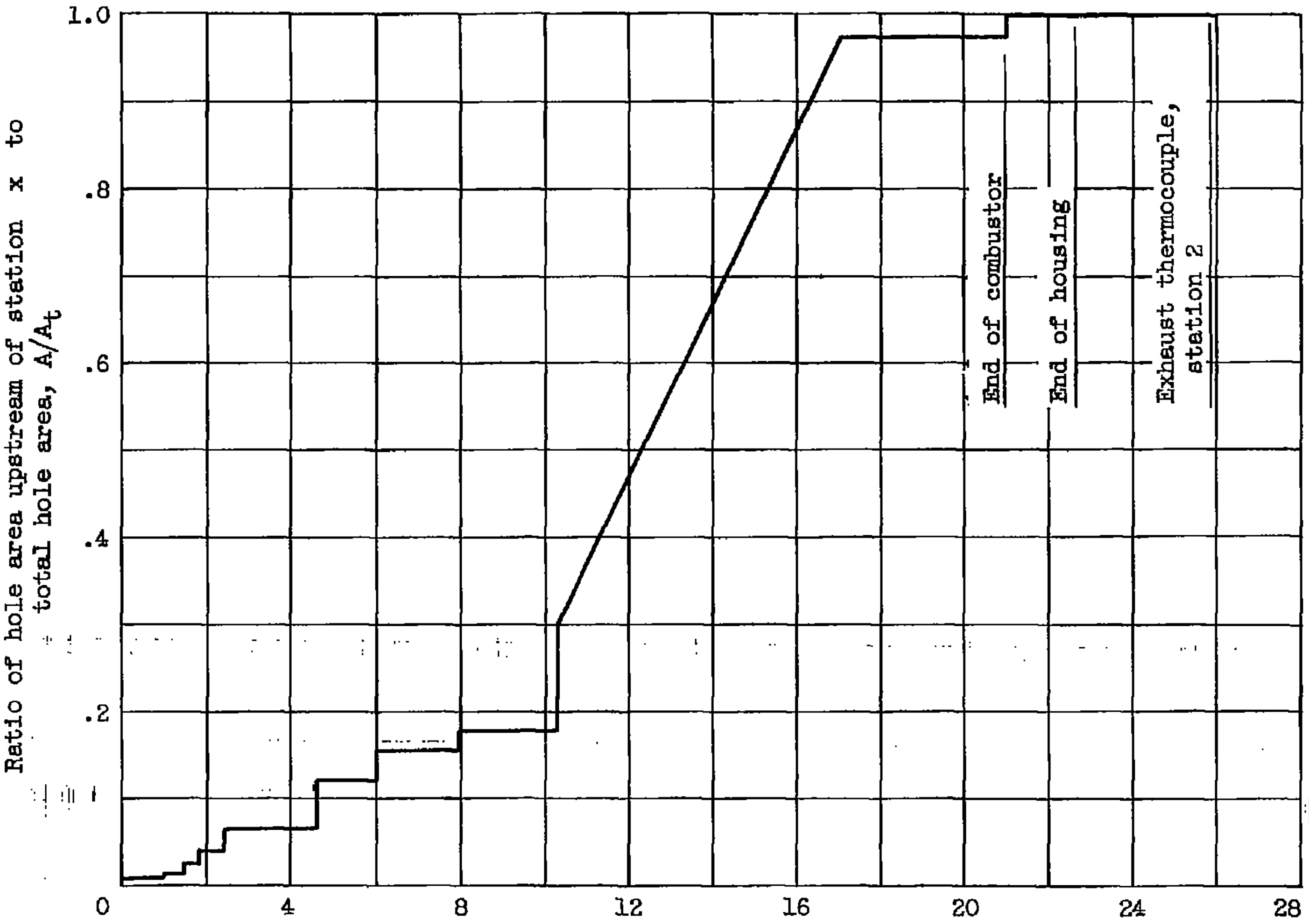


(b) Combustor profile.

Figure 4. - Continued. Liner details of combustor model 48. (Dimensions are in inches.)



(c) Open-hole-area distribution (open area, 95.9 sq in.).

Figure 4. - Concluded. Liner details of combustor model 48.

