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RESEARCH MEMORANDUM

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
March 30, 1953

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EFFECT OF AXIALLY STAGED FUEL INTRODUCTION ON PERFORMANCE OF ONE-QUARTER SECTOR OF ANNULAR TURBOJET COMBUSTOR

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SUMMARY

An investigation was conducted to determine the effect of staging the fuel introduction in the primary zone on the performance of a one-quarter sector of a single-annulus turbojet combustor. Pressure-atomized liquid fuel was introduced simultaneously through hollow-cone spray nozzles spraying axially from the upstream face of the combustor and through small fan spray nozzles spraying radially into the combustor and located on the walls of the combustor as much as 5 inches downstream of the main fuel manifold. The investigation was made at a constant combustor-inlet pressure of 15 inches of mercury absolute, at two combustor-inlet-air temperatures (80° and 270° F) and over a range of air flows from 1.5 to 3.6 pounds per second per square foot.

The results of this investigation indicate that for combustors designed for present-day turbojet engines (engines having a pressure ratio of 5.2, an air-handling capacity up to 25 lb/sq ft of compressor frontal area, and a limiting turbine-inlet temperature of 1500° F), staging the fuel introduction in the combustor primary zone can improve combustion efficiency considerably when air flows through the combustor are as much as 70 percent higher than those presently encountered. For air flows at present-day levels, fuel staging had a minor effect on combustion efficiency. The higher the fuel-air ratio at all air flows, the more the fuel introduction had to be spread over the length of the primary zone to realize the maximum advantages of fuel staging. The over-all effect of variation of fuel introduction from inner to outer wall on exhaust radial temperature distribution was not large, thus indicating that final control of temperature distribution should come from air-introduction changes on the walls of the combustor rather than from fuel-introduction changes.

INTRODUCTION

Turbojet-engine combustor development must keep pace with the extended design requirements for the engines as compressor and turbine components are improved. Current compressor development trends are towards higher air flows per unit cross section of compressor frontal area (ref. 1). This increased air flow requires combustor operation at higher mean air velocities if the combustor cross-sectional area is to be no greater than the frontal area of other components. The combustor will also be required to operate effectively over a much wider range of fuel-air ratios as turbine-cooling developments (refs. 2 and 3) are successfully applied to the engine. These improvements in the engine components are aimed at obtaining higher thrust per pound weight of engine; in addition, there is the ever-present need of obtaining higher combustion efficiency during high-altitude operation.

Past NACA research aimed at discovering methods of improving the altitude performance of combustors (i. e., combustion efficiency, combustion stability, and temperature distribution) has consisted principally in studying the distribution of the air into the combustor and the variation in fuel atomization for various types of combustion chambers (refs. 4 to 9). Another important design variable is the method of distributing the fuel in the combustor. Although some research has been conducted at the NACA Lewis laboratory on the effects of fuel distribution in tubular turbojet combustors (refs. 9 and 10), the work has neither been as extensive as that work directed at air distribution, nor has it been extended to annular combustors. Accordingly, the investigation reported herein was undertaken to study the effects on the performance of a single-annulus combustor of systematically varying the axial distribution of the fuel in the primary zone of the combustor.

The research equipment consisted of a one-quarter sector of a $25\frac{1}{2}$-inch single-annulus combustor similar to that reported in reference 11. Throughout the investigation a portion of the fuel was injected axially into the combustion zone through 10 hollow-cone spray nozzles located at the upstream face of the combustor. The rest of the fuel was introduced through fan spray nozzles spraying radially into the primary zone and located at various axial positions along the wall of the primary zone and at circumferential positions located between air-entry slots. This system was chosen in an attempt to maintain the fuel-rich and air-rich regions for the entire length of the primary zone (ref. 5).

A preliminary survey of a large number of variations in fuel distribution indicated those which have the best performance. The results presented herein are for 11 selected configurations which best illustrate the trends that were obtained. Each configuration was investigated over a range of air flows from 1.5 to 3.6 pounds per second per square foot, at conditions for which present-day turbojets with a 5.2 compression ratio operating at an altitude of 56,000 feet and cruise revolutions per minute would be required to pass approximately 2.1 pounds air per second per square foot.

SYMBOLS

The following symbols are used in this report:

A	maximum combustor cross-sectional area, sq ft
F/A	fuel-air ratio
P	total pressure, in. Hg abs
ΔP_T	total-pressure loss, lb/sq ft abs
q_r	reference dynamic pressure based on inlet density and velocity as computed from the combustion-chamber maximum cross-sectional area, lb/sq ft abs
T	temperature, $^{\circ}F$
w_a	air flow, lb/sec
η_b	combustion efficiency, percent
ρ	gas density, lb/cu ft

Subscripts:

1	combustor inlet
2	combustor outlet

APPARATUS

Combustor Installation

A schematic diagram of the combustor installation is shown in figure 1. Air of desired quantity, pressure, and temperature was drawn from the laboratory air-supply system, passed through the combustor, and exhausted into the altitude exhaust system. Combustor-inlet temperatures were controlled by use of a gasoline-fired preheater to burn a portion of the air upstream of the combustor. The quantity of air flowing through the bypass, the total air flow, and the combustion-chamber static pressure were regulated by three remote-control valves. Two observation windows were installed in the test section in order to permit visual observation of the combustion process.

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Instrumentation

Total temperatures and pressures were measured at the three stations indicated in figure 1. The position of the instruments in each of the three planes is shown in figure 2. Combustor-inlet total temperatures were measured with three bare-junction unshielded iron-constantan thermocouples at station 1, as shown in figure 2(a). Slightly upstream were located 12 total-pressure tubes, 3 tubes in each of 4 rakes as shown in figure 2(a). Combustor-outlet total temperatures were measured with 30 bare-junction unshielded chromel-alumel thermocouples; 5 thermocouples in each of 6 rakes were located across the duct at station 2, 23 inches from the upstream end of the combustor, as shown in figure 2(b). At station 3 were located 15 total-pressure tubes in 3 rakes of 5 pressure tubes each (fig. 2(c)). All instruments were located at approximate centers of equal areas. Static-pressure taps were installed at the walls, as shown in figure 2(c). Construction details of the pressure and temperature probes are shown in figure 3.

Combustor and Fuel System

The combustor consisted of a one-quarter section (90°) of a single-annulus combustor designed to fit into a one-quarter sector of an annular combustion-chamber housing and was similar to the combustor reported in reference 11. The outer diameter of the housing was $25\frac{1}{2}$ inches, the inner diameter, $10\frac{5}{8}$ inches. The combustor is illustrated schematically in figures 4 to 6. The combustor was fitted with a total of 40 fuel nozzles. Fuel was injected downstream of the upstream face of the combustor by means of 10 hollow-spray cone pressure atomizing nozzles (10.5 gal/hr or 3.0 gal/hr, 60° nominal spray angle). In addition, provision was made for injecting fuel through any combination of 30 fan nozzles located on 4 manifolds and spraying radially through the walls into the primary combustion zone with the fan spray in a plane parallel to the longitudinal axis of the combustor. The fan nozzles had a flow capacity of approximately 3 gallons per hour at 100 pounds pressure differential, had a spray angle of approximately 60°, and were arbitrarily located $3\frac{5}{16}$ inches and $5\frac{5}{16}$ inches from the upstream face of the combustor between the air-entry slots in the combustor liner (figs. 5 and 6). Filters were installed to eliminate clogging of the 0.010-inch wide slots. Separate rotameters were used to meter the flow through each of the 5 fuel manifolds and the total flow through all the manifolds used for any particular run. MIL-F-5624A, grade JP-4 fuel was used throughout the investigation.

PROCEDURE

The fuel-introduction configurations are listed in table I. Performance was recorded and studied for the combustor with first the 10.5-gallon-per-hour and then the 3.0-gallon-per-hour hollow-cone spray nozzles in the conventional upstream fuel manifold (configurations 1 and 2). Configurations 3 to 7 represented a progressively increasing axial spreading of the fuel. For these configurations, the quantity of fuel introduced through the outer wall at any given axial station was the same as that introduced through the inner wall at the same axial station. Configurations 8 to 11 represented an attempt to determine the effects of unsymmetrical fuel introduction on the outlet radial temperature distribution; therefore, the quantities of fuel introduced on the inner and outer walls were not the same for these configurations. Circumferentially, only three flat-spray nozzles per manifold were studied; the nozzles investigated are indicated in figure 6.

Preceding each run the fuel nozzles scheduled to be used were removed from the setup and checked for clogging. All configurations were investigated over a range of air flows from 1.5 to 3.6 pounds per second per square foot (based on maximum cross-sectional area of the combustor). The range of fuel-air ratios investigated for each configuration at each air flow was limited at the rich end to a value dictated by either of the following conditions: (1) a maximum obtainable temperature rise was encountered, or (2) a temperature rise of 1400° F was obtained.

The combustion efficiency is defined herein as the ratio of the actual total-temperature rise to the theoretical rise in total temperature possible. The charts of reference 11 were utilized for these computations. The thermocouple indications were taken as true values of the total temperature.

RESULTS AND DISCUSSION

The effect of numerous fuel-introduction configurations on combustion efficiency and temperature distribution in the one-quarter sector combustor was studied. The results of 11 configurations that best illustrate the performance trends obtained with fuel staging are presented in table II.

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Effect of Variations in Axial Fuel Distribution on Combustion Efficiency

It is well known that fuel-injection-nozzle size affects combustion efficiency in a combustor (refs. 9 and 10). Increasing the capacity of fuel nozzles increases drop size and hence decreases the vaporization rate, which can be considered as somewhat of an axial fuel staging effect. Figure 7 compares the results obtained with fuel nozzle capacities of 10.5 gallons per hour and with 3.0 gallons per hour, each without fuel staging. Combustion efficiency is shown as a function of the total fuel-air ratio at several values of air flow. At the lowest air flow (1.5 lb/(sec)(ft^2), fig. 7(a)), the efficiencies obtained with the 10.5-gallon-per-hour nozzles at low fuel-air ratios were lower than the efficiencies obtained with the 3.0-gallon-per-hour nozzles. As the fuel-air ratio was increased, the efficiencies for the 10.5-gallon nozzles also increased and eventually exceeded those for the 3.0-gallon nozzle. These results may indicate that the larger nozzles did not provide a finely atomized spray at low fuel-air ratios; however, the larger nozzle did provide more effective spreading of the fuel in an axial direction at higher fuel-air ratios. This trend indicates the effect of a small amount of axial spreading of the fuel. When the fuel is spread over the primary-zone length by injecting portions of the total fuel at several axial locations, the effect can be expected to be magnified. At air flows of 3.6 pounds per square foot (fig. 7(b)), the 10.5-gallon nozzles produced somewhat higher efficiencies at low fuel-air ratios than the 3.0-gallon nozzles. This is probably due to the finer atomization of the 3.0-gallon nozzles producing an over-rich condition in the primary zone. However, with the 3.0-gallon nozzles, the range of F/A over which operation is possible has been increased over the range of operation obtainable with the 10.5-gallon nozzles. This may possibly be a result of the flame seating in a less stable region of the combustor for the case of the 10.5-gallon nozzles and thus blow-out occurs at fuel-air ratios for which operation with 3.0-gallon nozzles remains stable.

