NASA TECHNICAL NOTE

NASA TN D-5688

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NASA TN D-5688

PRELIMINARY TESTS OF A SIMPLIFIED MODULAR TURBOJET COMBUSTOR

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Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1970

1. Report No.
NASA TN D-5688

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
PRELIMINARY TESTS OF A SIMPLIFIED MODULAR TURBOJET COMBUSTOR

5. Report Date
March 1970

6. Performing Organization Code

7. Author(s)
Richard W. Niedzwiecki

8. Performing Organization Report No.
E-5220

9. Performing Organization Name and Address
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio 44135

10. Work Unit No.
720-03

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D. C. 20546

13. Type of Report and Period Covered
Technical Note

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

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17. Key Words (Suggested by Author(s))
Simplified, carbureting combustor modules for turbojet combustors

18. Distribution Statement
Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	29	$3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

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SUMMARY

The performance of a rectangular sector of a turbojet combustor consisting of an array of 48 combustor modules was determined. Each module incorporated a carburetor which mixed ASTM-A1 fuel with air, a swirler, and a flat plate surrounding the swirler which stabilized combustion. The combustor had a height of 12 inches (30.5 cm), a width of 30 inches (76.2 cm), and a length from diffuser inlet to the combustor exit plane of 33 inches (83.8 cm).

Combustion tests were conducted at inlet air temperatures of 600° and 1050° F (589 and 839 K), a pressure of 3 atmospheres, reference velocities up to 150 feet per second (45.7 m/sec), and average combustor exit temperatures up to 2400° F (1589 K). Good performance was demonstrated with short-length combustor modules 1.56 inches (4.0 cm) long with low pressure carbureting fuel systems and flat plates for flame stabilization. Combustion efficiencies were near 100 percent for fuel-air ratios between 0.015 and 0.024. The best combustor had a total pressure loss of 6.4 percent at a diffuser inlet Mach number of 0.25 and a combustor exit to inlet temperature ratio of 2.5. Combustor exit-temperature distribution improved with increasing inlet air temperature. With 600° F (589 K) inlet air, the exit-temperature pattern factors were between 0.25 and 0.29. Pattern factors were reduced to 0.15 to 0.19 when 1050° F (839 K) inlet air was used. No combustor durability problems were encountered. Maximum metal temperatures on the modules were below 1470° F (1072 K).

A comparison of flat plate and swirl-can modules showed that the flat plate modules produced better pattern factors and circumferential and radial combustor exit temperature distributions, slightly better altitude relight performance and greater durability. Swirl-can modules produced higher combustion efficiencies especially at lower fuel-air ratios and slightly lower pressure loss. Both types of module arrays were evaluated in the same test facility under identical conditions.

INTRODUCTION

Advanced aircraft missions require turbojet engine combustors that are short, efficient, low in pressure loss, and capable of sustained performance at inlet air temperatures above 1000° F (811 K) and combustor exit temperatures above 2000° F (1366 K). In addition to the obvious problem of endurance, such operating requirements impose severe mixing problems. Thus a satisfactory combustor exit temperature distribution may be difficult to achieve with contemporary combustor designs.

Research is directed toward development of combustors suitable for advanced engines (ref. 1). One phase of this research deals with combustors composed of arrays of combustor modules. In the past, combustor arrays made up of swirl-can combustor modules have demonstrated good performance with gaseous fuels (ref. 2), vaporized liquid fuels (ref. 3), and with liquid fuel (refs. 4 and 5). The following advantages of combustor module arrays were shown:

(1) Durability was improved since diluent air entry ports which are frequently the source of liner failure were not required.

(2) Combustor exit temperature profile was adjustable by controlling fuel to individual rows of modules.

(3) Nozzle fouling problems, common at the high temperatures of interest here, were eliminated by the use of a low pressure fuel system with large flow passages within the combustor and control orifices located outside the combustor.

(4) Smoke formation was reduced by premixing of fuel and air in the carburetor.

In the present investigation each combustor module consisted of an inlet section which served as a carburetor, followed by a swirler and a flat plate. In operation, combustion air entered the carburetor and mixed with fuel. Fuel entered the carburetor through a relatively large diameter tube. The fuel-air mixture passed through the swirler and ignited downstream of the flat plate. Secondary combustion air flowed axially past the modules, recirculated in their wakes and completed the combustion reaction. Module walls did not extend into the burning zone. The mixing of diluent air and combustion products occurred because of recirculation and eddy diffusion.

An attempt was made to shorten the combustor modules of reference 5 while improving combustor exit temperature distribution. Burnout problems at trailing edges of the swirl-cans of reference 5, occurring at high inlet air temperatures, should be eliminated with the shorter modules. Module length was shortened from 3.5 to 1.56 inches (8.9 to 4.0 cm) by replacing the combustor cans of reference 5 with flat plates thereby removing all module surfaces from the combustion area. Results of reference 5 also showed that crossfire tabs were required between modules to propagate flame. Thus

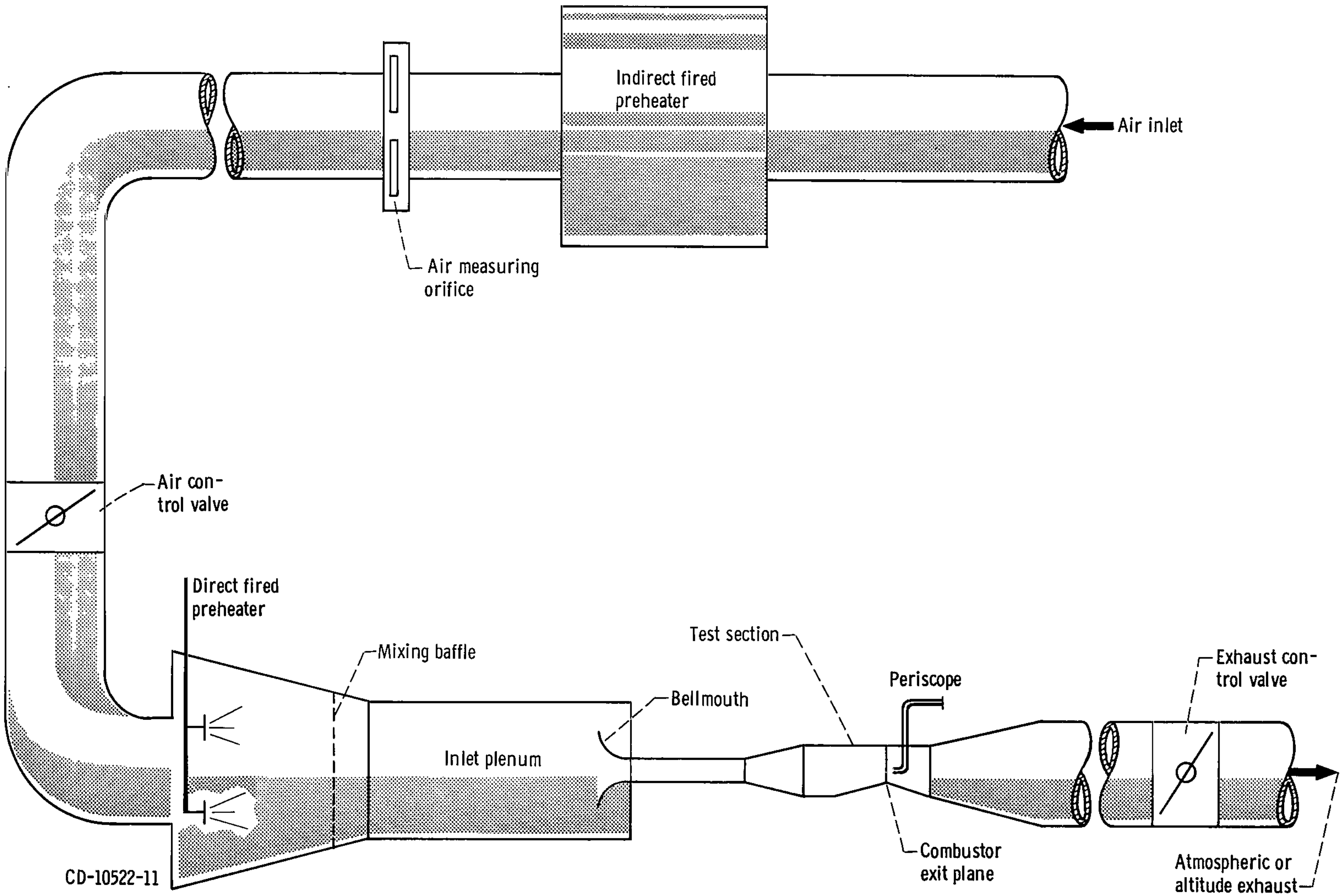


Figure 1. - Test facility and auxiliary equipment.

the flat plate modules were positioned in the array so that their corners intersected with the midpoints of adjacent modules thus producing the required flame paths.

APPARATUS

Facility

The test section was housed in the closed duct test facility shown in figure 1. The facility was connected to the laboratory air supply and exhaust systems. Remote control valves upstream and downstream of the test section regulated airflows and combustor pressure. An indirect fired heat exchanger supplied heated air up to 600° F (589 K). Higher inlet air temperatures were obtained by using a direct fired (vitiating) preheater. Baffles downstream of the vitiating preheater, a bellmouth, and a constant area section produced uniform temperature and airflow profiles at the combustor inlet.

Test Section

The test section (fig. 2) was scaled to simulate a 90° sector of a full annulus turbojet engine combustor with a 57-inch (1.45-m) outer diameter. The test sections were rectangular in cross section with a 12-inch (30.5-cm) height and a 30-inch (76.2-cm) width. The diffuser had an included angle of 33°. Five flow divider vanes installed in the upstream end of the diffuser improved the air profile at the combustor. The diffuser also contained the combustor module array which was positioned so that the module trailing edges were approximately 2 inches (5.1 cm) upstream of the diffuser exit. A diffuser hatch provided easy access to the combustor array. A 6-inch (15.2-cm) long constant area section and an exit ramp completed the test section. The length from the diffuser inlet to the combustor exit plane was 33 inches (84 cm). A film cooled liner, extending from the diffuser exit to the combustor exit plane, protected the housings. Installation of the test section in the facility is shown in figure 3.