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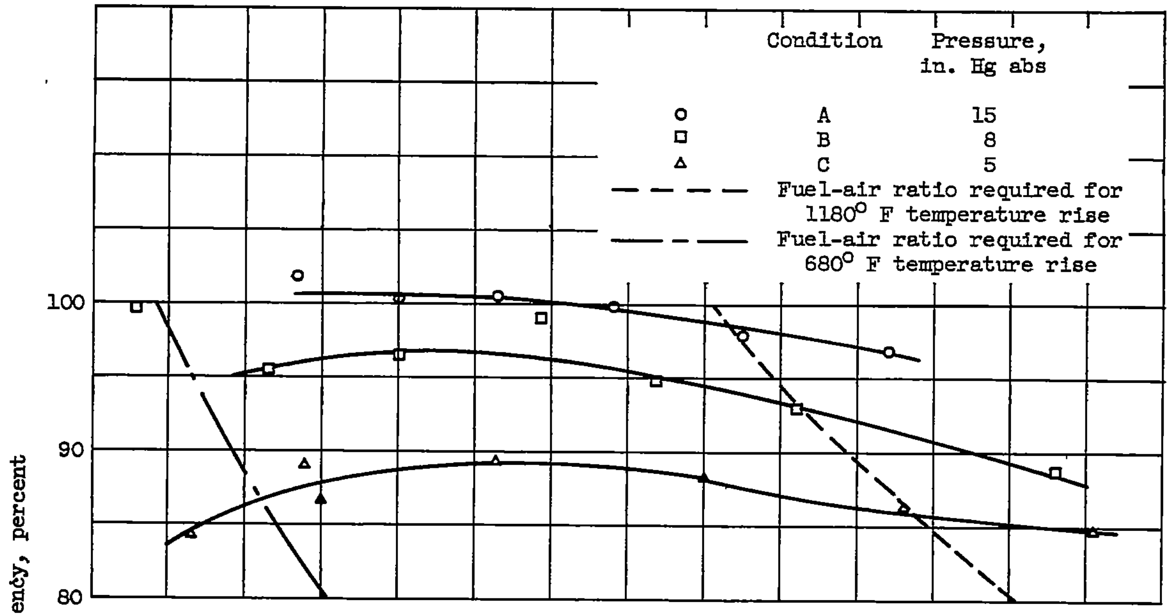
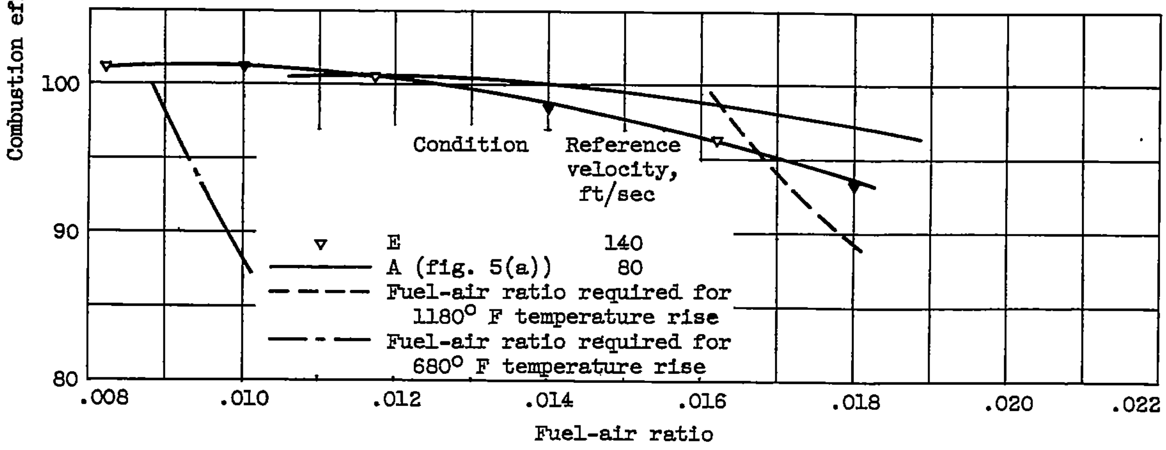