Results obtained with configurations 2 through 7 are presented in figure 8 and are grouped according to air flow through the combustor. Combustion efficiency is shown as a function of fuel-air ratio F/A. Figure 8(a) compares the various configurations for the lowest air flow investigated, 1.5 pounds per second per square foot, which corresponds to a combustor reference velocity (based on inlet density and maximum cross-sectional velocity) of about 56 feet per second for the conditions investigated. No advantages in combustion efficiency were noticed at this air flow with fuel staging as compared with no staging. Figure 8(b) shows that increasing the combustor reference velocity to 80 feet per second also results in no advantages from staging the fuel. It can be seen from figure 8(c) that there is an increase in combustion efficiency

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for all staging configurations over the nonstaging configuration. The air flow for the data presented in figure 8(c) corresponds to a combustor reference velocity of 119 feet per second. The combustor reference velocity of 134 feet per second, shown in figure 8(d), could be considered as about a 50-percent increase over present-day engine requirements at rated speed and 1/2-atmosphere combustor pressure. The efficiencies obtained with both staging configurations 5 and 7 are considerably higher than those obtained with the nonstaging configuration 2. If the staging of configuration 5 were employed at low fuel-air ratios and that of configuration 7 were employed at high fuel-air ratios, the resultant combustion efficiency would remain relatively constant over the range of fuel-air ratios investigated and would be higher than the combustion efficiency obtained with no fuel staging. It is apparent from this series of figures that fuel staging can be an advantage: (1) at relatively high combustor air flows, and (2) the higher the fuel-air ratio, the more the fuel should be spread axially in the primary zone of the combustor at the higher air flows.

Effect of Preheating the Inlet Air on Combustion Efficiency

Preheating the combustor inlet air should result in a condition similar to the effect of less staging of the fuel because of more rapid vaporization of the fuel.

The observed effect of increasing the inlet-air temperature from 80° to 268° F on efficiency was small as compared with the large effects resulting from staging the fuel injection positions (table II).

Effect of Unsymmetrical Fuel Introduction on Combustion Efficiency

Unsymmetrical introduction of the staged fuel did not greatly affect combustion efficiency, as shown in figure 9, except at the higher air flows where peak efficiencies occur when two-thirds of the total fuel is introduced through the outer wall. This appears to be a result of introducing a large portion of the fuel in a region where there are sufficient air, volume, and time for higher efficiencies.

Effect of Unsymmetrical Fuel Introduction on Temperature Distribution

Combustor-exhaust-gas radial temperature distributions are presented in figure 10 for several air flow values for the conditions of symmetrical and unsymmetrical introduction of the staged fuel in the primary zone of the combustor. The average temperature at combustor outlet is plotted for five radial stations at the combustor outlet section. Each data point is the average of four circumferential temperature readings at each radial distance from the inner-wall surface of the combustor-outlet section.

A desired combustor-outlet radial temperature profile was considered to be that shown by the dashed curve; this temperature profile represents an approximate average of those required in various turbojet engines. Configuration 6 (fig. 10(a)) presents an example of the radial temperature distribution with symmetrical staging of the fuel in the primary zone. In this case, one-sixth of the total fuel flow is introduced through each of the four fuel manifolds, and therefore the quantity of staged fuel between the inner and outer walls is equally divided. 2774

Results obtained with configurations 9 and 11, shown in figures 10(b) and 10(c), represent the effects of unsymmetrical fuel introduction on temperature distribution. For configuration 9 (fig. 10(b)), the staged fuel was introduced only through the outer-wall manifolds 2 and 3; for configuration 11 (fig. 10(c)), the staged fuel was introduced only through inner-wall manifolds 4 and 5. The temperature distributions obtained with configurations 6, 9, and 11 are compared at approximately the same fuel-air ratio.

The over-all effect on radial temperature distribution of variation of fuel introduction from the inner to the outer wall of the primary zone is shown (fig. 10) to be relatively small when wide variations in the fuel introduction and the air flow investigated are considered.

Pressure Drop

The ratio of the combustor total-pressure loss ΔP_T to the calculated reference dynamic pressure q_r is plotted as a function of the inlet to outlet gas density ratio ρ_1/ρ_2 in figure 11. The values of $\Delta P_T/q_r$ cited herein are about 2 to 3 times larger than those obtained on most contemporary engines.

SUMMARY OF RESULTS

The following results were obtained from an investigation to determine the effect of varying the distribution of fuel along the length of the primary zone of the combustor on the performance of a one-quarter sector of a single-annulus turbojet combustor:

1. Axial fuel staging had little effect on the performance of the one-quarter-sector combustor when the combustor was required to handle no more than the amount of air passing through a typical 5.2 compressor-ratio engine designed for an air flow 25 pounds per second per square foot of compressor frontal area.

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2. Axial fuel staging was most effective in improving combustion efficiencies at air-flow rates as much as 70 percent higher than values typical of current design practice. At higher fuel-air ratios, the most improvement was obtained by spreading the fuel introduction over a greater length of the primary zone.

3. The effect of unsymmetrical introduction of the staged fuel on exhaust radial temperature distribution was not large, thus indicating that final control of the temperature distribution should come from air-introduction changes on the walls of the combustor rather than fuel-introduction changes.

CONCLUDING REMARKS

The results of this brief research study indicate that there may not be too much advantage in fuel staging for the turbine engine designed to operate at turbine-inlet temperatures up to 1500° F and compressor-air loading capacities below 25 pounds per square foot of compressor frontal area. However, for engines designed for applications requiring higher compressor-air loading capacities and higher turbine-inlet temperatures, fuel staging may hold possibilities for improving combustor performance.

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TABLE I. - FRACTION OF TOTAL FUEL FLOW

INTRODUCED PER MANIFOLD

Configuration number	Fuel Manifold Number[a]				
	1	2	3	4	5
1	1[b]				
2	1[c]				
3	2/3[c]	1/6		1/6	
4	2/3[c]		1/6		1/6
5	1/3[c]	1/3		1/3	
6	1/3[c]	1/6	1/6	1/6	1/6
7	1/3[c]		1/3		1/3
8	2/3[c]	1/6	1/6		
9	1/3[c]	1/3	1/3		
10	2/3[c]			1/6	1/6
11	1/3[c]			1/3	1/3

[a]Refer to fig. 5 for manifold locations.
[b]Fuel nozzle capacity, 10.5 gal/hr.
[c]Fuel nozzle capacity, 3.0 gal/hr.

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TABLE II. - PERFORMANCE DATA OBTAINED WITH AXIAL FUEL STAGING ON ONE-QUARTER SECTOR OF ANNULAR TURBOJET COMBUSTOR