Combustor Module Design

The combustor module design is shown in figure 4. Each module contained three components: an inlet carburetor where fuel and air mixed, a swirler through which the

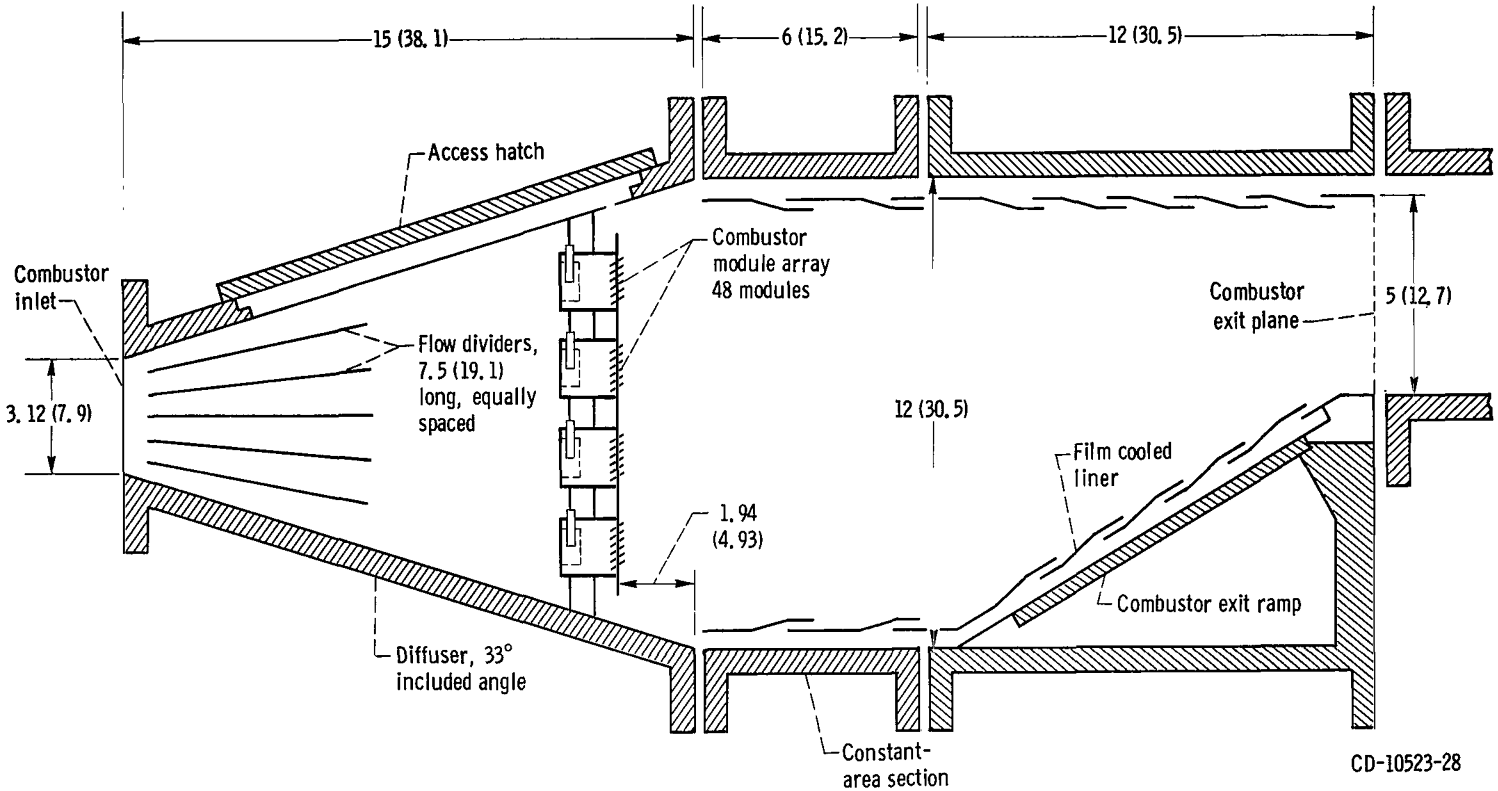


Figure 2. - Combustor installation in test section. (Dimensions are in inches (cm).)

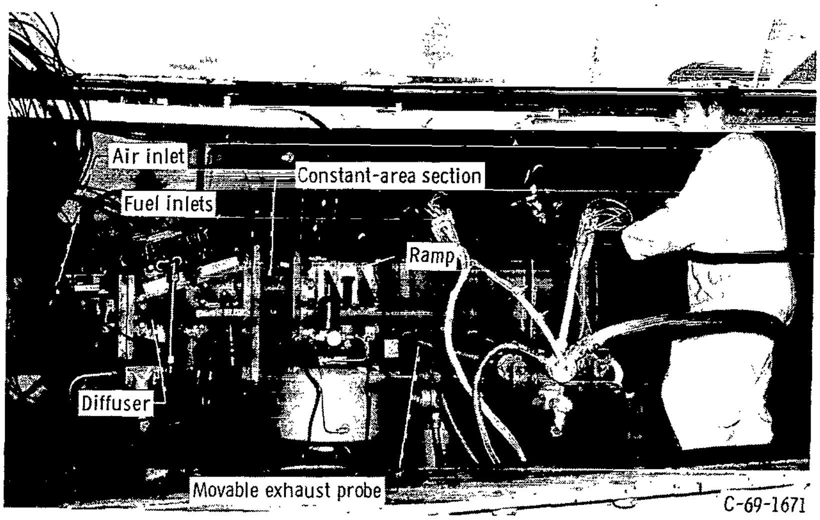


Figure 3. - Test installation.

mixture passed prior to combustion, and a flat plate which served as a flameholder. The carburetor and swirler were the same design used in reference 5. Fuel was supplied to each combustor module through a 0.19-inch (0.47-cm) inside diameter tube. The tube injected fuel tangentially into the carburetor. A control orifice was installed in the fuel tube and located outside the combustion chamber.

Combustor Module Arrays

Forty-eight combustor modules comprised each combustor array. The combustor modules were positioned in four horizontal rows of 12 each, so that the corners of each flat plate intersected with the midpoints of adjacent modules thereby providing a continuous blockage path across the array for flame propagation. Combustor module arrays are shown in figures 5(a) (view looking downstream) and 5(b) (view looking upstream). Several modifications of this array were tested. All modifications were made to improve combustor exit temperature distribution. For model 1, the top and bottom film cooled liners were extended to the plane of the flat plates and positioned so that a 0.19-inch (0.47-cm) gap existed between the flat plates and liners as shown in figure 6(a). The liner extensions were removed for models 2 and 3 and 0.63-inch (1.59-cm) wide strips were welded across the top and bottom of the array as shown in figure 6(b) (see also figs. 5(a) and (b)). The strips were attached to the flat plates and reduced the open flow area along the diffuser outside and inside diameter walls at the module trailing edges to 0.13-inch (0.32-cm) wide slots.