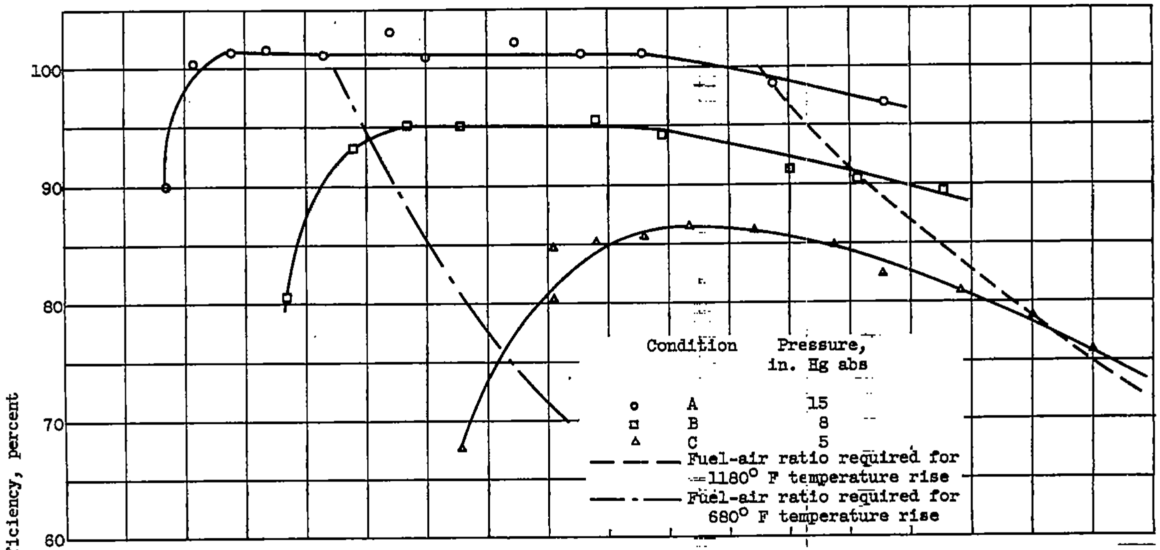
(a) Combustor reference velocity, 80 feet per second.



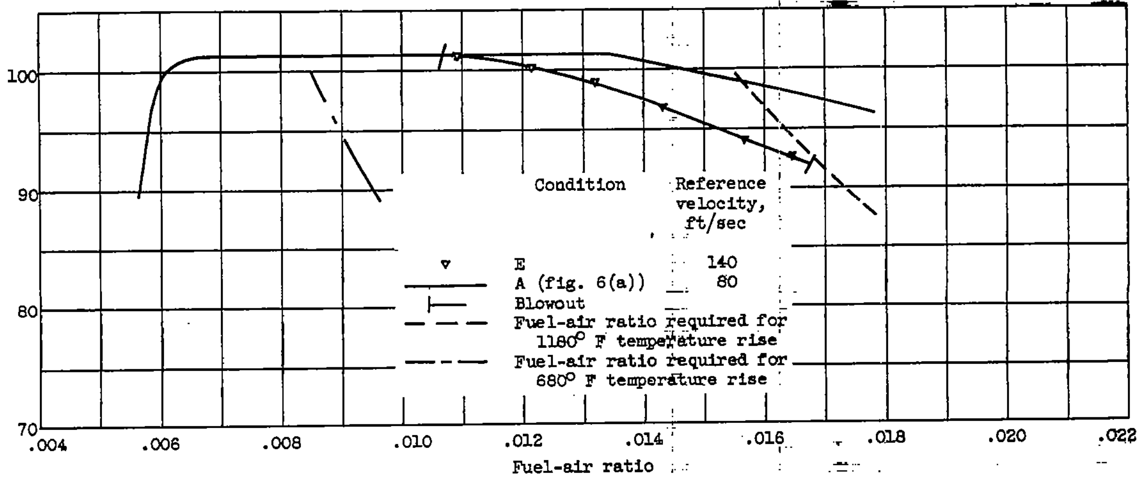
(b) Combustor-inlet pressure, 15 inches mercury absolute.

Figure 5. - Combustion efficiency of combustor model 48L with propane fuel and at an inlet air temperature of 268° F.

4252



(a) Combustor reference velocity, 80 feet per second.



(b) Combustor inlet pressure, 15 inches mercury absolute.

Figure 6. - Combustion efficiency of combustor model 48L with methane fuel and at an inlet air temperature of 268° F.