Configuration	Run	Air flow, w_a, lb/sec-ft^2	Inlet pressure, P_1, in. Hg abs	Inlet temperature, T_1, °F	Outlet temperature, T_2, °F	T_1-T_2, °F	Fuel-air ratio, F/A	Combustion efficiency, η_b	$\frac{P_{T_2}-P_{T_1}}{q_r}$ (a)	Gas density ratio, ρ_1/ρ_2	Figure
1	1	1.5	14.92	85	1054	969	0.0186	0.747	50.3	2.873	7(a), 11
1	2	1.5	14.92	85	1282	1197	.0214	.816	55.02	3.275	7(a), 11
1	3	1.5	14.92	85	1432	1347	.0234	.851	53.8	3.663	7(a), 11
1	4	1.5	14.92	85	1537	1452	.0255	.850	52.0	3.725	7(a), 11
1	5	3.2	15.0	77	836	759	.0135	.777	40.28	3.035	11
1	6	2.78	15.0	78	925	847	.0131	.890	38.5	3.89	11
1	7	2.78	15.0	78	1059	981	.0170	.818	41.18	3.25	11
1	8	2.78	15.0	78	1222	1144	.0214	.777	43.7	3.67	11
1	9	2.14	15.0	83	1022	939	.01575	.841	50.2	2.95	11
1	10	2.14	15.0	83	1182	1099	.0187	.850	54.1	3.63	11
1	11	2.14	15.0	83	1307	1224	.0234	.771	51.6	3.6	11
1	12	2.14	15.0	83	1514	1431	.0282	.770	54.07	4.115	11
1	13	1.4	8.0	80	773	693	.019	.52	45.19	2.617	11
1	14	1.4	8.0	80	875	795	.0223	.52	52.0	2.841	11
1	15	1.142	8.0	80	1014	934	.0204	.662	48.46	3.11	11
1	16	1.142	8.0	80	1130	1050	.0236	.652	48.19	3.268	11
1	17	1.142	8.0	80	1268	1188	.0281	.637	47.99	3.561	11
1	18	1.5	15.0	270	1188	918	.0155	.85	44.66	2.715	11
1	19	1.5	15.0	267	1313	1046	.01765	.865	40.72	2.585	11
1	20	1.5	15.0	262	1389	1127	.0196	.848	48.01	2.728	11
1	21	1.5	15.0	269	1518	1249	.0213	.88	41.65	2.901	11
1	22	2.78	15.0	270	1081	811	.0135	.853	42.99	2.652	11
1	23	2.78	15.0	270	1158	888	.0150	.848	42.85	2.538	11
1	24	2.78	15.0	271	1247	976	.0164	.866	43.46	2.854	11
[b]1	25	1.5	15.0	80	80	----	-------	-----	36.57	1.018	11
[b]1	26	2.14	15.0	80	80	----	-------	-----	36.3	1.055	11
[b]1	27	2.78	15.0	80	80	----	-------	-----	32.1	1.091	11
[b]1	28	3.2	15.0	80	80	----	-------	-----	32.8	1.145	11
[b]1	29	3.6	15.0	80	80	----	-------	-----	36.5	1.203	11
1	30	3.6	15.0	77	630	553	.0116	.65	----	-----	7(b)
1	31	3.6	15.0	77	630	553	.0149	.52	----	-----	7(b)
2	32	1.494	14.95	92	920	828	.01426	.803	----	-----	7(a), 8(a)
2	33	1.5	14.95	92	990	898	.0155	.815	----	-----	7(a), 8(a)
2	34	1.5	14.95	92	1130	1038	.0175	.843	----	-----	7(a), 8(a)
2	35	1.5	14.95	92	1205	1113	.0195	.821	----	-----	7(a), 8(a)
2	36	1.5	14.95	92	1270	1178	.0210	.814	----	-----	7(a), 8(a)
2	37	1.5	14.95	92	1385	1293	.0241	.792	----	-----	7(a), 8(a)
2	38	1.5	14.95	92	1457	1365	.0254	.800	----	-----	7(a), 8(a)
2	39	2.14	15.01	82	886	804	.0135	.826	----	-----	8(b)
2	40	2.14	15.06	82	978	896	.0151	.834	----	-----	8(b)
2	41	2.14	15.06	86	1077	991	.0176	.802	----	-----	8(b)
2	42	2.14	15.06	86	1169	1083	.0189	.82	----	-----	8(b)
2	43	2.14	15.06	86	1248	1162	.0204	.88	----	-----	8(b)
2	44	2.14	15.06	86	1356	1270	.0230	.809	----	-----	8(b)
2	45	2.14	15.06	86	1408	1322	.0249	.786	----	-----	8(b)
2	46	3.20	15.01	82	780	698	.01285	.751	----	-----	8(c)
2	47	3.20	15.01	82	844	762	.0155	.691	----	-----	8(c)
2	48	3.20	15.01	84	871	787	.0169	.661	----	-----	8(c)
2	49	3.21	14.96	87	974	887	.0192	.668	----	-----	8(c)
2	50	3.21	14.96	87	1031	944	.0208	.66	----	-----	8(c)
2	51	3.21	14.96	87	1103	1016	.0224	.665	----	-----	8(c)
2	52	3.21	14.96	87	1233	1146	.0250	.681	----	-----	8(c)
2	53	3.6	14.96	82	676	594	.022	.412	----	-----	7(b), 8(d)
2	54	3.6	15.01	82	708	626	.0232	.396	----	-----	7(b), 8(d)
2	55	3.6	15.01	82	571	489	.0201	.352	----	-----	7(b), 8(d)
2	56	3.6	14.96	82	574	492	.01715	.406	----	-----	7(b), 8(d)
2	57	3.6	15.1	82	632	550	.01395	.55	----	-----	7(b), 8(d)
2	58	3.6	14.96	82	579	497	.01225	.558	----	-----	7(b), 8(d)
3	59	1.5	14.97	95	1220	1125	.0211	.775	----	-----	8(a)
3	60	1.5	14.97	95	1485	1390	.0254	.817	----	-----	8(a)
3	61	2.14	15.0	92	1175	1083	.01945	.804	----	-----	8(b)
3	62	2.14	15.02	92	1245	1153	.0216	.78	----	-----	8(b)
3	63	2.14	15.02	92	1300	1208	.023	.772	----	-----	8(b)
3	64	2.14	14.97	92	1380	1288	.0250	.762	----	-----	8(b)
3	65	2.14	15.0	92	1460	1368	.0270	.757	----	-----	8(b)
3	66	3.17	15.06	98	1010	912	.0168	.762	----	-----	8(c)
3	67	3.17	14.94	97	1050	953	.0195	.702	----	-----	8(c)
3	68	3.17	14.94	97	1150	1053	.0220	.70	----	-----	8(c)
3	69	3.17	15.01	97	1250	1153	.0246	.694	----	-----	8(c)
3	70	3.17	15.01	97	1310	1213	.0271	.670	----	-----	8(c)
3	71	3.17	15.06	98	1300	1202	.0294	.630	----	-----	8(c)
3	72	3.17	15.06	98	1270	1172	.0306	.588	----	-----	8(c)
3	73	3.60	14.96	99	760	661	.0163	.57	----	-----	8(d)
3	74	3.60	14.96	98	770	672	.0184	.52	----	-----	8(d)
3	75	3.60	14.96	98	840	742	.0206	.52	----	-----	8(d)
3	76	3.60	14.96	98	900	802	.0227	.519	----	-----	8(d)

[a]Total-pressure loss function.

[b]This data from a similar combustor, in a similar setup.

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TABLE II. - Concluded. PERFORMANCE DATA OBTAINED WITH AXIAL FUEL STAGING IN ONE-QUARTER SECTOR OF ANNULAR TURBOJET COMBUSTOR

Configuration	Run	Air flow, w_a, lb/sec-ft^2	Inlet pressure, P_1, in. Hg abs	Inlet temperature, T_1, °F	Outlet temperature, T_2, °F	T_1-T_2, °F	Fuel-air ratio, F/A	Combustion efficiency, η_b	$\frac{P_{T_2}-P_{T_1}}{q_r}$ (a)	Gas density ratio, ρ_1/ρ_2	Figure
4	77	1.52	14.98	90	1130	1140	0.0193	0.847	-----	-----	8(a)
4	78	1.507	14.98	91	1460	1369	.0253	.802	-----	-----	8(a)
4	79	2.14	14.98	92	1150	1058	.0191	.796	-----	-----	8(b)
4	80	2.14	14.98	92	1250	1158	.0208	.803	-----	-----	8(b)
4	81	2.14	14.98	92	1310	1218	.0225	.796	-----	-----	8(b)
4	82	2.14	14.98	93	1375	1282	.0244	.778	-----	-----	8(b)
4	83	2.14	14.98	93	1460	1367	.0268	.763	-----	-----	8(b)
4	84	3.24	15.01	89	940	851	.0161	.747	-----	-----	8(c)
4	85	3.23	15.01	89	985	896	.01765	.723	-----	-----	8(c)
4	86	3.23	15.01	90	1100	1010	.0204	.715	-----	-----	8(c)
4	87	3.20	15.01	90	1175	1085	.0232	.690	-----	-----	8(c)
4	88	3.20	15.01	90	1260	1170	.0253	.685	-----	-----	8(c)
4	89	3.20	15.01	91	1310	1219	.0278	.66	-----	-----	8(c)
4	90	3.20	15.01	92	1375	1283	.0297	.66	-----	-----	8(c)
4	91	3.60	15.01	92	850	758	.0180	.602	-----	-----	8(d)
5	92	1.5	15.00	94	1450	1356	.0240	.835	-----	-----	8(a)
5	93	1.5	15.00	94	1550	1456	.0266	.820	-----	-----	8(a)
5	94	1.5	14.90	94	1280	1186	.0212	.820	-----	-----	8(a)
5	95	1.5	14.90	94	1060	966	.0189	.728	-----	-----	8(a)
5	96	2.15	15.0	96	1180	1084	.0184	.84	-----	-----	8(b)
5	97	2.15	15.0	96	1275	1179	.020	.853	-----	-----	8(b)
5	98	2.15	15.0	96	1350	1254	.0216	.848	-----	-----	8(b)
5	99	2.15	15.0	96	1495	1399	.0237	.868	-----	-----	8(b)
5	100	3.2	15.0	92	1015	923	.0159	.814	-----	-----	8(c)
5	101	3.2	15.02	90	1160	1070	.0183	.831	-----	-----	8(c)
5	102	3.2	15.02	92	1240	1148	.0206	.811	-----	-----	8(c)
5	103	3.2	15.02	92	1270	1178	.0232	.749	-----	-----	8(c)
5	104	3.2	15.02	92	1200	1108	.02495	.655	-----	-----	8(c)
5	105	3.6	15.07	92	955	863	.0163	.74	-----	-----	8(d)
5	106	3.6	15.00	92	1020	928	.0184	.72	-----	-----	8(d)
5	107	3.6	15.00	92	840	748	.0206	.528	-----	-----	8(d)
6	108	1.535	15.12	90	995	905	.0198	.66	-----	-----	8(a)
6	109	1.506	15.02	90	1301	1211	.0232	.767	-----	-----	8(a)
6	110	1.506	15.0	90	1668	1578	.0283	.841	-----	-----	8(a)
6	111	2.15	14.94	90	779	689	.0161	.604	-----	-----	8(b)
6	112	2.15	14.94	90	1079	989	.0204	.701	-----	-----	8(b)
6	113	2.15	14.94	90	1342	1252	.0234	.787	-----	-----	8(b)
6	114	2.15	14.94	90	1456	1366	.0255	.796	-----	-----	8(b)
6	115	3.2	14.99	89	763	674	.01472	.641	-----	-----	8(c)
6	116	3.2	14.99	89	963	874	.0174	.712	-----	-----	8(c)
6	117	5.2	14.99	89	1112	1023	.0201	.737	-----	-----	8(c)
6	118	3.2	14.99	89	1299	1210	.0237	.752	-----	-----	8(c)
6	119	3.2	15.07	88	1354	1266	.0256	.737	-----	-----	8(c)
6	120	3.59	15.07	89	838	749	.01665	.637	-----	-----	8(d)
6	121	3.59	15.07	89	1150	1061	.01945	.788	-----	-----	8(d)
7	122	1.5	14.99	86	1200	1114	.0227	.722	-----	-----	8(a)
7	123	1.5	14.99	86	1350	1264	.0252	.747	-----	-----	8(a)
7	124	1.5	14.99	86	1540	1454	.0273	.797	-----	-----	8(a)
7	125	2.14	14.99	86	900	814	.0176	.662	-----	-----	8(b)
7	126	2.14	14.99	86	1125	1039	.0207	.728	-----	-----	8(b)
7	127	2.14	14.99	86	1380	1294	.0241	.793	-----	-----	8(b)
7	128	2.14	14.94	86	1500	1414	.0260	.807	-----	-----	8(b)
7	129	3.2	14.93	82	780	698	.0166	.63	-----	-----	8(c)
7	130	3.2	14.98	82	980	898	.0172	.742	-----	-----	8(c)
7	131	3.2	14.99	86	1130	1044	.0197	.763	-----	-----	8(c)
7	132	3.2	14.99	86	1275	1189	.0222	.781	-----	-----	8(c)
7	133	3.2	14.99	86	1365	1279	.0246	.772	-----	-----	8(c)
7	134	3.2	14.99	86	1480	1394	.0268	.78	-----	-----	8(c)
7	135	3.6	14.98	82	830	748	.01672	.641	-----	-----	8(d)
7	136	3.6	14.98	82	1030	948	.020	.682	-----	-----	8(d)
7	137	3.6	14.98	82	1150	1068	.0222	.703	-----	-----	8(d)
7	138	3.6	14.98	82	1200	1118	.0243	.682	-----	-----	8(d)
8	139	1.5	14.96	77	1410	1333	.0248	.796	-----	-----	9
8	140	2.14	14.94	78	1410	1332	.0244	.810	-----	-----	9
8	141	2.78	14.99	77	1327	1250	.0233	.79	-----	-----	9
8	142	3.2	14.98	81	1121	1040	.0228	.67	-----	-----	9
9	143	1.5	14.99	80	1425	1345	.02577	.775	-----	-----	9
9	144	2.14	14.99	78	1425	1347	.02417	.822	-----	-----	9
9	145	2.78	15.02	85	1380	1295	.0214	.88	-----	-----	9
9	146	3.2	15.0	88	1450	1362	.0262	.78	-----	-----	9
10	147	3.2	15.02	83	1210	1127	.0277	.62	-----	-----	9
10	148	2.78	15.02	83	1350	1267	.0255	.74	-----	-----	9
10	149	2.14	15.02	83	1350	1267	.0243	.766	-----	-----	9
10	150	1.5	15.02	83	1500	1417	.0250	.842	-----	-----	9
11	151	3.2	14.97	85	1300	1215	.0275	.652	-----	-----	9
11	152	2.78	14.99	86	1180	1094	.02176	.734	-----	-----	9
11	153	2.14	14.99	86	1480	1394	.02786	.753	-----	-----	9
11	154	1.5	14.99	86	1480	1394	.02655	.787	-----	-----	9

[a]Total-pressure loss function.