Different amounts of fuel were supplied to each horizontal row of modules. The

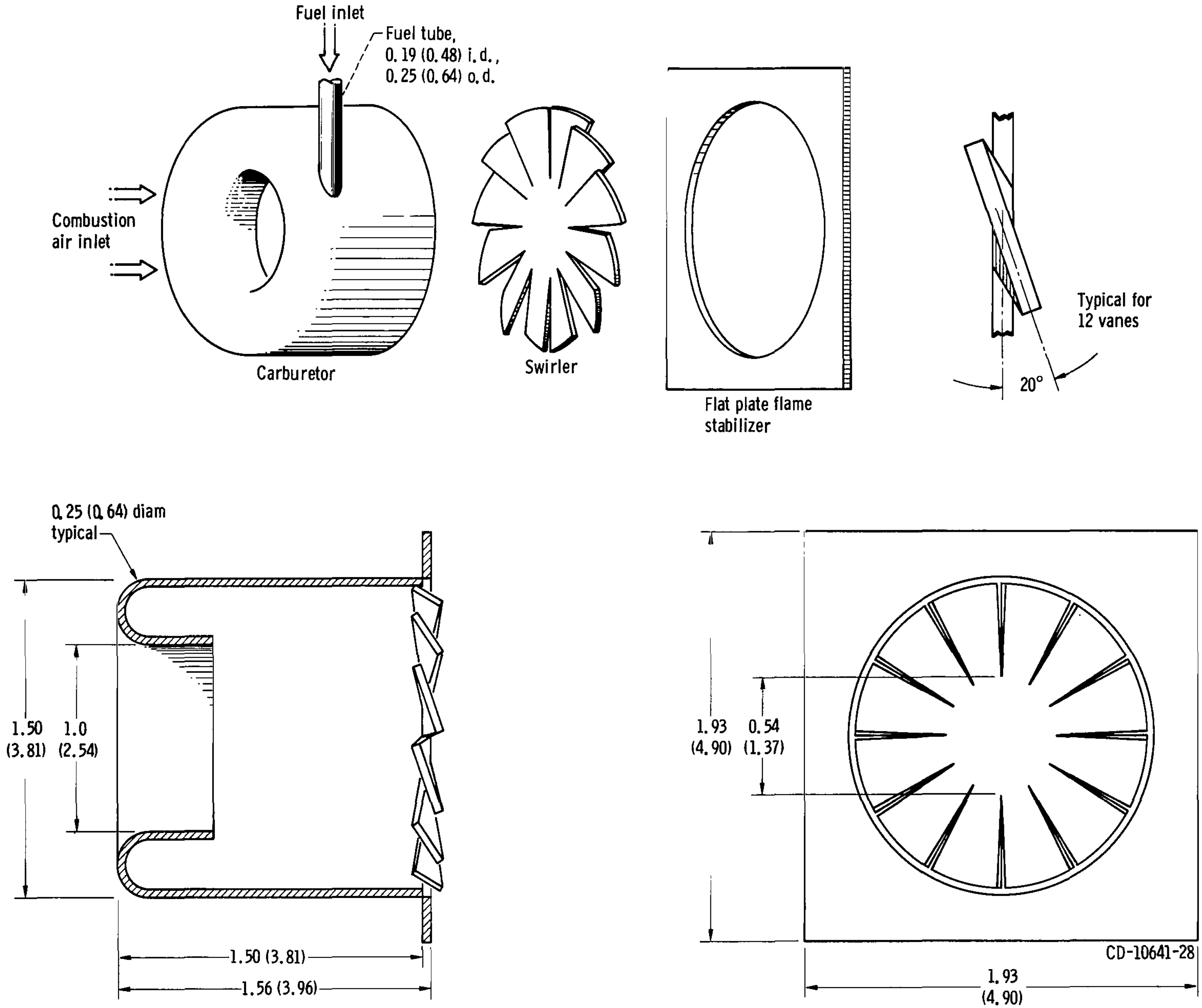
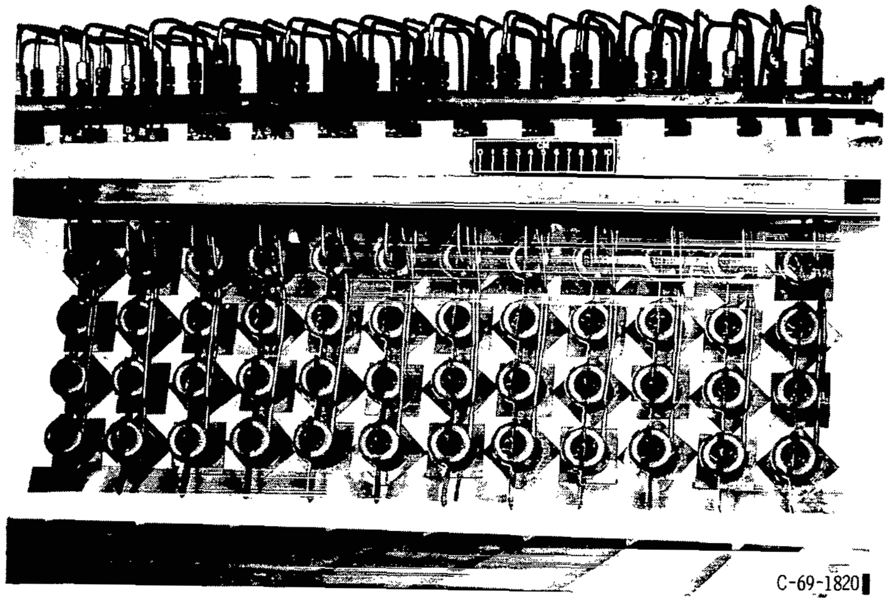
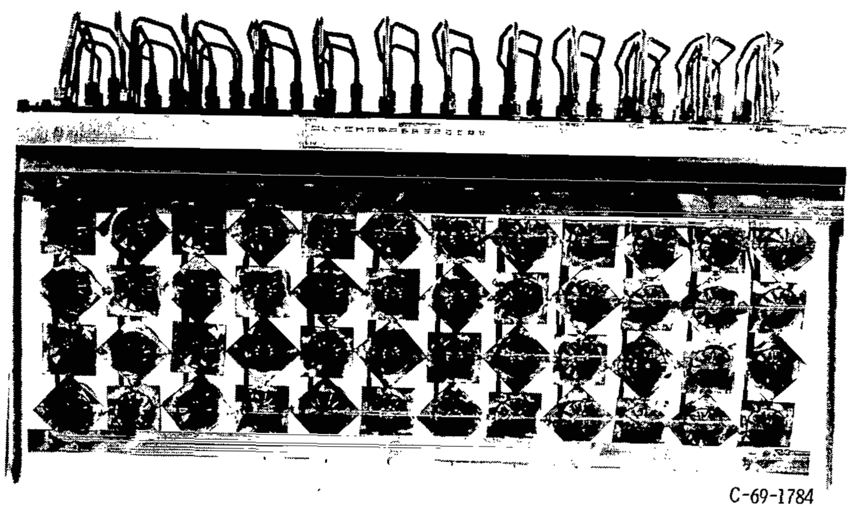


Figure 4. - Combustor module details. (Dimensions are in inches (cm).)



(a) View looking downstream.



(b) View looking upstream.

Figure 5. - Combustor module array, model 3.

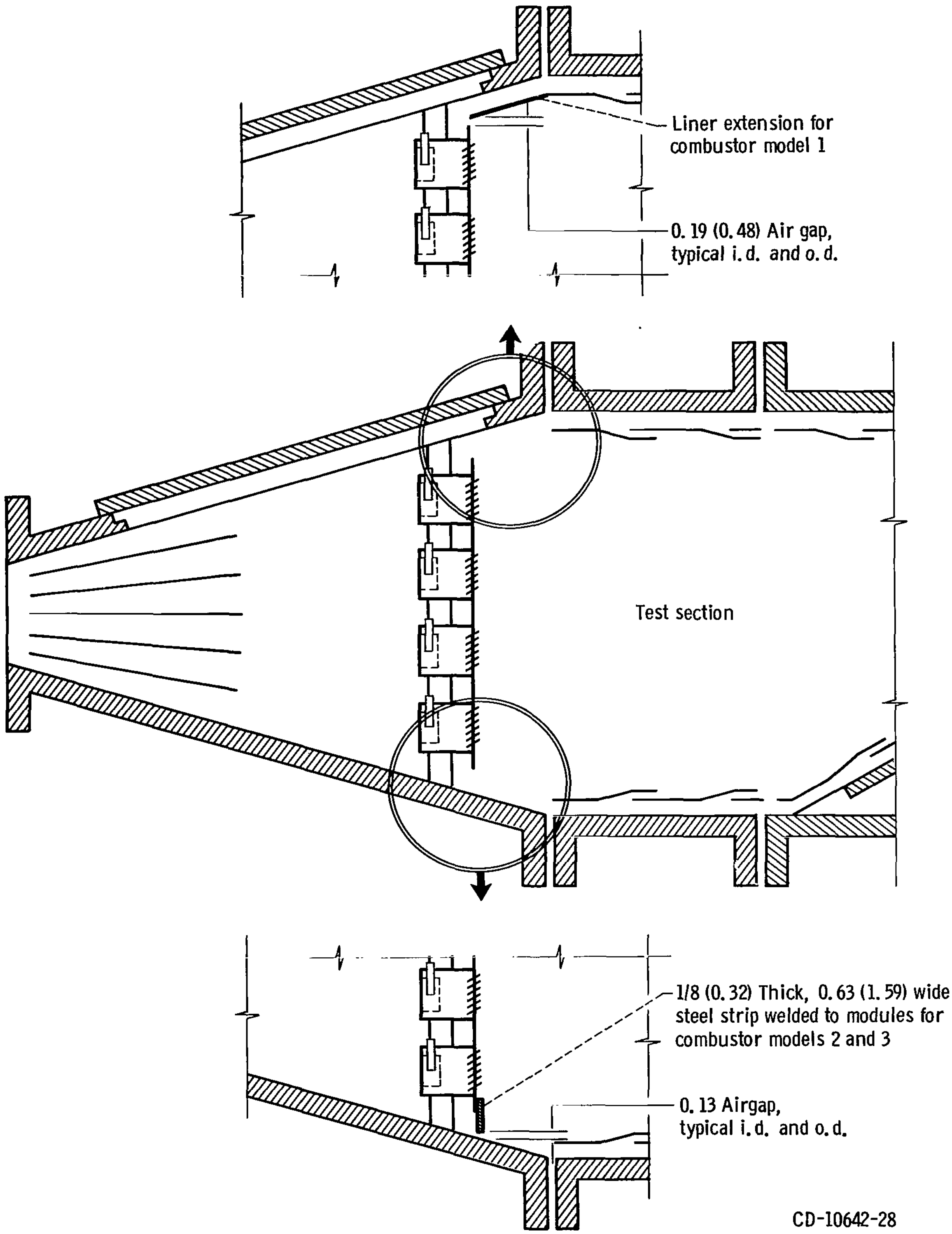


Figure 6. - Liner modifications for combustor model 1 and blockage modifications for models 2 and 3. (Dimensions are in inches (cm).

model 1 modification had the liner extensions, and the fuel orifice diameters from top to bottom were 0.043, 0.036, 0.036, 0.043 inch (0.11, 0.09, 0.09, 0.11 cm). Models 2 and 3 had the blockage strips welded to the modules and differed only in fuel flow distribution. Model 2 had the same fuel flow distribution as model 1. For model 3 the fuel orifice diameters from top to bottom were 0.040, 0.036, 0.036, 0.049 inch (0.10, 0.09, 0.09, 0.124 cm).

Ignition

A capacitor discharge type ignition system which supplied a maximum energy of 20 joules to the spark ignitor ignited the combustors. The ignitor was positioned approximately 1 inch (2.54 cm) downstream of the combustor module's trailing edge.

Instrumentation

Details of instrumentation are contained in the appendix. Fixed temperature and pressure probes were located at the diffuser inlet. A traversing probe measured temperatures and pressures at the combustor exit plane. A periscope, mounted downstream of the combustor provided a view of burning during test runs.

TEST CONDITIONS

Tests were conducted over a range of fuel-air ratios at the combustor inlet conditions in table I. All testing was done at a nominal combustor pressure of 3 atmospheres. At each reference velocity fuel-air ratios were increased until a local combustor exit temperature exceeded 2700° F (1756 K).

A jet fuel conforming to ASTM-A1 specifications was used for all tests. This fuel had an average hydrogen-carbon ratio of 0.161 and a lower heating value of 18 600 Btu per pound (43 300-J/g).

TABLE I. - COMBUSTOR NOMINAL TEST CONDITIONS

[Nominal pressure, 3 atm.]

Combustor model	Combustor inlet temperature, °F	Combustor inlet temperature, K	Combustor inlet Mach number	Combustor reference Mach number	Combustor reference velocity[a], ft/sec	Combustor reference velocity[a], m/sec
1	600	589	0.193	0.050	80	24.4
			.241	.063	100	30.5
			.361	.094	150	45.7
2	600	589	0.193	0.050	80	24.4
			.241	.063	100	30.5
			.289	.075	120	36.6
3	600	589	0.193	0.050	80	24.4
	600	589	.241	.063	100	30.5
	1050	839	.192	.050	95	29.0
	1050	839	.232	.060	115	35.1
	1050	839	.303	.080	150	45.7

[a]Reference velocity is the volumetric flow rate, based on total density at the combustor inlet, divided by the maximum cross-sectional area of the combustor housing. In this case the maximum cross-sectional area is 2.5 ft^2 (0.232 m^2).