[redacted]

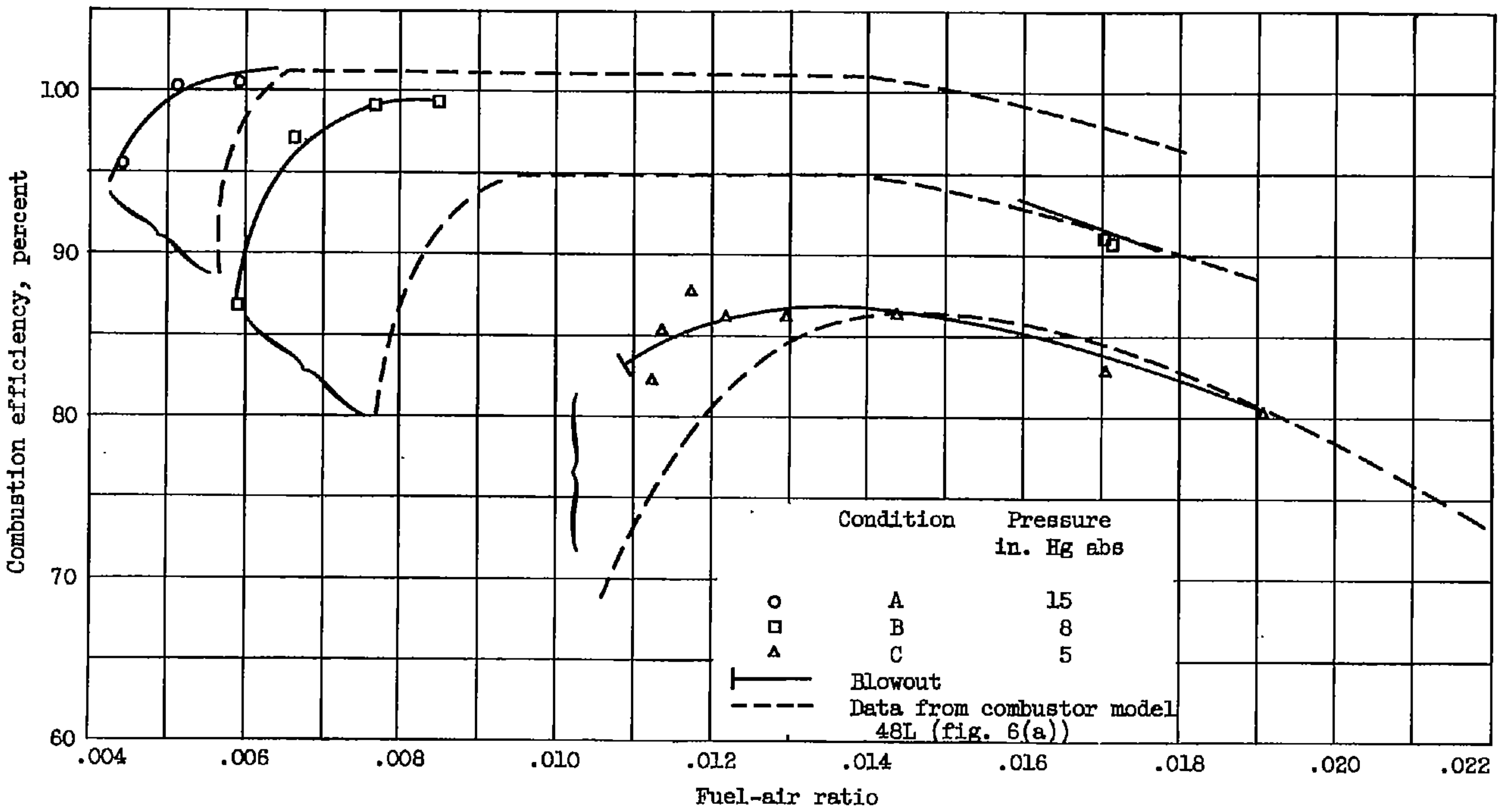


Figure 7. - Combustion efficiency of combustor model 48R with methane fuel and at an inlet air temperature of 268° F.