[b]This data from a similar combustor, in a similar setup.

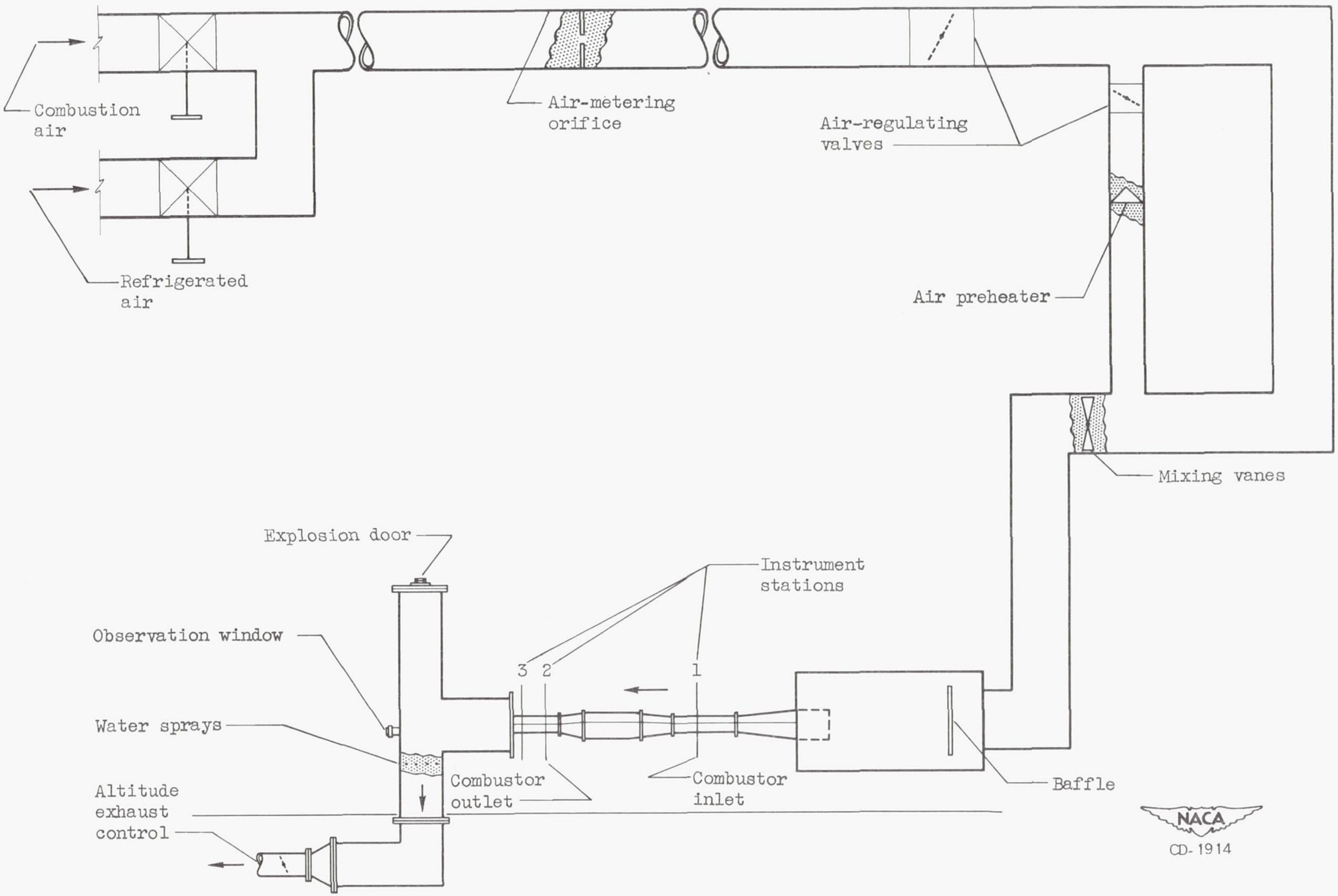

Figure 1. - Arrangement of one-quarter sector of 25 1/2-inch-diameter annular-combustor setup.

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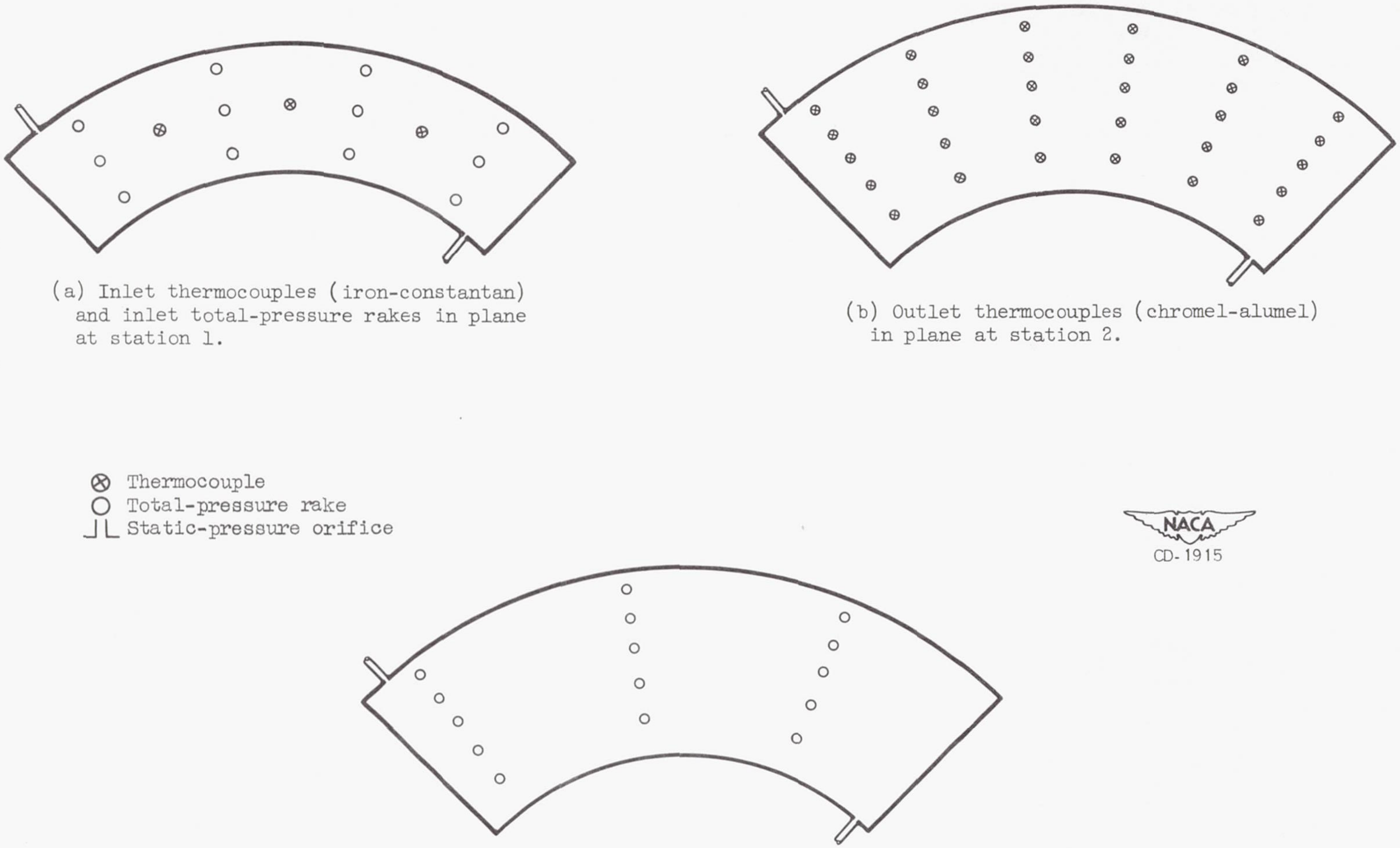

(a) Inlet thermocouples (iron-constantan) and inlet total-pressure rakes in plane at station 1.

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

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

Figure 2. - Instrumentation.

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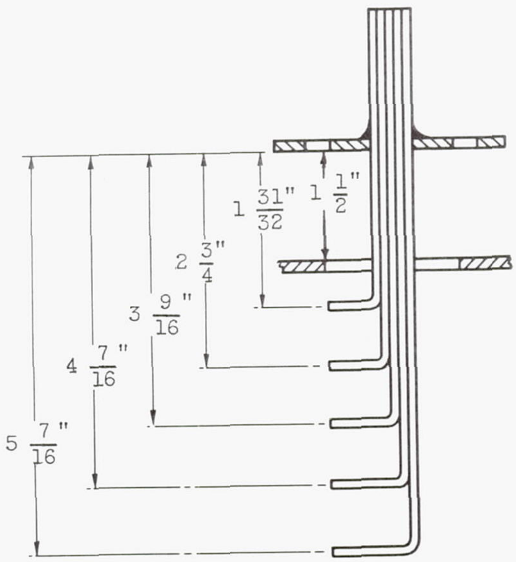
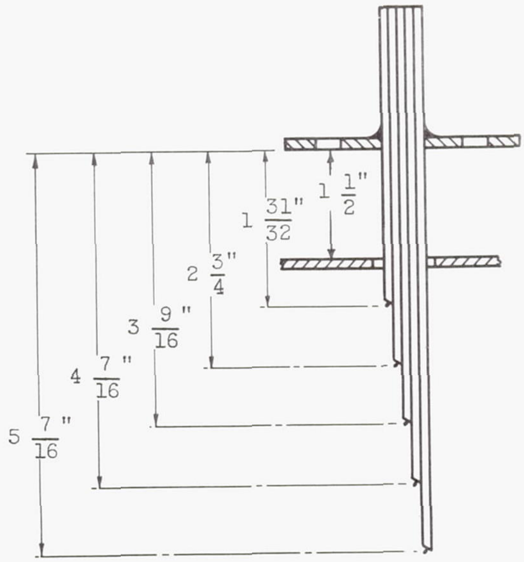
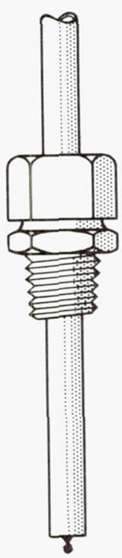


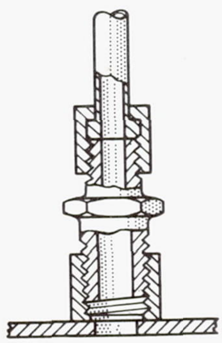
(a) Outlet total-pressure rake.