RESULTS AND DISCUSSION

Combustor Development

Combustor modifications were evaluated by comparing combustion efficiency, pressure loss, and combustor exit temperature distribution at the test conditions given in table I. Combustor model 1 was the basic array with the top and bottom cooling liners extended. Combustor models 2 and 3 incorporated blockage strips across the top and bottom of the array. The effect of the blockage strips on performance can be obtained by a comparison of models 1 and 2 since these combustor models were otherwise identical. The effect of 2 different fuel-flow distributions on combustion performance can be obtained by a comparison of models 2 and 3. Test results are summarized in table II for models 1 to 3.

Combustor exit temperature distribution was the main criterion by which performance was judged since combustion efficiencies of all the combustor models proved to be near 100 percent for the fuel-air ratios of prime interest (0.020 to 0.024), and the

TABLE II. - COMBUSTOR PERFORMANCE DATA

[Pressure, 3 atm.]

Run	Inlet-air temperature		Airflow		Diffuser inlet Mach number	Nominal reference velocity		Fuel-air ratio	Mass-weighted combustor exit temperature		Combustion efficiency, percent	Total pressure loss ratio, P/P, percent	Corrected for side wall effects				
													Average combustor exit temperature		Temperature distribution parameters		
	°F	K	lb/sec	kg/sec		ft/sec	m/sec		°F	K			°F	K	δ_{stator}	δ_{rotor}	$\bar{\delta}$
(a) Model 1 - basic array with film cooling liners extended to array; fuel orifice diameters for each horizontal row of modules from top to bottom, 0.043, 0.036, 0.036, and 0.043 inch (0.11, 0.09, 0.09, and 0.11 cm)																	
1	592	584	22.8	10.34	0.200	80	24.4	------	----	----	---	2.92	----	----	----	----	----
2	592	584	22.9	10.39	.201			0.0099	1221	934	93	3.03	1270	961	0.40	0.15	0.48
3	594	585	23.2	10.52	.202			.0114	1374	1019	101	3.03	1426	1047	.39	.13	.47
4	593	585	23.0	10.43	.197			.0138	1527	1104	102	3.14	1606	1147	.41	.17	.48
5	596	586	23.1	10.48	.201			.0160	1678	1187	102	3.30	1759	1232	.36	.21	.42
6	594	585	23.1	10.48	.198			.0181	1816	1264	102	3.13	1917	1320	.39	.19	.44
7	595	586	29.5	13.38	.256	100	30.5	------	----	----	---	4.85	----	----	----	----	----
8	594	585	29.6	13.43	.262			.0094	1132	884	84	5.17	1203	924	.41	.08	.50
9	594	585	29.3	13.29	.254			.0111	1317	987	96	5.19	1400	1033	.35	.10	.43
10	593	585	29.6	13.43	.257			.0127	1456	1064	101	5.21	1547	1115	.37	.11	.44
11	585	580	29.7	13.47	.260			.0139	1543	1112	102	5.38	1626	1159	.37	.13	.43
12	588	582	29.2	13.25	.260			.0169	1737	1220	102	5.33	1794	1252	.45	.15	.50
13	592	584	29.2	13.25	.259			.0189	1863	1290	102	5.48	1969	1349	.37	.15	.41
14	593	585	29.6	13.43	.263			.0202	1935	1330	102	5.60	2068	1404	.40	.16	.45
15	590	583	43.2	19.60	.404	150	45.7	------	----	----	---	11.62	----	----	----	----	----
16	588	582	43.6	19.78	.407			.0113	1201	922	80	12.52	1282	967	.55	.13	.63
17	585	580	43.7	19.82	.400			.0143	1497	1087	96	12.55	1608	1149	.41	.18	.47
18	580	577	43.4	19.69	.409			.0161	1634	1164	100	12.82	1700	1200	.46	.19	.51
19	581	578	43.8	19.87	.411			.0173	1738	1221	102	12.96	1798	1254	.47	.19	.47
20	586	581	43.8	19.78	.405			.0184	1802	1256	102	13.04	1877	1298	.45	.19	.49
(b) Model 2 - basic array with blockage strips along top and bottom of array; fuel orifice diameters for each horizontal row of modules from top to bottom, 0.043, 0.036, 0.036, and 0.043 inch (0.11, 0.09, 0.09, and 0.11 cm)																	
1	595	566	23.1	10.48	0.201	80	24.4	------	----	----	---	3.48	----	----	----	----	----
2	627	604	22.2	10.07	.193			0.0184	1796	1253	99	3.57	1903	1312	0.26	0.14	0.30
3	593	585	21.4	9.71	.187			.0188	1815	1264	101	3.61	1897	1309	.23	.08	.27
4	587	581	23.8	10.80	.205			.0203	1924	1324	102	3.69	2071	1406	.22	.07	.25
5	596	586	21.4	9.71	.185			.0210	1984	1357	102	2.99	2070	1405	.22	.08	.25
6	585	580	23.6	10.70	.203			.0222	2030	1384	102	4.16	2124	1435	.23	.08	.27
7	594	585	21.0	9.53	.184			.0228	2045	1391	101	3.41	2141	1445	.23	.08	.27
8	585	580	29.6	13.43	.260	100	30.5	------	----	----	---	5.82	----	----	----	----	----
9	605	591	29.7	13.47	.262			.0145	1355	1008	79	6.69	146	1067	.40	.18	.43
10	588	582	29.8	13.52	.274			.0176	1682	1190	95	6.76	1780	1244	.23	.09	.28
11	588	582	29.8	13.52	.259			.0189	1791	1250	98	6.72	1880	1300	.23	.07	.27
12	588	582	29.8	13.52	.263			.0209	1923	1324	100	6.78	2024	1380	.25	.07	.29
13	594	585	29.5	13.38	.252			.0229	2069	1405	102	6.44	2165	1458	.26	.06	.29
14	601	589	34.2	15.51	.302	120	36.6	------	----	----	---	7.94	----	----	----	----	----
15	599	588	34.5	15.65	.307			.0196	1836	1275	98	9.08	1940	1333	.23	.07	.27
16	601	589	34.2	15.51	.304			.0218	1985	1358	100	9.46	2088	1415	.24	.06	.29
17	601	589	34.2	15.51	.300			.0228	2065	1402	102	9.37	2159	1455	.26	.07	.29

TABLE II. - Concluded. COMBUSTOR PERFORMANCE DATA

[Pressure, 3 atm.]

Run	Inlet-air temperature		Airflow		Diffuser inlet Mach number	Nominal reference velocity		Fuel-air ratio	Mass-weighted combustor exit temperature		Combustion efficiency, percent	Total pressure loss ratio, P/P, percent	Corrected for side wall effects				
													Average combustor exit temperature		Temperature distribution parameters		
	°F	K	lb/sec	kg/sec		ft/sec	m/sec		°F	K			°F	K	δ_{stator}	δ_{rotor}	$\bar{\delta}$
(c) Model 3 - basic array with blockage strips along top and bottom of array; fuel orifice diameters for each horizontal row of modules from top to bottom, 0.040, 0.036, 0.036, and 0.049 inch (0.10, 0.09, 0.09, and 0.124 cm)																	
1	580	577	23.6	10.70	0.197	80	24.4	------	----	----	---	3.51	----	----	----	----	----
2	584	580	23.2	10.52	.196			0.0145	1467	1070	92	3.64	1546	1115	0.25	0.12	0.31
3	590	583	22.8	10.34	.195			.0168	1655	1175	97	3.57	1746	1225	.21	.06	.25
4	594	585	22.5	10.21	.199			.0185	1771	1234	98	3.71	1862	1290	.21	.06	.25
5	590	583	23.1	10.48	.192			.0200	1402	1312	102	3.72	1985	1358	.22	.06	.26
6	590	583	22.9	10.39	.192			.0218	1998	1365	102	4.14	2108	1426	.23	.06	.26
7	591	584	23.0	10.43	.199			.0238	2134	1441	102	4.06	2225	1491	.25	.06	.29
8	594	585	29.5	13.38	.259	100	30.5	------	----	----	---	6.02	----	----	----	----	----
9	593	585	29.2	13.25	.256			.0188	1779	1244	98	6.77	1872	1295	.20	.04	.26
10	592	584	29.8	13.52	.254			.0195	1857	1287	101	6.56	1952	1340	.21	.03	.25
11	594	585	29.7	13.47	.252			.0209	1952	1340	101	6.34	2040	1389	.22	.04	.26
12	594	585	29.2	13.25	.252			.0229	2044	1391	100	6.55	2149	1449	.22	.03	.26
13	596	586	29.5	1338	.250			.0240	2133	1440	102	6.67	2237	1498	.22	.03	.26
14	1050	839	19.0	8.62	.194	95	29.0	------	----	----	---	3.17	----	----	----	----	----
15	1056	842	18.8	8.53	.198			.0175	2108	1427	99	3.30	2162	1456	.11	.05	.15
16	1059	844	18.8	8.53	.195			.0189	2203	1479	100	3.33	2270	1516	.12	.04	.17
17	1056	842	19.0	8.62	.198			.0205	2327	1548	101	3.30	2396	1586	.13	.05	.17
18	1060	844	19.3	8.75	.191			.0224	2406	1592	100	3.31	2480	1633	.13	.05	.17
19	1024	824	23.0	10.43	.236	115	35.1	------	----	----	---	5.02	----	----	----	----	----
20	1024	824	22.7	10.25	.236			.0179	2066	1403	98	5.25	2115	1430	.15	.05	.18
21	1017	820	23.2	10.52	.242			.0210	2206	1481	98	5.32	2230	1494	.14	.06	.19
22	1008	815	23.3	10.57	.243			.0214	2302	1534	100	5.57	2355	1564	.15	.04	.19
23	998	810	22.6	10.25	.239			.0227	2386	1581	101	5.64	2444	1608	.17	.05	.19
24	998	810	29.4	13.34	.306	150	45.7	------	----	----	---	8.64	----	----	----	----	----
25	1008	815	29.6	13.43	.306			.0160	1999	1366	100	----	2066	1391	.23	.04	.19
26	1006	814	29.7	13.47	.307			.0171	2092	1417	101	9.41	2146	1443	.15	.03	.17
27	1001	811	29.5	13.38				.0190	2133	1440	99	9.58	2198	1466	.17	.02	.17
28	1008	815	29.6	13.43	.307			.0202	2222	1490	100	9.38	2274	1515	.19	.04	.15
29	1005	814	29.7	13.47	.313			.0217	2385	1580	101	9.52	2449	1616	.12	.04	.15

pressure loss for all models were within 1.2 percent. The model 3 combustor produced the most uniform combustor exit temperature distribution.