[redacted]

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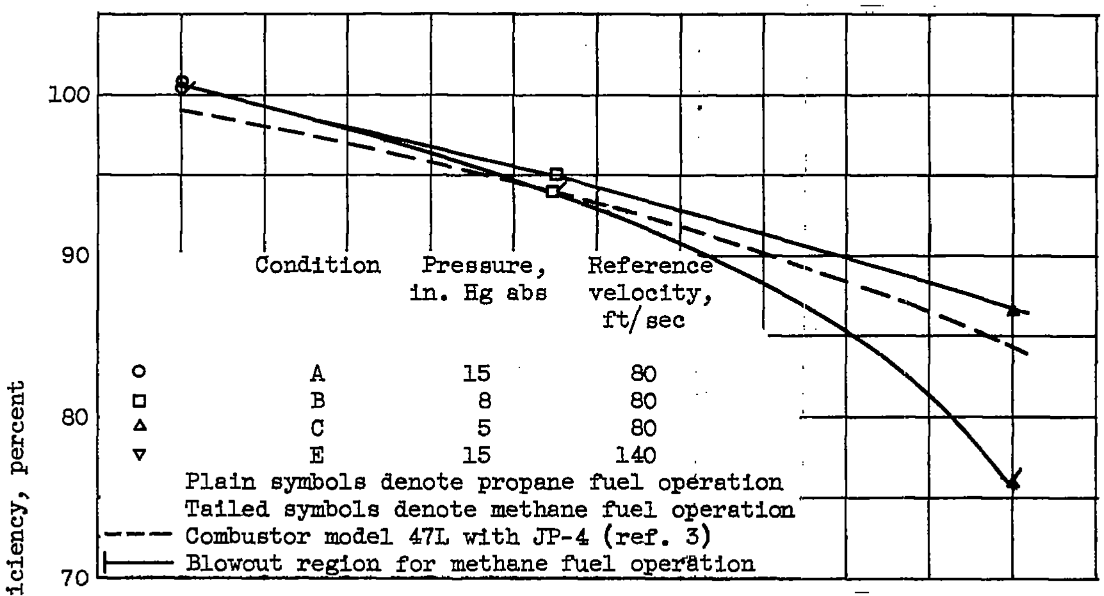
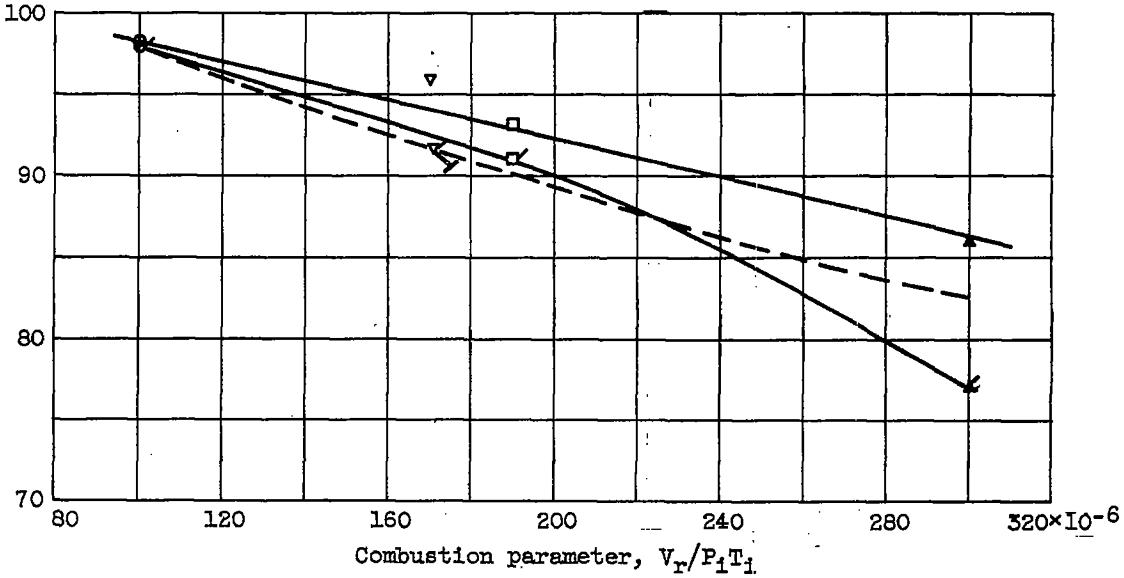


(a) Temperature rise of 680° F.