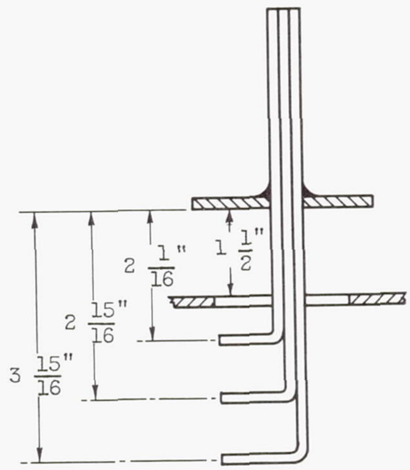
(b) Outlet thermocouple rake.



(c) Inlet thermocouple.



(d) Static-pressure orifice.



(e) Inlet total-pressure rake.

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Figure 3. - Details of instrumentation.

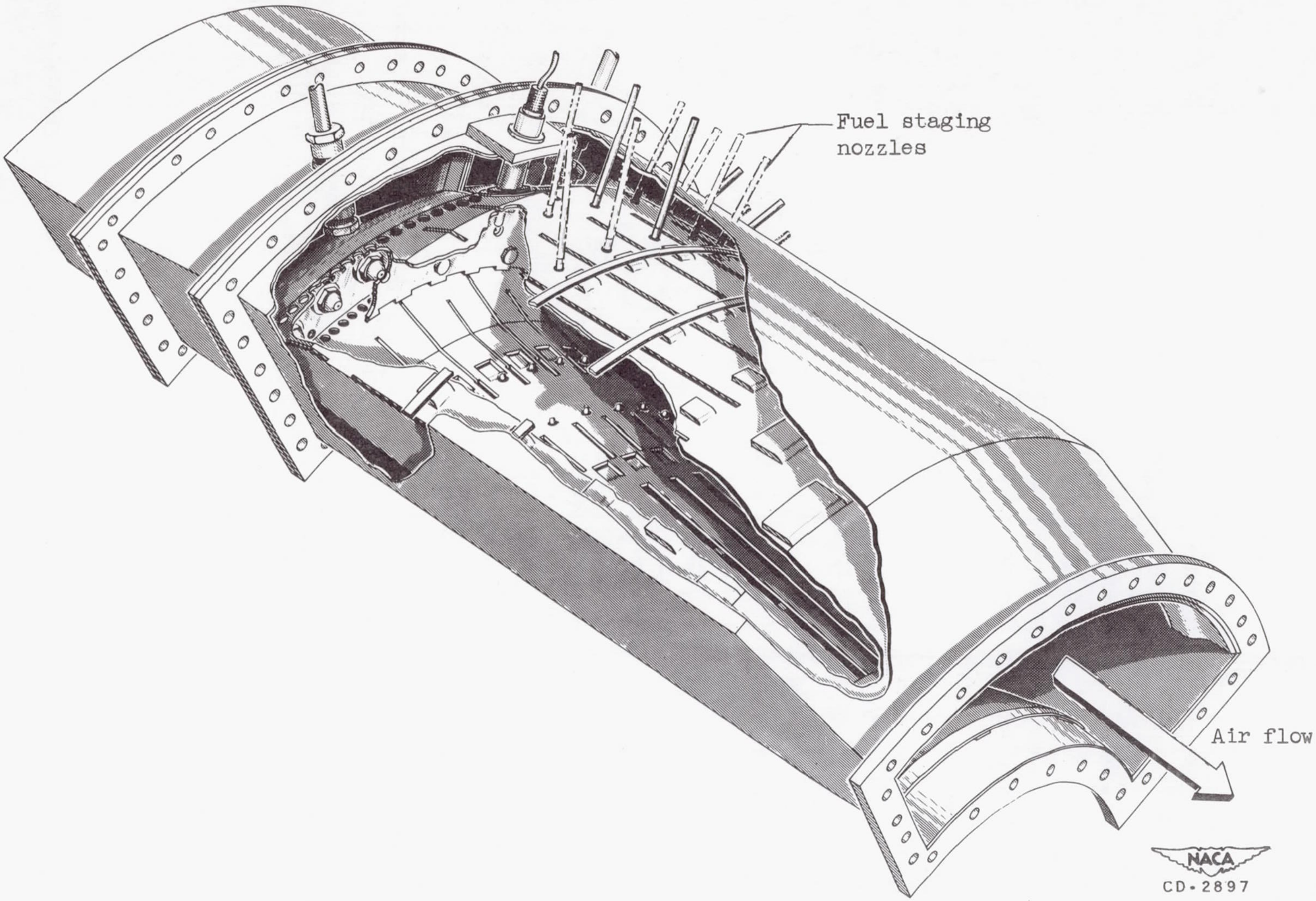

Figure 4. - Cutaway of one-quarter annulus combustor assembled in outer housing showing provisions for injecting staged fuel.

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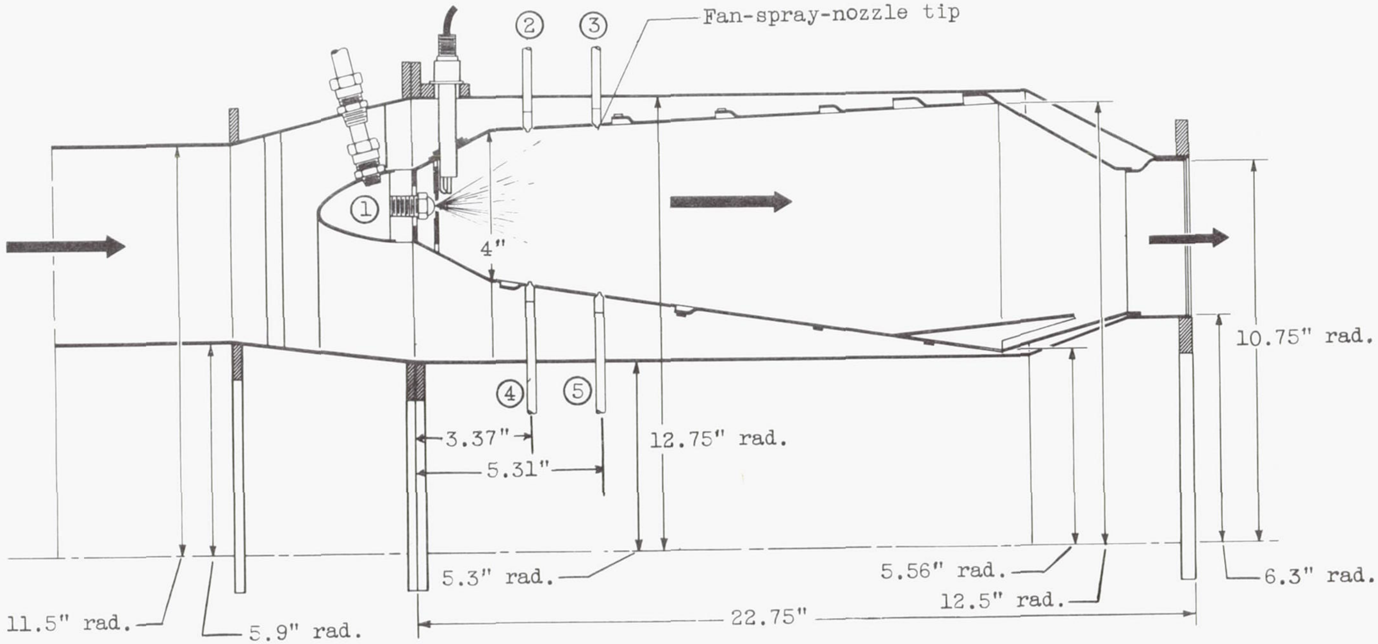

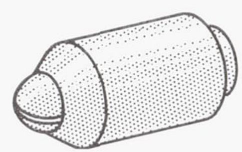

Fan-spray-nozzle tip

Figure 5. - Longitudinal cross section of combustor assembly showing detail of fan spray nozzle. (All dimensions are in inches.)