In general, all combustor models performed well over the span of test conditions investigated. Flames were short and blue and did not extend through the combustor exit plane at any of the test conditions.

Combustion Efficiency

Combustion efficiency was defined as the ratio of actual temperature rise to theoretical temperature rise. Combustor exit temperatures were mass weighted. The average exit temperature used for efficiency calculations was based on the total number of readings taken at the combustor exit plane (in excess of 385). Oxygen depletion resulting from vitiation of the combustion air was taken into account in combustion efficiency calculations.

Combustion efficiencies of combustor models 1 to 3 with 600° F (589 K) inlet air and at several reference velocities are presented in figures 7(a) to (c), respectively. Combustion efficiency improved with increasing fuel-air ratio and decreasing reference velocity for all models. At fuel-air ratios greater than 0.015 combustion efficiencies were near 100 percent. Since lower fuel-air ratios were not of primary interest, no attempt was made to improve performance by altering module geometry. The combustion efficiency of model 3 with 1050° F (839 K) is shown in figure 7(d). At the higher

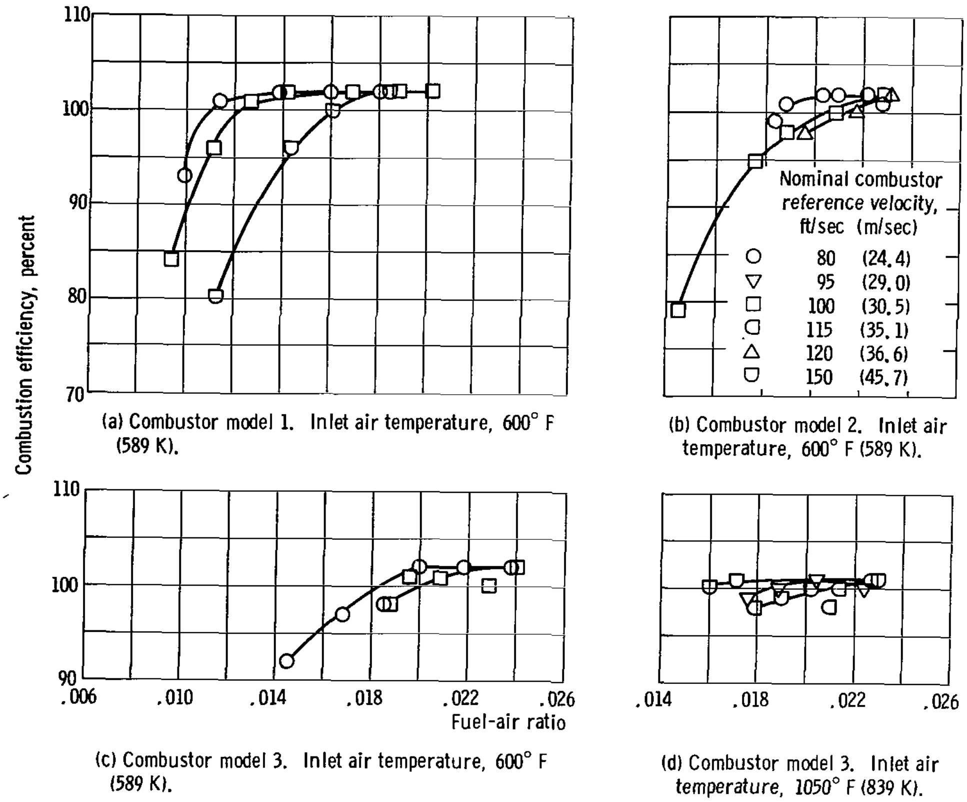


Figure 7. - Combustion efficiency of combustor models 1, 2, and 3 at a combustor total pressure of 3 atmospheres.

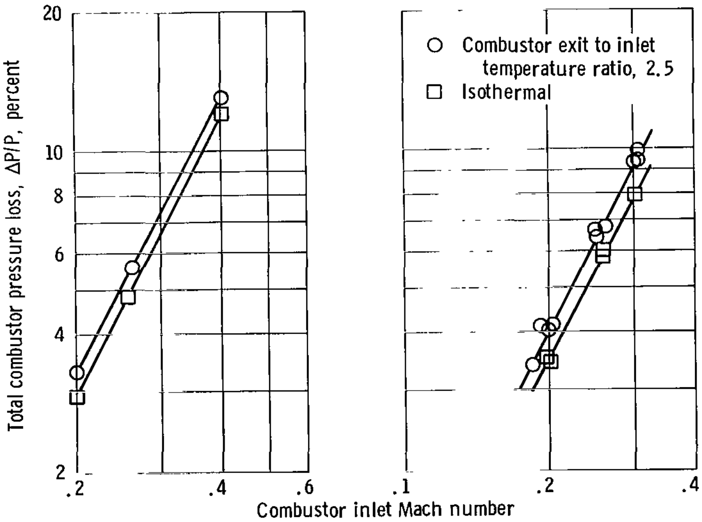
inlet air temperature combustion efficiency was not affected by reference velocity, but slight reductions in efficiency occurred at lower fuel-air ratios.

Pressure Loss

Combustor total pressure loss, $\Delta P/P$ includes the diffuser pressure loss and is defined by the following expression

$$\frac{\Delta P}{P} = \frac{(\text{Average diffuser inlet total pressure}) - (\text{Average combustor exit total pressure})}{\text{Average diffuser inlet total pressure}}$$

Figure 8 shows the effect of diffuser inlet Mach number on pressure loss. Figure 8(a) shows that at a diffuser inlet Mach number of 0.25 and a combustor exit to inlet temperature ratio of 2.5, the pressure loss of model 1 was 5.2 percent. Since models 2 and 3 were geometrically the same except for fuel distribution, their pressure loss, shown in figure 8(b) was the same. At a diffuser inlet Mach number of 0.25 and a combustor exit to inlet temperature ratio of 2.5 their pressure loss was 6.4 percent.



(a) Combustor model 1. (b) Combustor models 2 and 3.

Figure 8. - Effect of combustor inlet Mach number on pressure loss. Combustor total pressure, 3 atmospheres, combustor inlet temperature, 600° F (589 K).

Combustor Exit Temperature Distribution

Temperature distribution parameters. - The following temperature distribution parameters were established to describe combustor exit temperature distributions:

$$\delta_{stator} = \frac{(T_{r,local} - T_{r,design})_{max}}{\Delta T}$$

where $(T_{r,local} - T_{r,design})_{max}$ is the largest temperature differential between the highest local temperature on any radius, $T_{r,local}$, and the design temperature for that radius and where ΔT is the average temperature rise across the combustor. The design temperature, $T_{r,design}$, was obtained from a design radial temperature profile which is typical of profiles encountered in advanced supersonic engines.

$$\delta_{rotor} = \frac{(T_{r,av} - T_{r,design})_{max}}{\Delta T}$$

where $(T_{r,av} - T_{r,design})_{max}$ is the largest temperature differential between the average circumferential temperature on any radius and the design temperature for that radius.

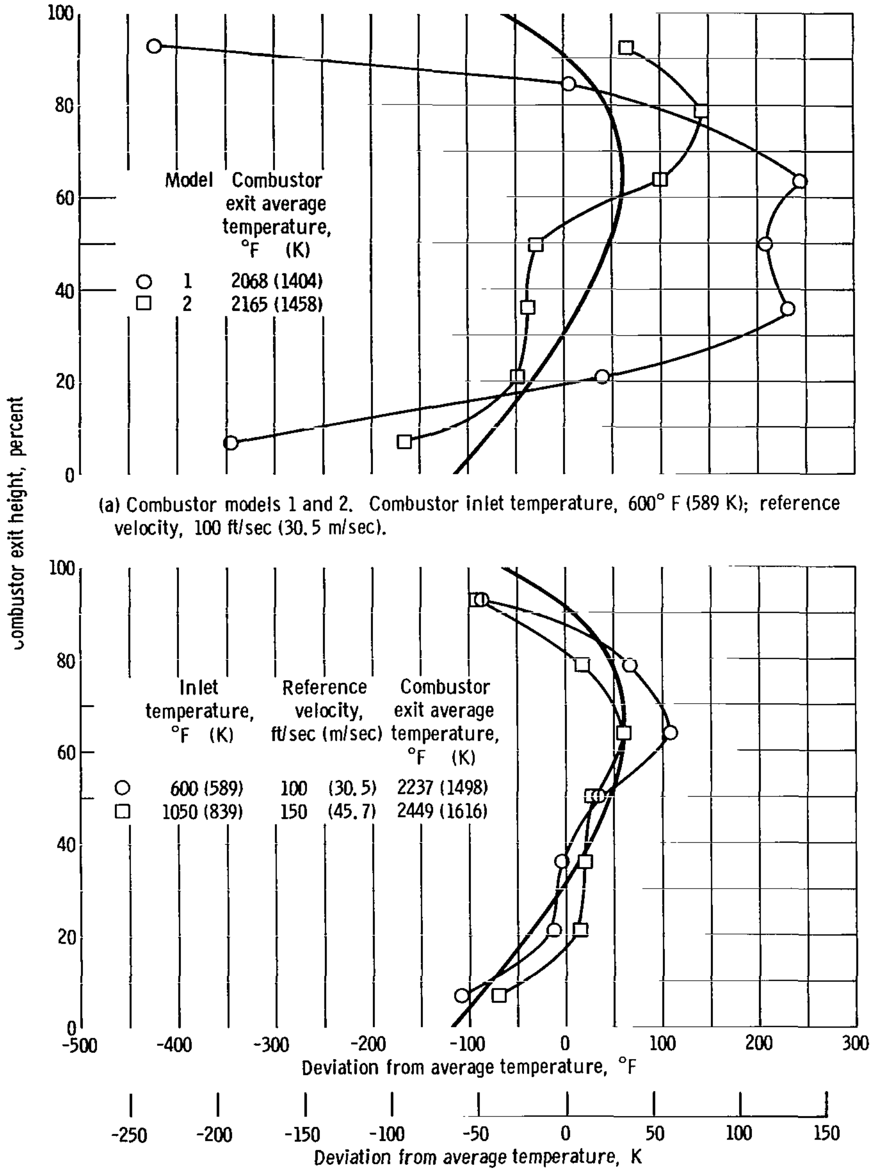
Another temperature distribution parameter in common usage in the aircraft industry was also employed. This parameter is the pattern factor and is defined by the expression:

$$\text{Pattern factor} = \bar{\delta} = \frac{T_{max} - T_{av}}{\Delta T}$$

where T_{max} is the highest local combustor exit temperature, T_{av} is the average combustor exit temperature and ΔT is the combustor temperature rise.