(b) Temperature rise of 1180° F.

Figure 8. - Correlation of combustion efficiency data of combustor model 48L with vapor fuel and comparison with combustor model 47L (48L with prevaporizer) with JP-4 fuel and at an inlet air temperature of 268° F.

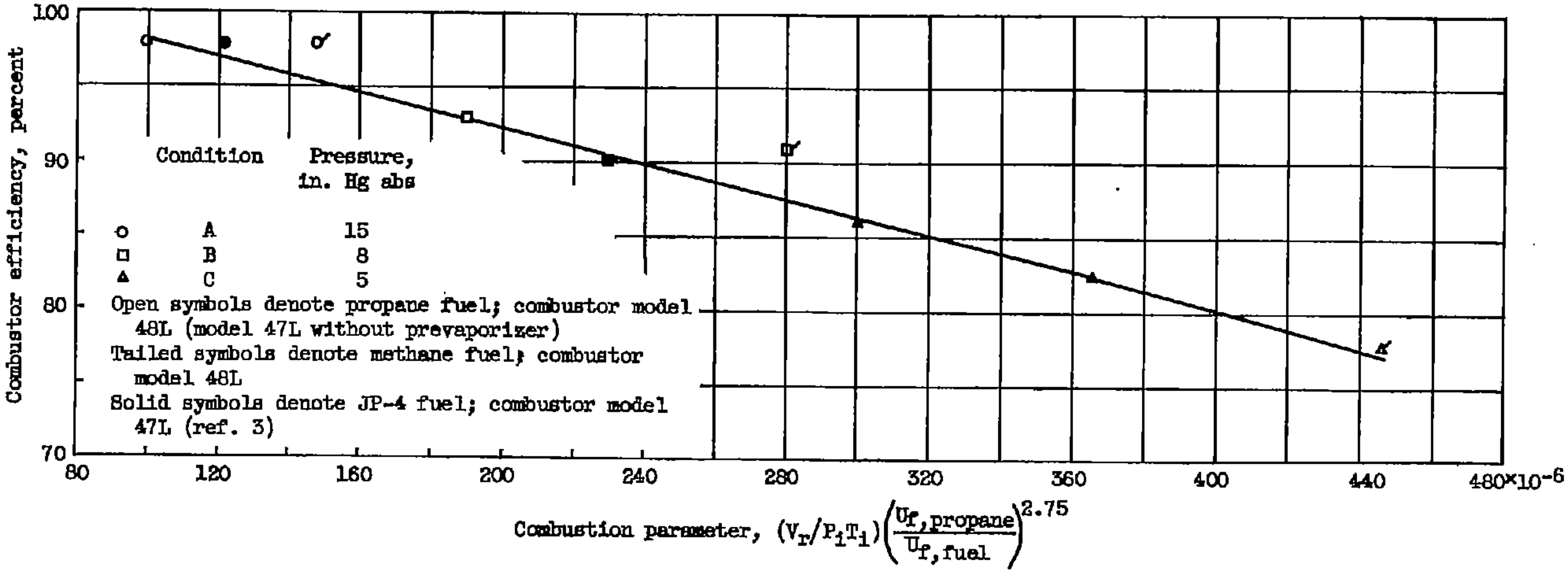
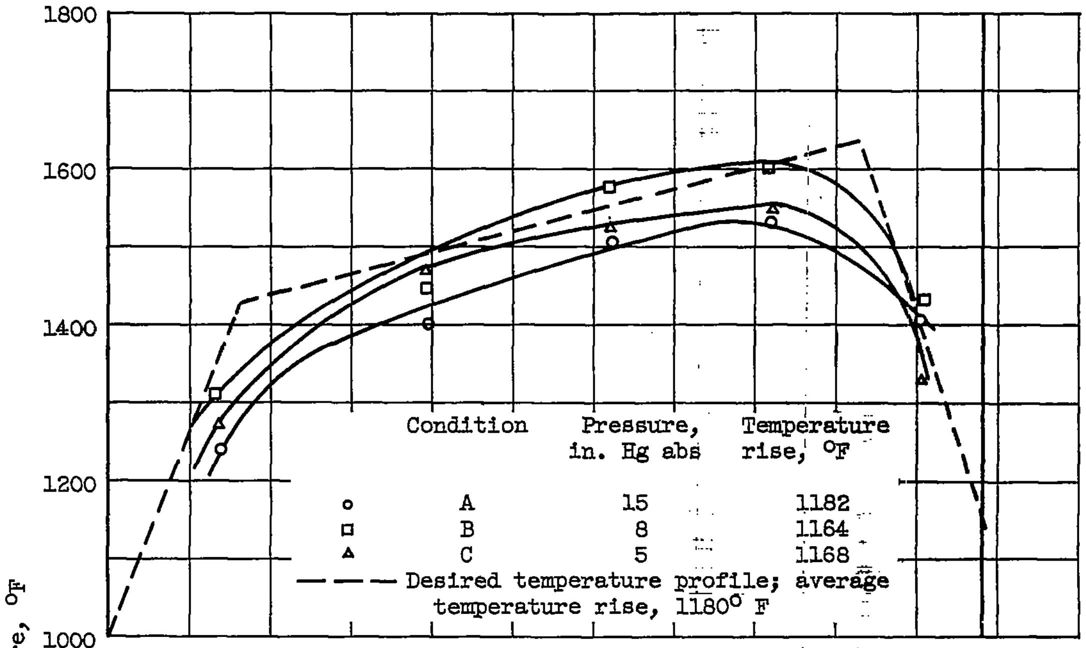
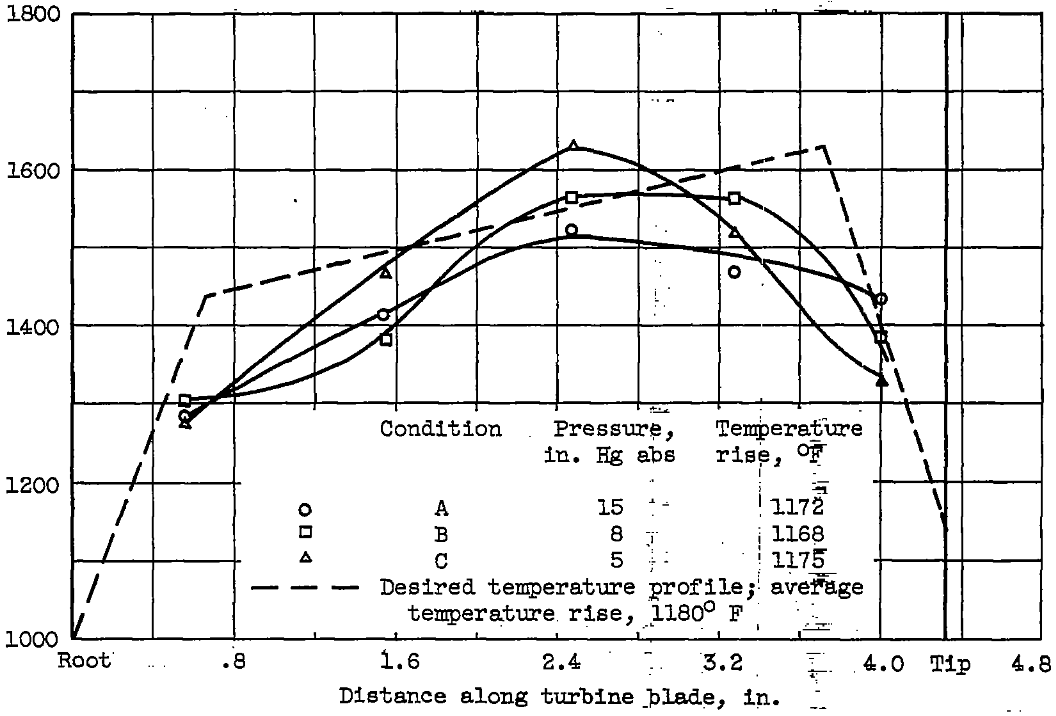