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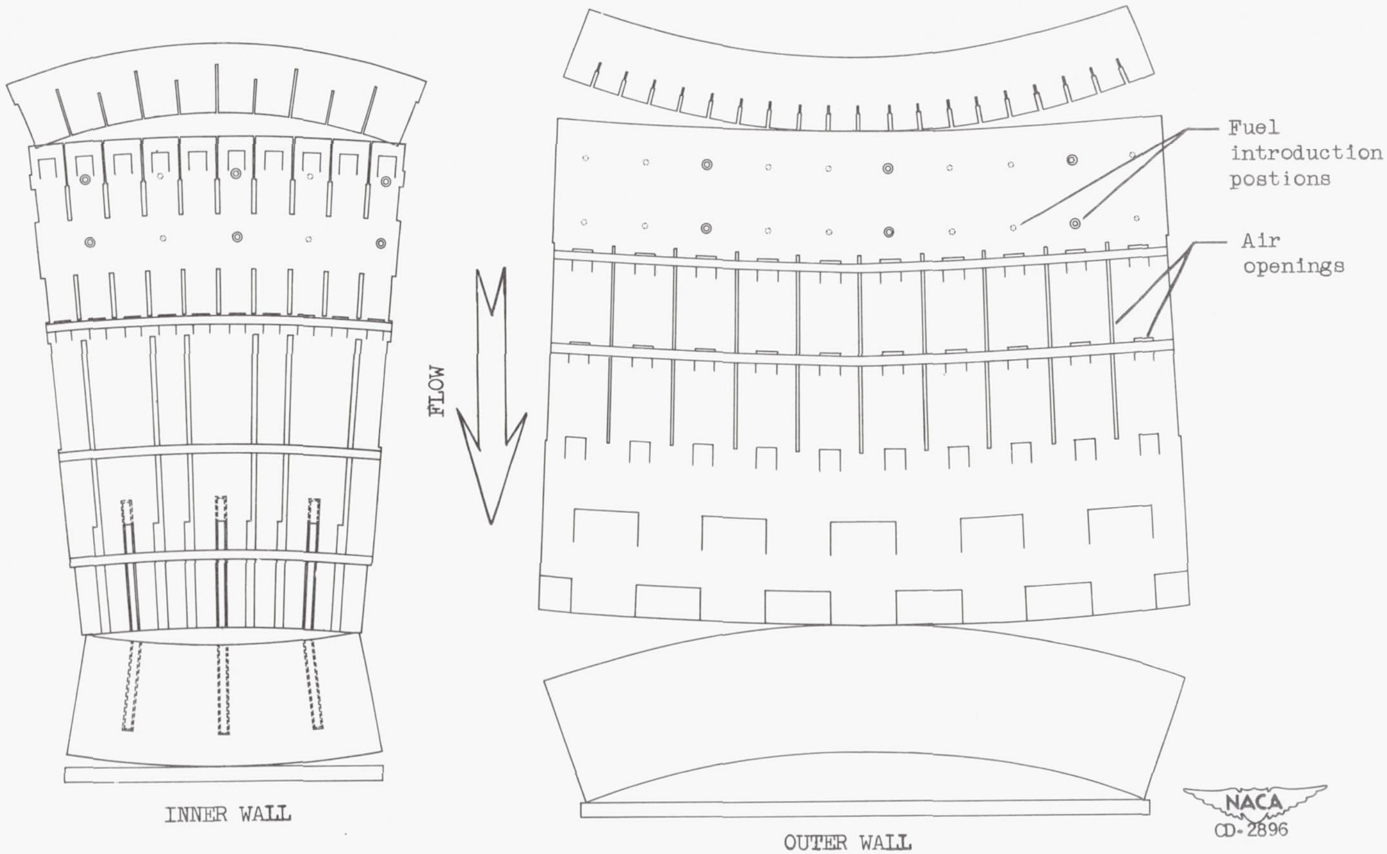

Figure 6. - Development of inner and outer walls of combustor liner showing geometry of air openings and location of fuel-injection positions. Circumferential fuel-injection positions for which results are presented are indicated by double circles.

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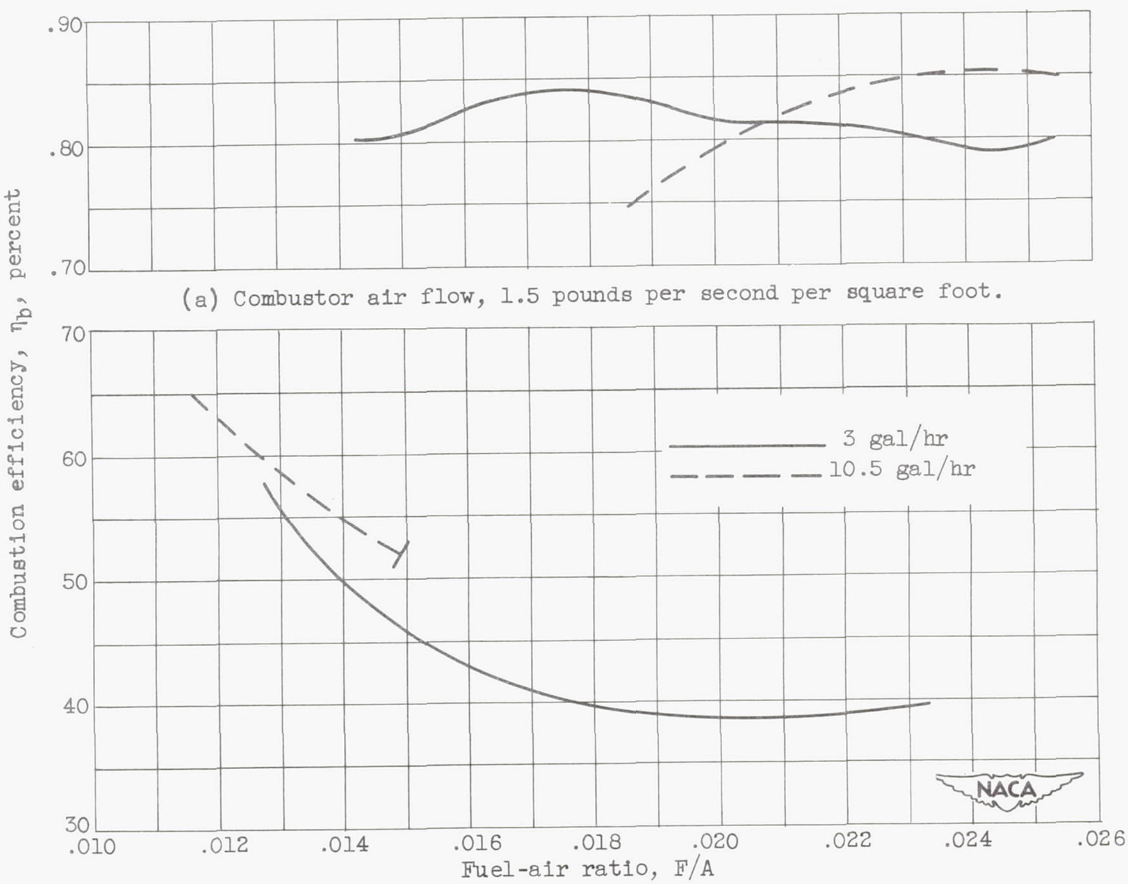

(a) Combustor air flow, 1.5 pounds per second per square foot.

(b) Combustor air flow, 3.6 pounds per second per square foot.

Figure 7. - Variation of combustion efficiency with fuel-air ratio for two fuel-injection nozzle sizes. Combustor-inlet pressure, 15 inches of mercury absolute; inlet temperature, 80° F.

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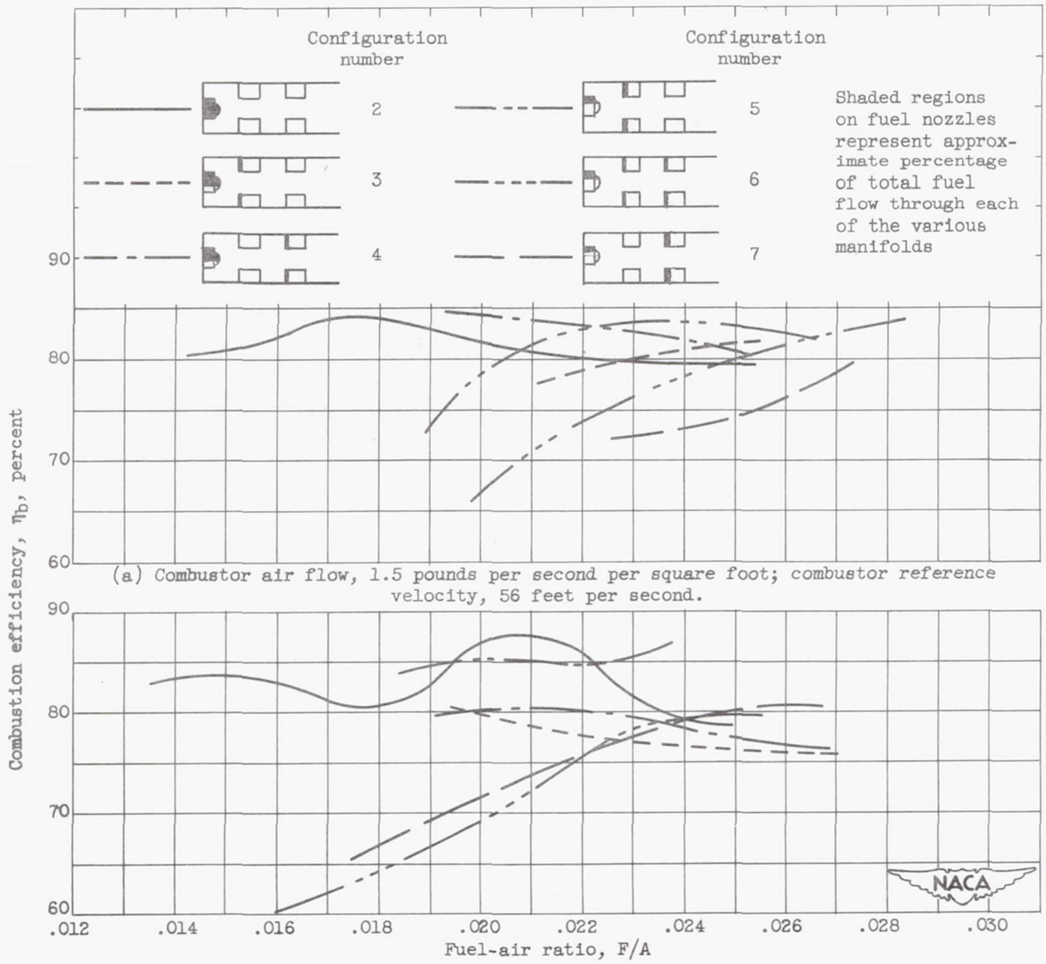

(b) Combustor air flow, 2.14 pounds per second per square foot; combustor reference velocity, 80 feet per second.

Figure 8. - Variation of combustion efficiency with fuel loading for various fuel-injection configurations. Combustor-inlet pressure, 15 inches mercury absolute; inlet temperature, 80° F. All configurations are represented for 3.0-gallon fuel nozzles in number one manifold (see fig. 5).