For calculations of temperature distribution parameters, nonweighted temperatures were used. Approximately 10 percent of the temperature readings at each combustor side wall were disregarded to eliminate the side wall effects which are always present in sector tests.

Calculated values of δ_{stator}, δ_{rotor}, and $\bar{\delta}$ are given in table II for the three combustor models. The best temperature distribution parameters were obtained with the model 3 combustor. For fuel-air ratios greater than 0.015 and 600° F (589 K) inlet air temperature the pattern factor $\bar{\delta}$ varied between 0.25 and 0.29, δ_{stator} varied between 0.20 and 0.25, and δ_{rotor} varied between 0.02 and 0.06. When the inlet temperature was increased to 1050° F (839 K), the distribution parameters improved to



(a) Combustor models 1 and 2. Combustor inlet temperature, 600° F (589 K); reference velocity, 100 ft/sec (30.5 m/sec).

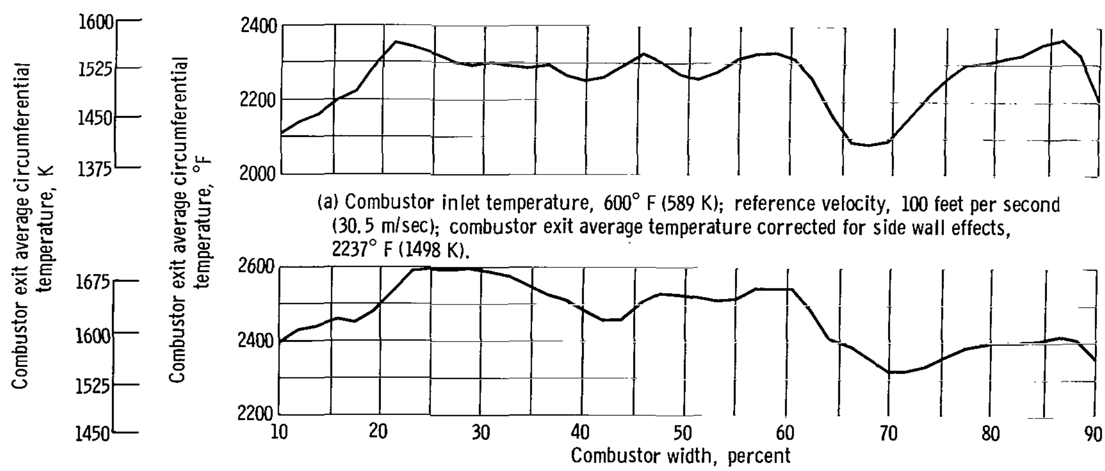
(b) Combustor model 3.

Figure 9. - Combustor exit average radial temperature profile (corrected for side wall effects) for combustor models 1, 2, and 3. Combustor pressure, 3 atmospheres.

values of $\bar{\delta}$ from 0.15 to 0.19, δ_{stator} from 0.11 to 0.19, and δ_{rotor} from 0.02 to 0.06. The model 2 combustor also produced acceptable exit temperature parameters. Poor values were obtained with the model 1 combustor with $\bar{\delta}$ increasing to 0.51 and δ_{stator} to 0.47. These results indicate the necessity of the blockage strips across the top and bottom of the module array. They also show the effectiveness of improving the temperature distribution by redistribution of fuel to the module rows.

Average radial temperature profiles. - Average radial temperature profiles for all combustor models are shown in figure 9. At each radial position, combustor exit temperatures were averaged circumferentially. The difference between these values and the average temperature are plotted against radial position. Radial position is expressed as percentage of combustor exit height. The ideal radial profile shown on these plots is representative of the requirements of current supersonic turbojet engines. Model 1 radial profiles were poor with cold zones along the inner and outer annulus. Model 2 radial profiles were considerably better and were improved further in model 3 by tailoring the fuel flow to the module rows. Average radial profiles matched the ideal profile more closely at the higher combustor inlet temperature.

Average circumferential temperature profiles. - Combustor exit temperatures, averaged along a radius and plotted against circumferential position, for the model 3 combustor are shown in figure 10. Profiles again improved as the combustor inlet temperature was increased from 600° F (589 K) to 1050° F (839 K). Approximately a 270° F (150 K) span occurred between the highest and lowest average temperatures at all circumferential locations within the array. This span was lowered to 260° F (144 K) when



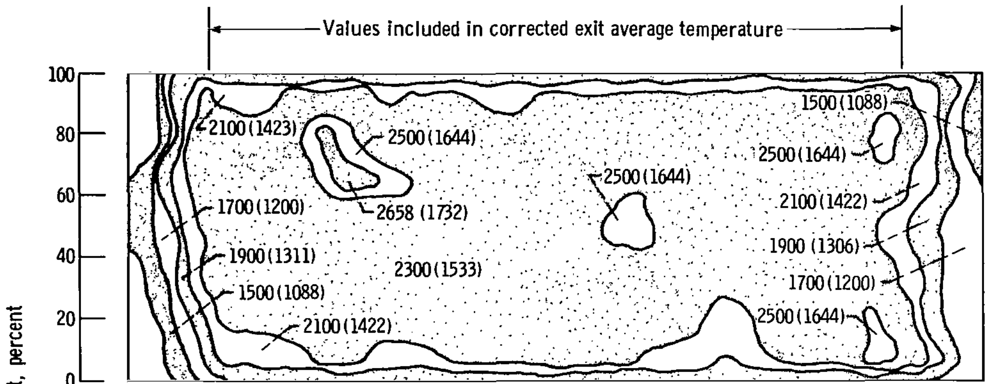
(a) Combustor inlet temperature, 600° F (589 K); reference velocity, 100 feet per second (30.5 m/sec); combustor exit average temperature corrected for side wall effects, 2237° F (1498 K).

(b) Combustor inlet temperature, 1050° F (839 K); reference velocity, 150 feet per second (45.7 m/sec); combustor exit average temperature corrected for side wall effects, 2449° F (1616 K).

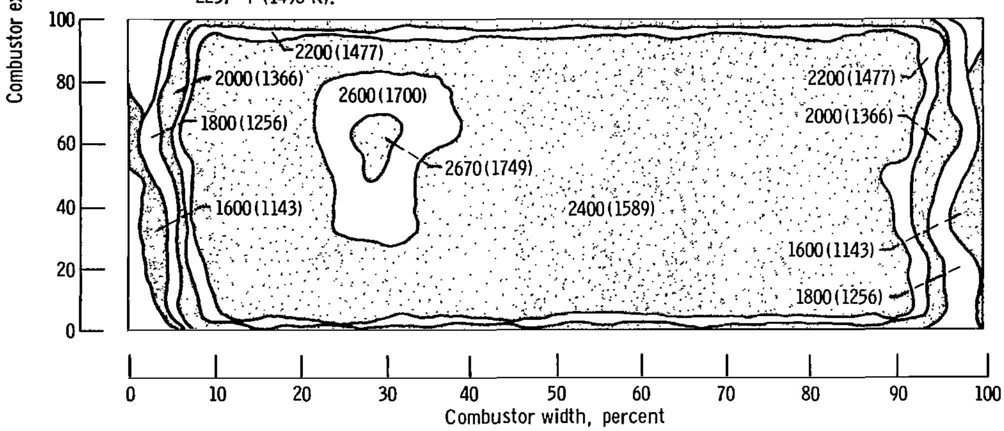
Figure 10. - Combustor exit average circumferential temperature profiles looking upstream for combustor model 3. Combustor pressure, 3 atmospheres.

1050° F (839 K) inlet air was supplied even though the average temperature was increased from 2237° F (1498 K) to 2449° F (1616 K)

Combustor exit temperature contours. - Exit temperature contours for the model 3 combustor at two inlet air temperatures are shown in figure 11. Generally, temperature distribution improved with increasing inlet air temperature and fuel-air ratio and was impaired by increasing reference velocity.



(a) Combustor inlet temperature, 600° F (589 K); reference velocity, 100 feet per second (30.5 m/sec); combustor exit average temperature corrected for side wall effects, 2237° F (1498 K).



(b) Combustor inlet temperature, 1050° F (839 K); reference velocity 150 feet per second (45.7 m/sec); combustor exit average temperature corrected for side wall effects, 2449° F (1616 K).

Figure 11. - Combustor exit temperature contours (in °F (K)) for combustor model 3. Combustor pressure, 3 atmospheres. View looking upstream into combustor.

Altitude Blowout and Relight

Altitude blowout and relight tests were made for combustor model 3. Blowout points were obtained by setting the combustor inlet air temperature and pressure and increasing airflow until blowout occurred. This procedure was repeated for combustor inlet temperatures of 600°, 400°, 300°, 200°, and 100° F (589, 477, 422, 367, and 311 K), and inlet pressures of 0.5 to 2.5 atmospheres. The fuel-air ratio was 0.017 for all tests. Blowout occurred when less than one-half to two-thirds of the combustor modules were lit or when additional fuel did not produce corresponding increases in combustor exit temperature. Once combustor blowout data was obtained, attempts were made to ignite the combustor as near to the blowout points as possible.