Figure 9. - Empirical correlation of combustion efficiency with combustor operating conditions and fundamental flame speed for methane, propane, and JP-4 fuels. Temperature rise through combustor, 1180° F. Reference velocity, 80 feet per second and inlet air temperature of 268° F for all test conditions.



(a) Propane.



(b) Methane.

Figure 10. - Outlet-radial temperature profiles with combustor model 48L. Combustor reference velocity, 80 feet per second; inlet air temperature of 268° F.

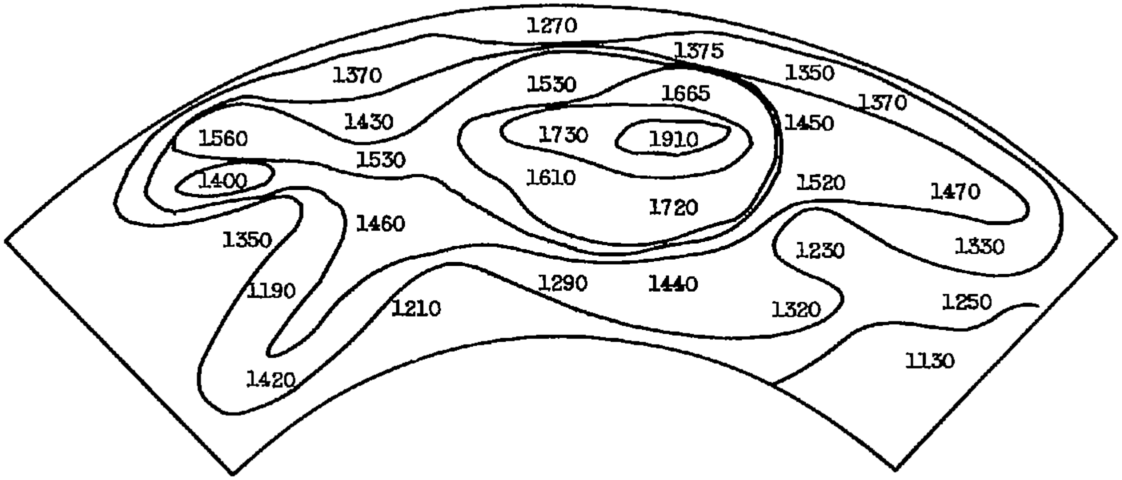


Figure 11. - Isothermal contour patterns at combustor outlet of experimental model 48L with methane fuel operation. Test condition B: pressure 8 inches mercury absolute; reference velocity, 80 feet per second; inlet air temperature, 268° F; average outlet temperature, 1440° F.

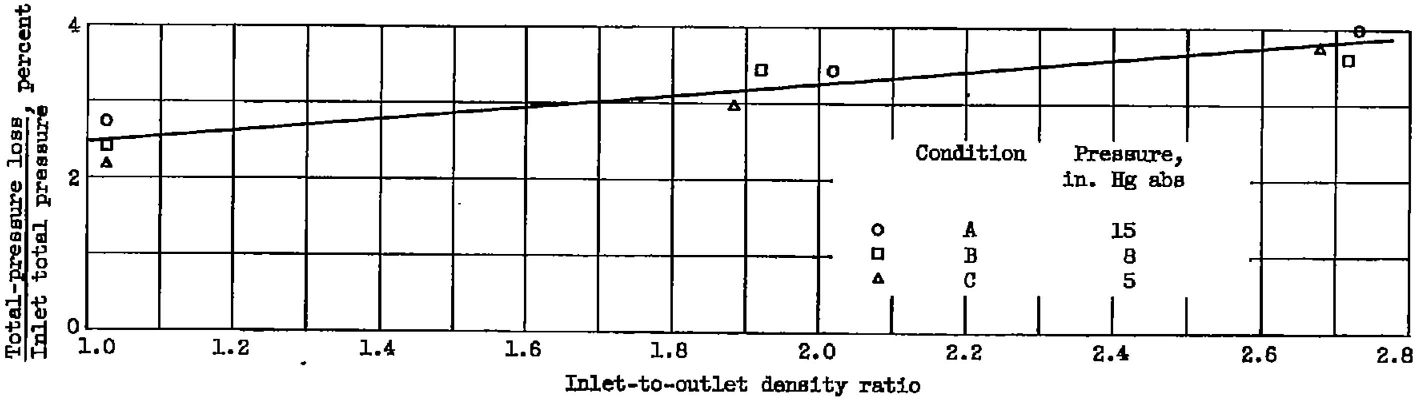


Figure 12. - Pressure losses of combustor model 48L at a combustor reference velocity of 80 feet per second and inlet air temperature of 268° F.