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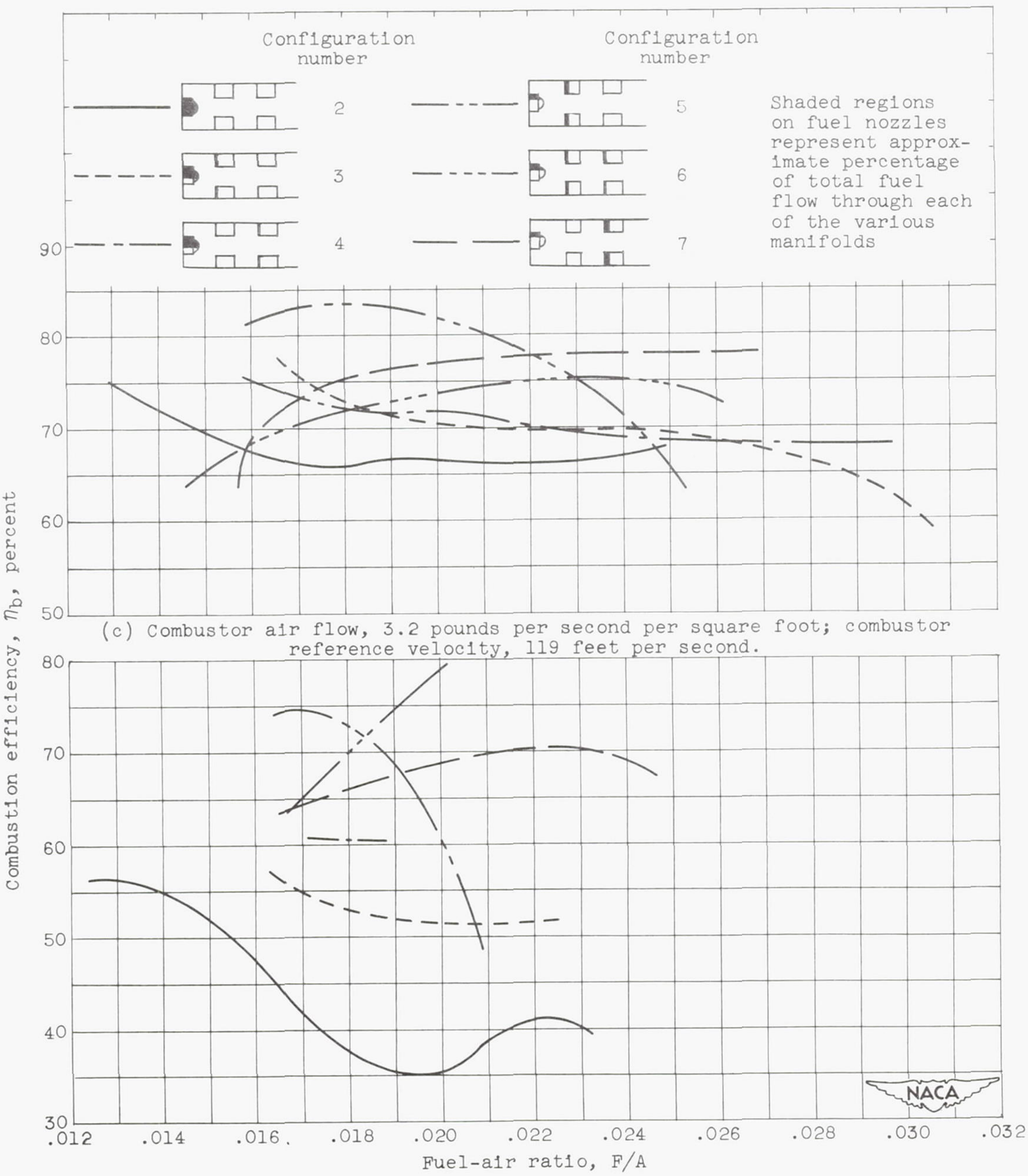

(c) Combustor air flow, 3.2 pounds per second per square foot; combustor reference velocity, 119 feet per second.

(d) Combustor air flow, 3.6 pounds per second per square foot; combustor reference velocity, 134 feet per second.

Figure 8. - Concluded. Variation of combustion efficiency with fuel loading for various fuel-injection configurations. Combustor-inlet pressure, 15 inches mercury absolute; inlet temperature, 80° F. All configurations are represented for 3.0-gallon fuel nozzles in number one manifold (see fig. 5).

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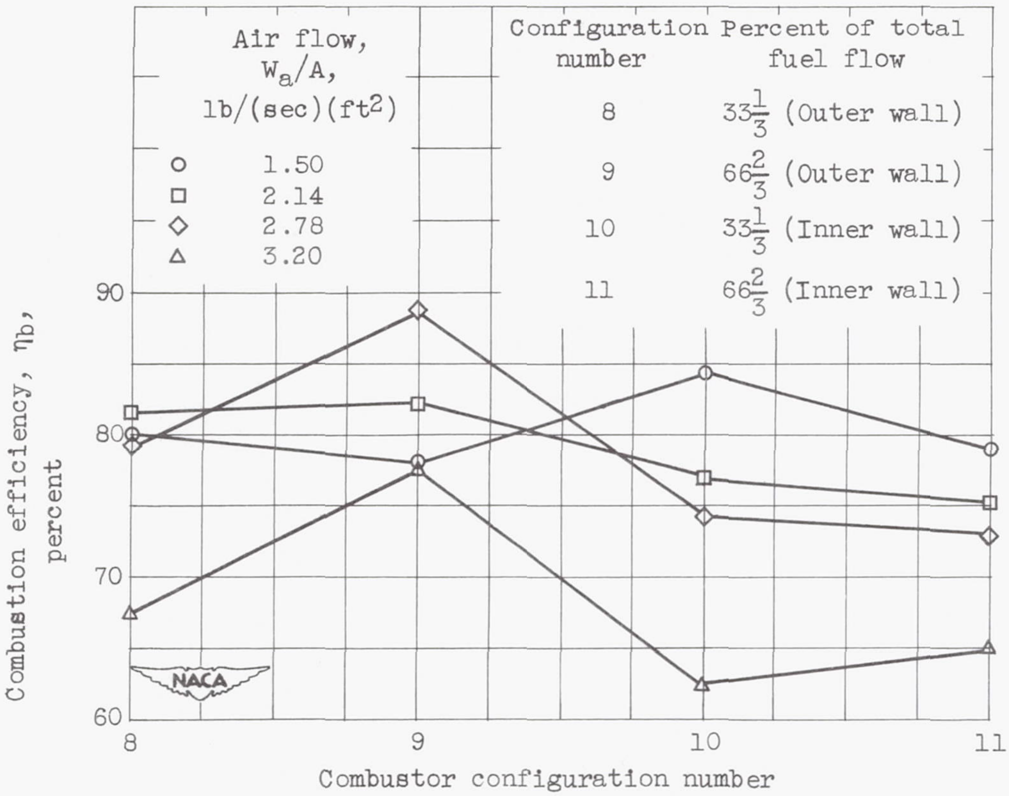

Figure 9. - Variation in combustion efficiency for unsymmetrical fuel introduction for various air flows. Combustor-inlet pressure, 15 inches mercury absolute; inlet temperature, 540° R.

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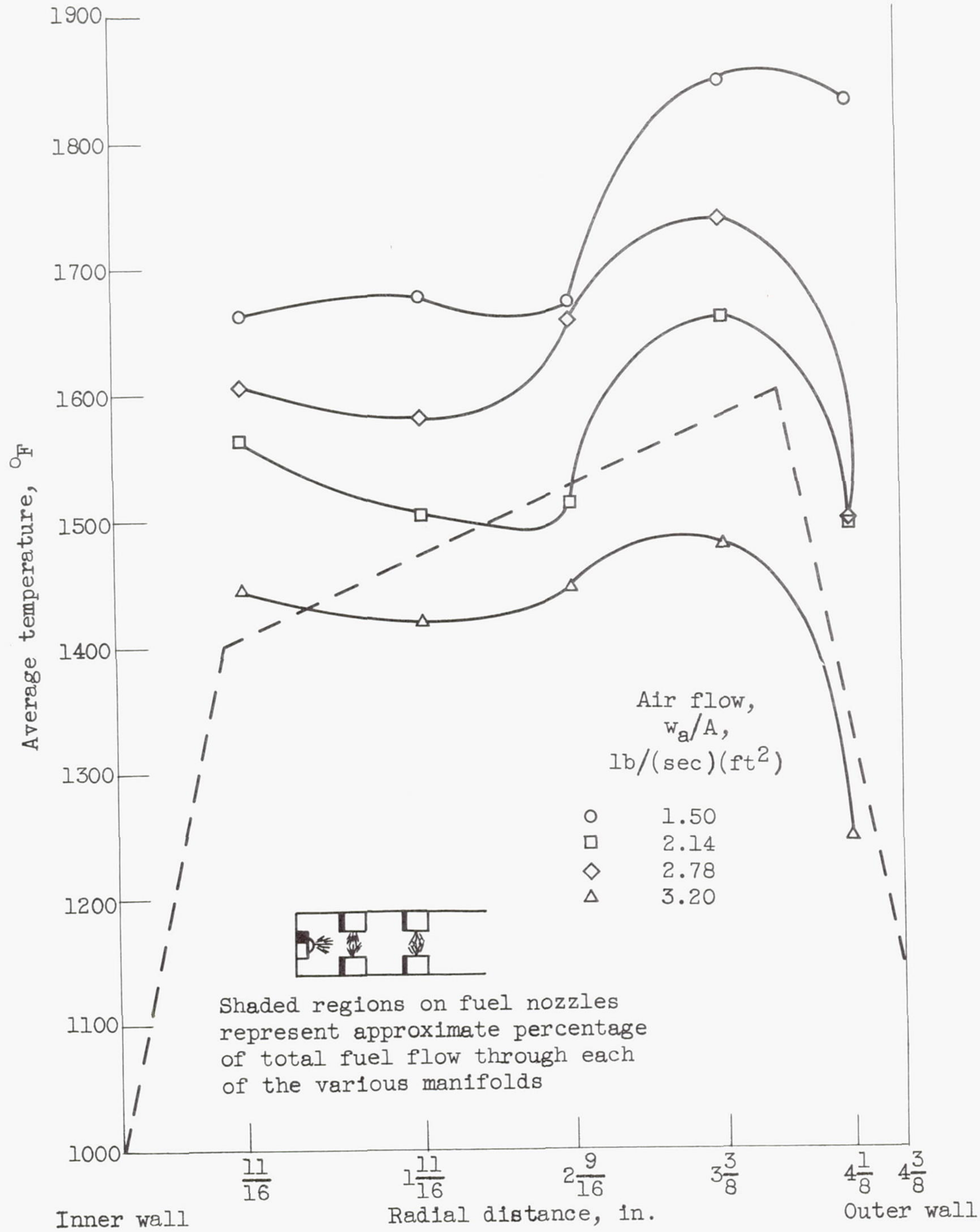
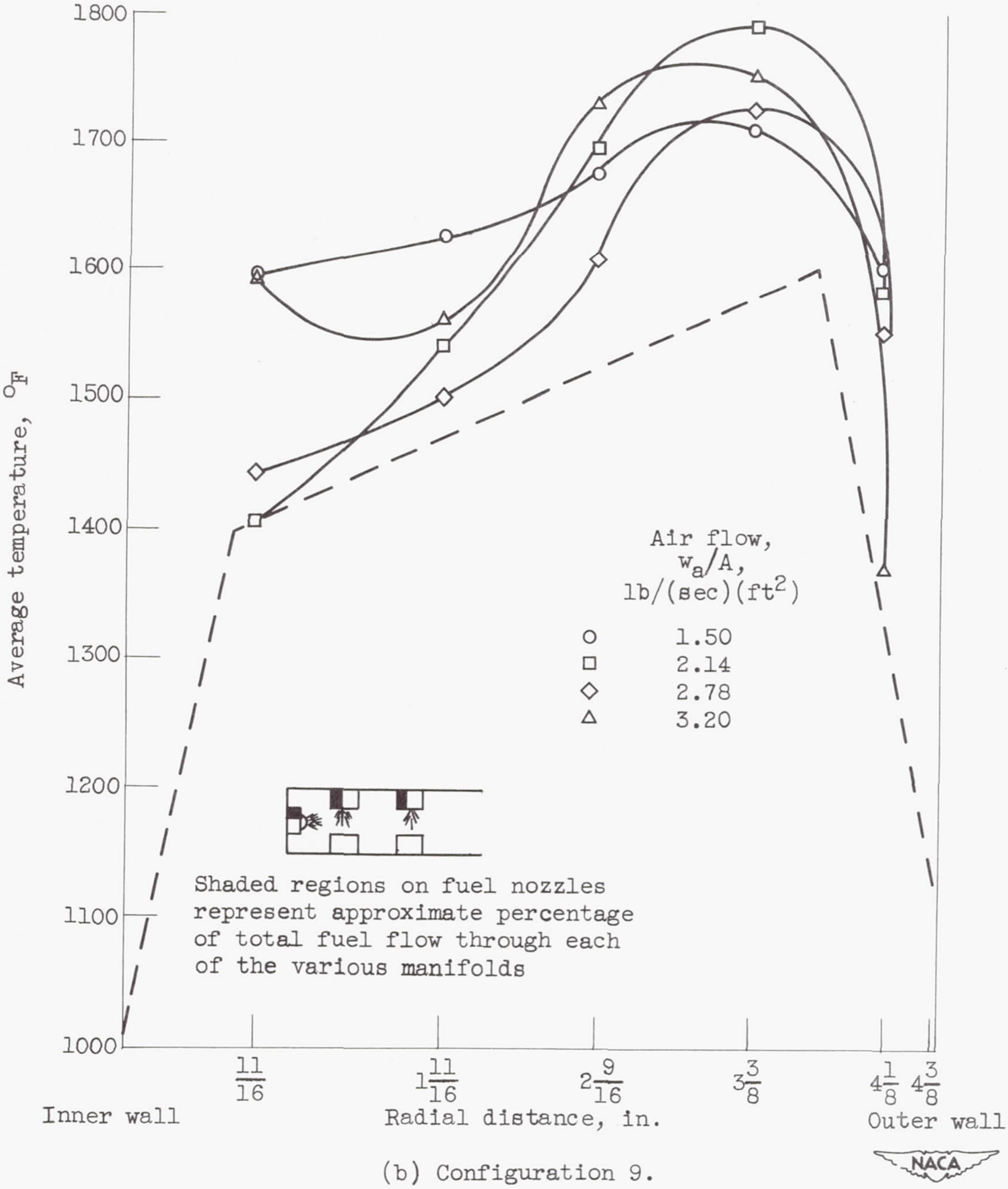