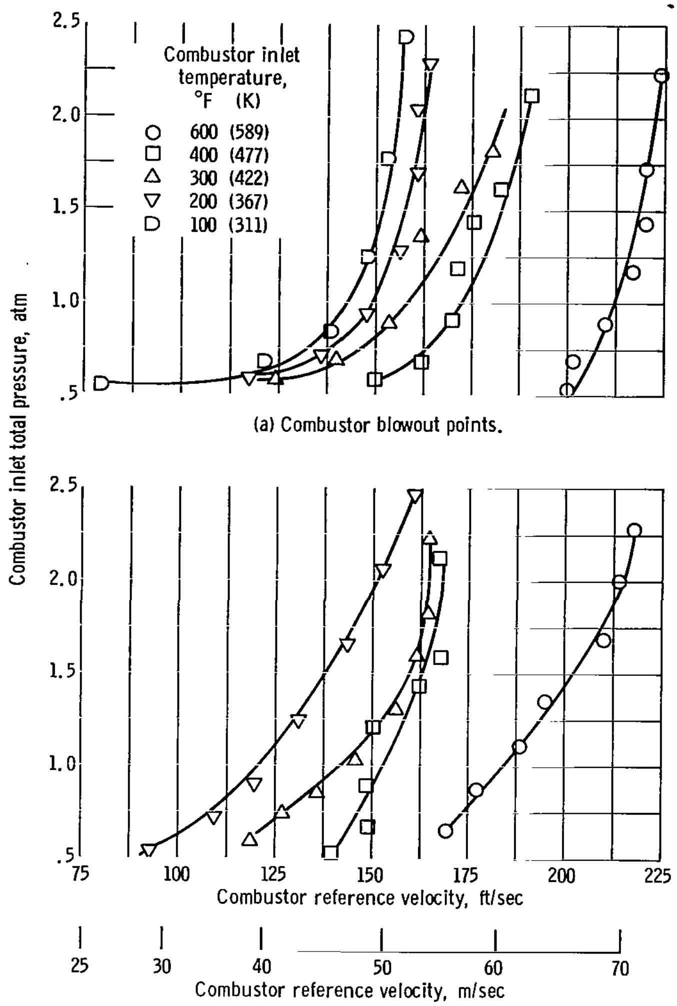
Results of blowout and relight tests are given in figures 12(a) (blowout) and 12(b) (relight). The combustor was stable over the entire range of temperatures and pressures investigated. However, as inlet temperatures and pressures were decreased, the maximum reference velocity for which stable burning could be maintained also decreased. With 600° F (589 K) inlet air, combustion was stable for reference velocities up to 200 to 225 feet per second (61 to 69 m/sec). As inlet temperature was decreased to 100° F (311 K) reductions of reference velocity to maximum values of 78 to 150 feet per second (24 to 45.7 m/sec) were required to maintain stable combustion.

Relight performance was similarly affected by decreasing pressure and temperature. With 100° F (311 K) inlet air temperature the combustor could not be relit. Increasing inlet air temperature to 200° F (367 K) permitted ignition over the entire span of inlet pressures.

Changes of combustor geometry were not made to improve combustor blowout and relight performance. Performance could probably have been improved by relocating the spark probe, increasing the energy to the spark probe, replacing the spark probe with a torch ignitor which could supply a combustion source to numerous combustor modules simultaneously, preheating the fuel, or by decreasing the airflow through the combustor modules by restricting the swirler flow area.

Durability

Extended combustor durability tests were not made. However, no module burnout problems were encountered during performance tests. Temperature sensitive coating showed that maximum module temperatures occurred on the flat plates. These temperatures were below 1470° F (1072 K) even at the extreme condition when 1050° F (839 K) inlet air was supplied.



(b) Altitude relight points (no relight with 100° F (311 K) inlet air).

Figure 12. - Performance of combustor model 3 at altitude relight conditions. Fuel-air ratio, 0.017.

Comparison of Combustor Performance of Flat Plate Modules and Swirl-Can Modules

The same test facility and test section was used to evaluate the swirl-can combustor modules of reference 5 and the flat plate modules. Also since the same carburetor and swirler designs were used for both types of modules, the effects of replacing the conical combustor cans of reference 5 with flat plates can be determined. Forty-eight modules were used for both arrays and their inlets were positioned at the same axial location in the diffuser.

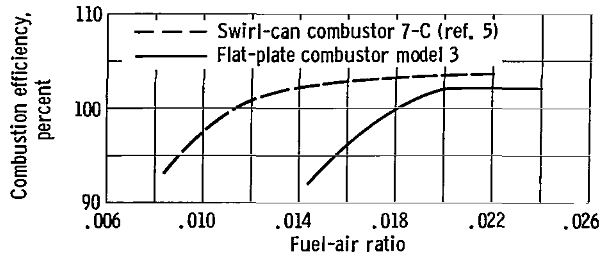


Figure 13. - Combustion efficiency of swirl-can modular combustor and flat-plate modular combustor. Inlet air temperature, 600° F (589 K); pressure, 3 atmospheres; nominal performance velocity, 80 feet per second (18.3 m/sec).

Combustion efficiency. - For both types of modules combustion efficiencies were reduced by decreasing fuel-air ratio and increasing reference velocity. Effects of decreasing fuel-air ratio was more pronounced for the flat plate modules as shown in figure 13. Since lower fuel-air ratios were not of primary interest, no attempt was made to improve performance by altering the flat plate geometry. Reductions in combustion efficiency at low fuel-air ratios occurring with the swirl-can combustor were minimized by reducing the airflow through the swirl-can carburetor. This was accomplished by reducing the flow area between swirler vanes by reducing vane angle. Similar swirler area flow reductions should be made for the flat plate modules if high efficiencies at low fuel-air ratios are required.

Pressure loss. - Pressure loss for a swirl-can and a flat plate modular combustor are compared in figure 14. Although the pressure loss of the flat plate combustor was higher than for the swirl-can combustor, a comparison of pressure loss should be qualified. The carburetor inlets for both arrays were located in the diffuser at the same axial location. However, since the flat plate modules were approximately 2 inches (5.1 cm) shorter, their maximum blockage (less than the swirl-can maximum blockage) occurred further upstream in the diffuser where the area was 12 percent less than the corresponding area for the swirl-can array. The Mach number past the trailing edges was therefore greater for the flat plate combustor for given inlet and reference Mach numbers.

Combustor exit temperature distribution. - Good combustor exit temperature distribution was obtained with both the swirl-can modular combustor of reference 5 and the model 3 flat plate combustor. The flat plate combustor produced slightly better results since the exit profiles conformed more closely to the design profiles. Better temperature contours and temperature distribution parameters were also obtained with the flat plate combustor. With 600° F (589 K) inlet air temperature fuel-air ratios up to 0.024 were achieved with the flat-plate combustor. Maximum local exit temperatures restricted performance of the swirl-can combustor to fuel-air ratios of 0.023 or less. With 1050° F

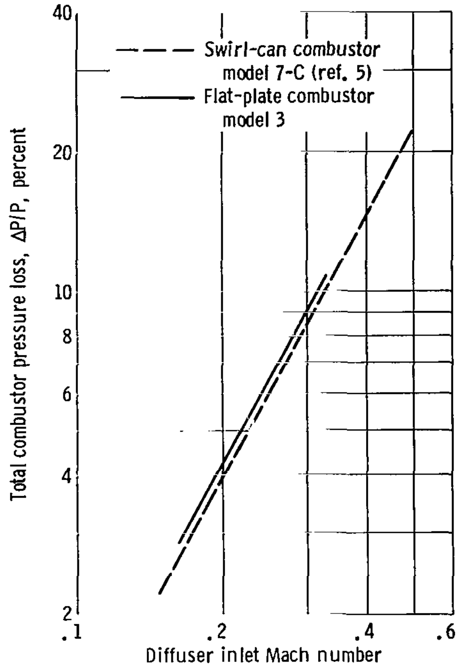


Figure 14. - Comparison of pressure loss of swirl-can combustor and flat-plate combustor. Combustor pressure, 3 atmospheres; combustor inlet air temperature, 600° F (589 K); combustor exit to inlet temperature ratio, 2.5.

(839 K) inlet air the flat plate combustor was operable up to fuel-air ratios of 0.0227, and the swirl-can combustor was restricted to fuel-air ratios of 0.0185 or less.

Altitude Blowout and Relight

The flat plate combustor exhibited better altitude blowout and relight performance than the swirl-can combustor of reference 5, with major differences occurring at lower inlet air temperatures. The swirl-can combustor did not relight with 200° F (367 K) inlet air at low inlet air pressure and produced resonance with 100° F (311 K) inlet air. The flat plate combustor relit at all pressures investigated with 200° F (367 K) inlet air and did not produce resonance. Although neither combustor could be relit with 100° F (311 K) inlet air, the flat plate combustor appeared to be more stable over the entire range of temperatures and pressures investigated. The improvement was probably due to increased flame paths between combustor modules.

Durability. - Although extended combustor durability tests were not made for either the flat plate combustor or the swirl-can combustor, the flat plate combustor appeared to be considerably more durable. Temperature sensitive coatings showed that maximum temperatures of the flat plate modules were below 1470° F (1072 K). No burnout problems were encountered. The swirl-can combustor modules, however, performed with the trailing edges of the combustor cans glowing. Occasionally combustor cans burned through. Thus swirl-can modules require further modifications, such as film cooling slots at their trailing edges. The flat plate modules appear capable of operation with higher inlet temperature and temperature rise.

CONCLUDING REMARKS

This experimental evaluation of a combustor module array using flat plate flame stabilizers is preliminary in nature. No extensive effort has yet been made to reduce the pressure loss or improve combustion efficiency at reduced fuel-air ratios. The encouraging results obtained to date, however, indicate that future module-type combustors should employ flame stabilizers consisting of flat plates or very shallow cans, rather than the deep cans previously used in references 2 to 5.

