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PERFORMANCE OF SHORT LENGTH TURBOJET COMBUSTOR INSENSITIVE TO RADIAL DISTORTION OF INLET AIRFLOW

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16. Abstract

An annular turbojet combustor was designed to be insensitive to shifts in the radial velocity profile at the compressor outlet. No airflow was introduced into the combustor through the inner liner wall except for a small amount required for cooling. Thus, no large shifts in airflow between outer and inner liners could occur as a result of inlet velocity profile shifts. Also, scoops were added to the air entry ports on the outer liner. These scoops extended completely across the passage which carried the air to be admitted through the outer liner. Thus, each scoop captured the correct amount of air regardless of changes in the radial velocity profile near the air entry port it covered. Tests were conducted to evaluate the concept. A rectangular segment apparatus was used. Test conditions were atmospheric pressure, 600° F (589 K) inlet air temperature, and combustor average exit temperatures up to 2200° F (1478 K). Obstructions were installed in the inlet duct to produce the desired distortions of the inlet radial velocity profile. The fuel used was ASTM A-1. The tests showed that the temperature profile at the combustor exit was largely unaffected by severe shifts in the inlet radial velocity profile. In addition, the pattern factor obtained was low for a combustor of such short length.

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SUMMARY

An annular turbojet combustor was designed to be insensitive to shifts in the radial velocity profile at the compressor outlet. No airflow was introduced into the combustor through the inner liner wall except for a small amount required for cooling. Thus, no large shifts in airflow between outer and inner liners could occur as a result of inlet velocity profile shifts. Also, scoops were added to the air entry ports on the outer liner. These scoops extended across the passage which carried the air to be admitted through the outer liner. Thus each scoop captured the correct amount of air regardless of changes in the radial velocity profile near the air entry port it covered.

The combustor was 22 inches (0.559 m) long from compressor outlet to turbine inlet with a liner depth of 6.6 inches (0.168 m). The distance from the plane of the fuel nozzles to the turbine inlet was 14.0 inches (0.356 m).

Tests were conducted to evaluate the concept. A rectangular segment apparatus 10 inches (0.254 m) by 15 inches (0.381 m) was used. Test conditions were atmospheric pressure, 600° F (589 K) inlet air temperature, and combustor average exit temperatures up to 2200° F (1478 K). Obstructions were installed in the inlet duct to produce the desired distortions of the inlet radial velocity profile. The fuel used was ASTM A-1.

A number of configurations were tested during the program. The final configuration demonstrated the following performance. The exit temperature pattern factor ranged from 0.25 to 0.32. Average combustor exit temperatures near 2200° F (1478 K) were attained with measured combustion efficiencies from 90 to 95 percent. At these exit temperatures, the total pressure loss of the combustor (including the diffuser) was 5.3 percent at a diffuser inlet Mach number of 0.24. The temperature profile at the combustor exit was largely unaffected by severe shifts in the inlet radial velocity profile.

INTRODUCTION

Turbojet engines often encounter inlet flow distortions or require variations in engine speed which cause changes in the compressor outlet velocity distribution. When changes to the radial velocity profile occur, this can cause a redistribution of the airflow between the inner and outer annuli of a conventional annular combustor (ref. 1). Such a shift in combustor airflow can produce significant variations in the temperature distribution at the combustor exit. This jeopardizes the life of the turbine.

Remedy techniques have been suggested (ref. 1) which incorporate inlet profile correcting devices in the diffuser. One proposed device redistributes the airflow in the diffuser such that a uniform outlet profile is always achieved. Another device divides the compressor discharge annulus into sector passages formed by radial walls to alternately supply the inner and outer annuli. Such devices may be necessary with conventional annular combustors. However, a combustor concept which was previously investigated in reference 2, had only one passage to supply all the dilution air. The dilution air was passed through flush entry ports in a single liner wall of the combustor. Such an approach obviously has promise for relieving the flow distortion problem. Therefore, this concept was further investigated as part of the NASA program on very short, advanced annular combustors for high-temperature aircraft engines (ref. 3).

Based on the concept of reference 2, a combustor design was proposed to get insensitivity to radial variations of inlet airflow as well as short length. The proposed design is referred to as a side-entry combustor. The design differs from the one described in reference 2 in that scoops are added to the air entry slots in the outer combustion liner and extend to the full height of the airflow passage. The scoops capture on entire radial velocity sample and thus inject the proper air mass fraction into each air entry slot regardless of compressor radial profile shifts. By controlling the air splits and thereby keeping the dilution jet penetration relatively constant, the combustor exit temperature radial profile should remain steady even though inlet radial flow distortions occur. A further advantage of bringing all of the dilution air to the outside of the combustor is to increase the hydraulic radius of the combustion zone. This tends to increase combustion efficiency, as shown in reference 4.