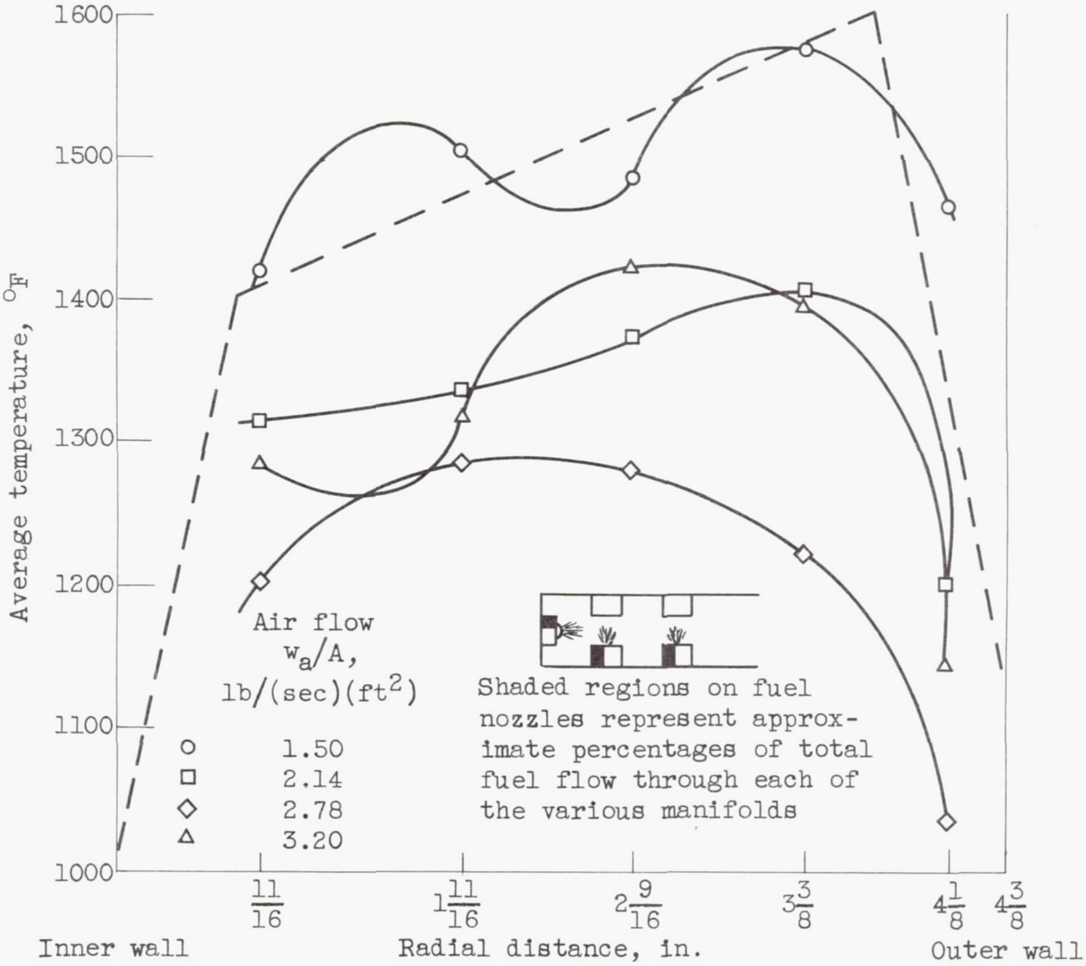
(a) Configuration 6.

Figure 10. - Radial temperature distribution of exhaust gas for various air flows. Fuel-air ratio, 0.0235 to 0.0275 (average of 4 rakes). Dashed curve represents approximate desired profile.



(b) Configuration 9.

Figure 10. - Continued. Radial temperature distribution of exhaust gas for various air flows. Fuel-air ratio, 0.0235 to 0.0275 (average of 4 rakes). Dashed curve represents approximate desired profile.



(c) Configuration 11.

Figure 10. - Concluded. Radial temperature distribution of exhaust gas for various air flows. Fuel-air ratio, 0.0235 to 0.0275 (average of 4 rakes). Dashed curve represents approximate desired profile.

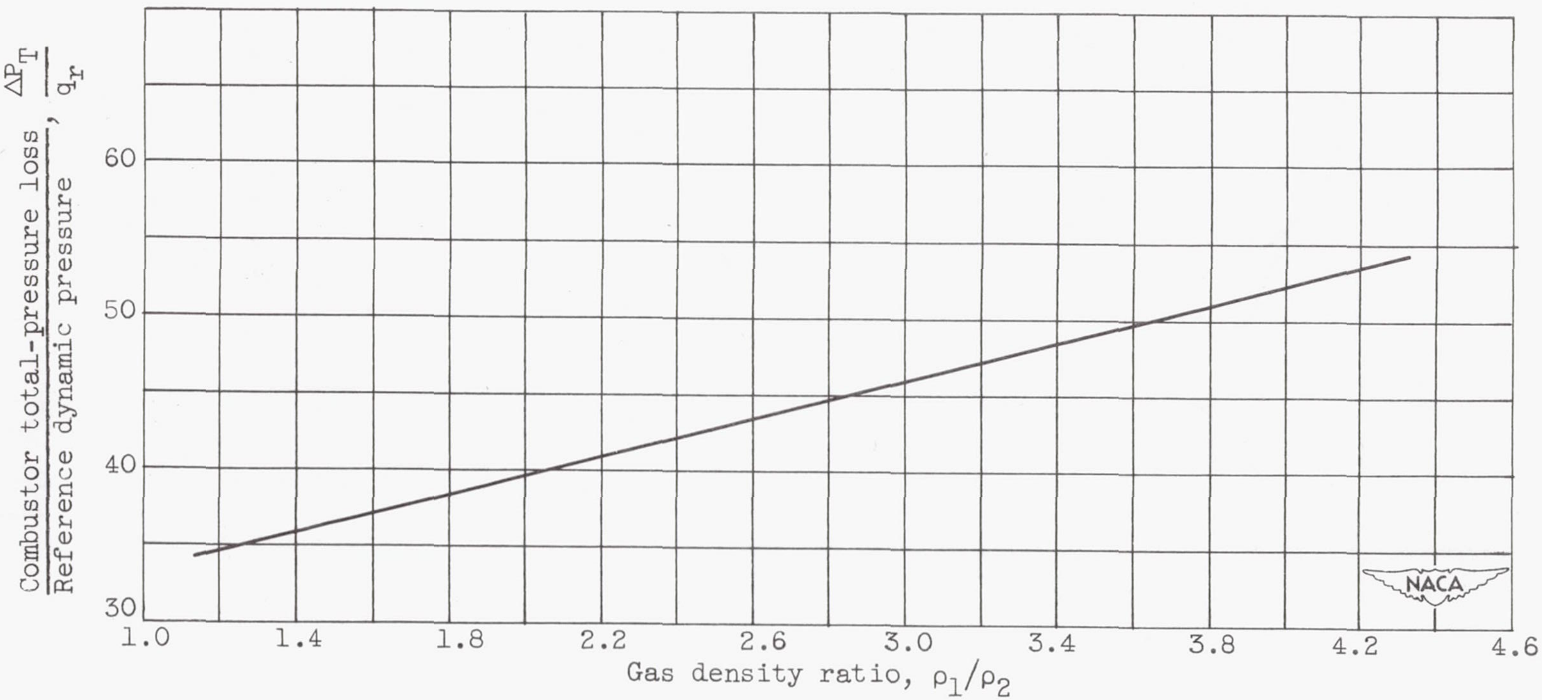


Figure 11. - Total-pressure loss through combustor segment as a function of gas density ratio.

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