SUMMARY OF RESULTS

A 48 module combustor was evaluated in a rectangular test section with ASTM-A1 fuel. The modules were 1.56 inches (4.0 cm) long and consisted of a low pressure carburetor inlet, a swirler, and a flat plate. Test conditions were an inlet pressure of 3 atmospheres, combustor inlet air temperatures of 600 and 1050° F (589 and 839 K), and reference velocities up to 150 feet per second (45.7 m/sec).

The best combustor modification produced the following results:

1. Combustion efficiencies near 100 percent were obtained for average combustor exit temperatures of 2000° F (1366 K) or greater.

2. The overall pressure loss (including diffuser) was 6.4 percent at a diffuser inlet Mach number of 0.25 and a combustor exit to inlet temperature ratio of 2.5

3. Combustor exit temperature distribution improved with increasing combustor inlet-air temperature and fuel-air ratio. At an inlet-air temperature of 600° F (589 K), a fuel-air ratio of 0.024, and a reference velocity of 100 feet per second (30.5 m/sec), the temperature distribution parameters δ_{stator} and δ_{rotor} had values of 0.22 and 0.03, respectively. The pattern factor, $\overline{\delta}$, was 0.26. At an inlet-air temperature of 1050° F (839 K), a fuel-air ratio of 0.0217 and a reference velocity of 150 feet per second (45.7 m/sec) the values of these parameters were δ_{stator}, 0.12; δ_{rotor}, 0.04; $\overline{\delta}$, 0.15.

4. Exit temperature profile was improved by increasing blockage along the inner and outer surfaces of the diffuser and by supplying different amount of fuel flow to the combustor module rows.

5. Altitude blowout and relight tests showed that stable combustion occurred with inlet air temperatures and pressures of 100° to 600° F (311 to 589 K) and 0.5 to 2.5 atmospheres, respectively. Decreasing inlet-air temperatures and pressures produced corresponding decreases of maximum reference velocities for which stable combustion could be maintained. The combustor could be relit over the entire span of pressures with inlet air temperatures of 200° F (367 K) or greater. No ignition was achieved with 100° F (311 K) inlet-air temperature.

6. A performance comparison of the flat plate modular combustor with the best performing swirl-can modular combustor of reference 5 produced the following results: (a) combustion efficiency for the swirl-can combustor was higher, especially at lower fuel-air ratios; (b) the pressure loss for the flat plate combustor was 0.4 percent higher than for the swirl-can combustor; (c) the flat plate combustor produced better combustor exit temperature distributions thus allowing operation to higher fuel-air ratios; and (d) no durability problems were encountered with the flat plate combustor; module temperatures did not exceed 1470° F (839 K). Swirl can modules operated with glowing trailing edges and encountered occasional burnout problems.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 4, 1969,
720-03.

APPENDIX - INSTRUMENTATION

Airflow rates were measured by square-edged orifices installed according to ASME specifications. Fuel flows were measured by turbine type flowmeters which were connected to frequency-to-voltage converters.

Locations of pertinent instrumentation planes and arrangements of pressure and temperature probes are shown in figure 15. Pressures in the inlet section were measured by five rakes, each consisting of five-point total pressure tubes, and by four wall static pressure taps (section A-A, fig. 15). Temperatures were measured by 10 chromel-alumel thermocouples (section B-B, fig. 15). Combustor exit total pressures and tem-

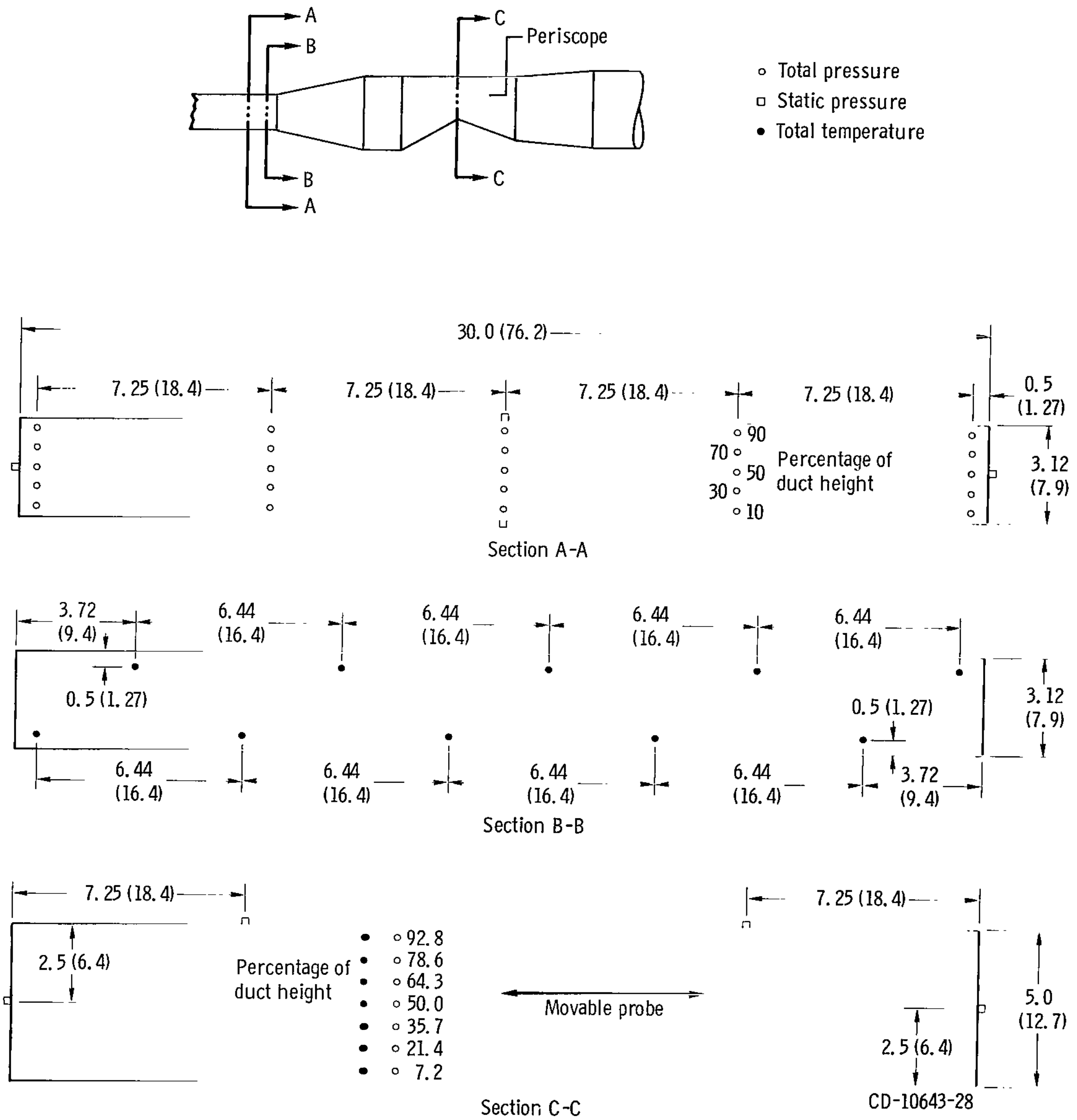


Figure 15. - Locations of pertinent instrumentation planes and locations of temperature and pressure probes in instrumentation planes. Dimensions are in inches (cm).

peratures were recorded by a movable seven-point total pressure and seven-point total-temperature rake (section C-C, fig. 15). The exit rake is shown in figure 16. The temperature probes were constructed of platinum-13-percent-rhodium platinum and were the high recovery aspirating type referred to as type 6 in reference 6. Four static pressure taps measured static pressure at the combustor exit plane. Temperature and presure surveys at the combustor exit were made by traversing the probe horizontally across the exit plane at a speed which produced approximately one reading every 0.5 inch (1.3 cm). Additional temperature and pressure instrumentation was placed in the diffuser and on the combustor liners to monitor combustor performance during test runs.

All pressures exclusive of the total pressures on the exit rake were measured and recorded by the laboratory's Digital Automatic Multiple Pressure Recorder (DAMPR). Exit probe total pressures were measured by strain-gage pressure transducers and were processed by the laboratory's Central Automatic Data Processing System (ref. 7), which also processed thermocouple and fuel flowmeter outputs.

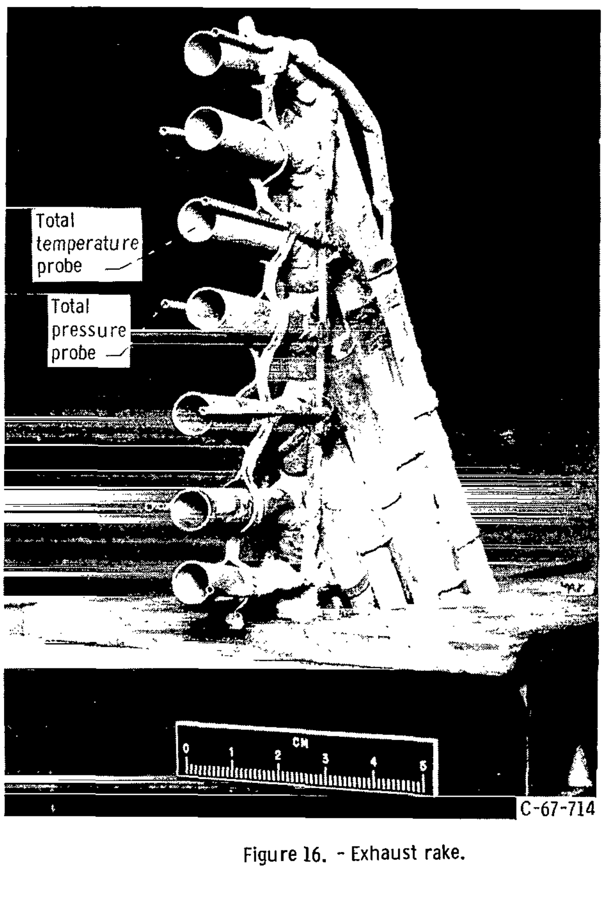


Figure 16. - Exhaust rake.

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