An experimental investigation of limited scope was conducted with this side-entry combustor design to determine if the desired exit temperature profile could be achieved in conjunction with low pressure loss and reduced sensitivity to radially distorted inlet velocity profiles. A rectangular test section representative of a one-sixth sector of a full annular combustor was chosen for conducting this evaluation. The development plan was to first establish a design which achieved the desired exit temperature distribution, then to check its sensitivity to inlet flow distortion. Further development was directed toward achieving pressure-loss levels comparable to those of existing combustor designs while maintaining insensitivity to flow distortion.

Tests were conducted in a facility capable of only atmospheric exhaust. Inlet total temperature and inlet total pressure were held at nominal values of 600° F (589 K) and 1 atmosphere, respectively. The design average exit temperature was 2200° F (1478 K). ASTM A-1 fuel was used. Combustion efficiency, overall total pressure loss, and temperature distributions were obtained. Performance data for the final configuration with uniform and distorted inlet velocity profiles are presented. Supplementary data show performance for a range of fuel-air ratios and inlet Mach numbers.

APPARATUS AND PROCEDURE

Test Facility

The combustor test facility shown in figure 1 was supplied from a source of dry combustion air at a nominal air temperature of 50° F (283 K). The orifice was sized to measure flow rates up to 5 pounds per second (2.267 kg/sec) as set with the flow control valve. By exhausting directly to the atmosphere, combustor inlet pressures were maintained just slightly above the local barometric pressure. To attain combustor inlet air temperatures of 600° F (589 K), a direct-fired (vitiating) preheater heated a portion of the air supply which then was dumped and mixed with a bypassed portion in a large plenum chamber. The plenum chamber was 36 inches (0.914 m) in diameter and 56 inches

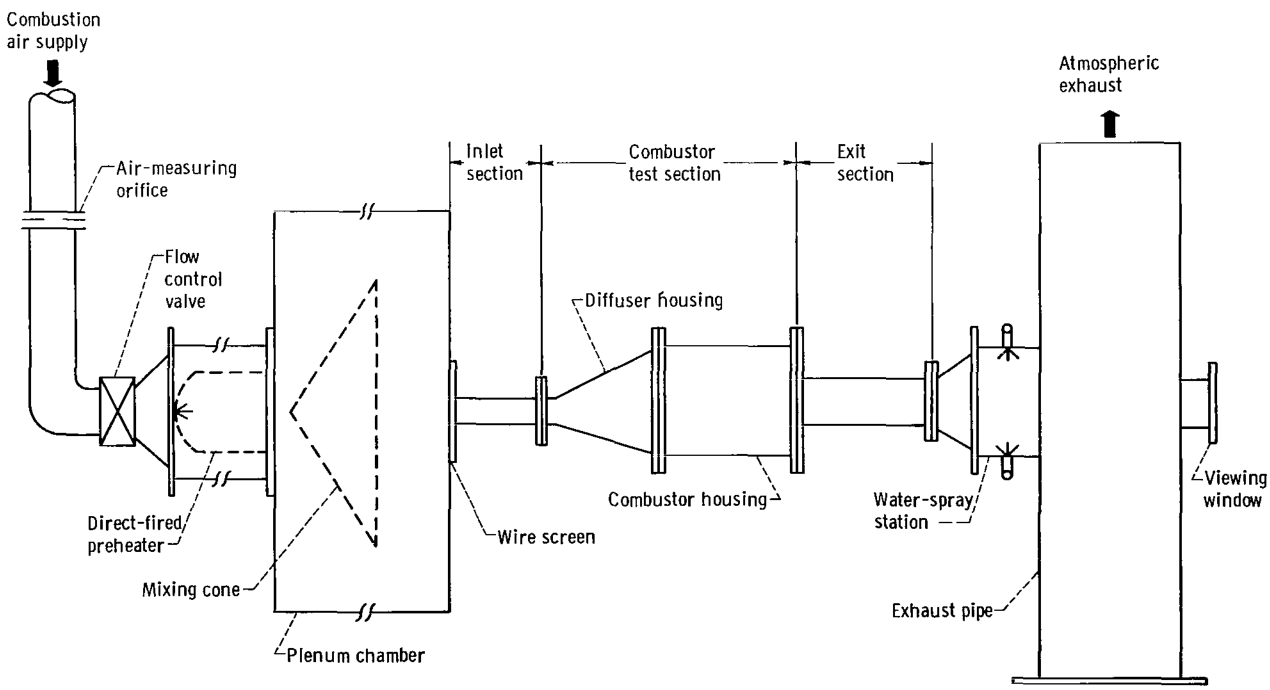


Figure 1. - Schematic diagram of combustor test facility

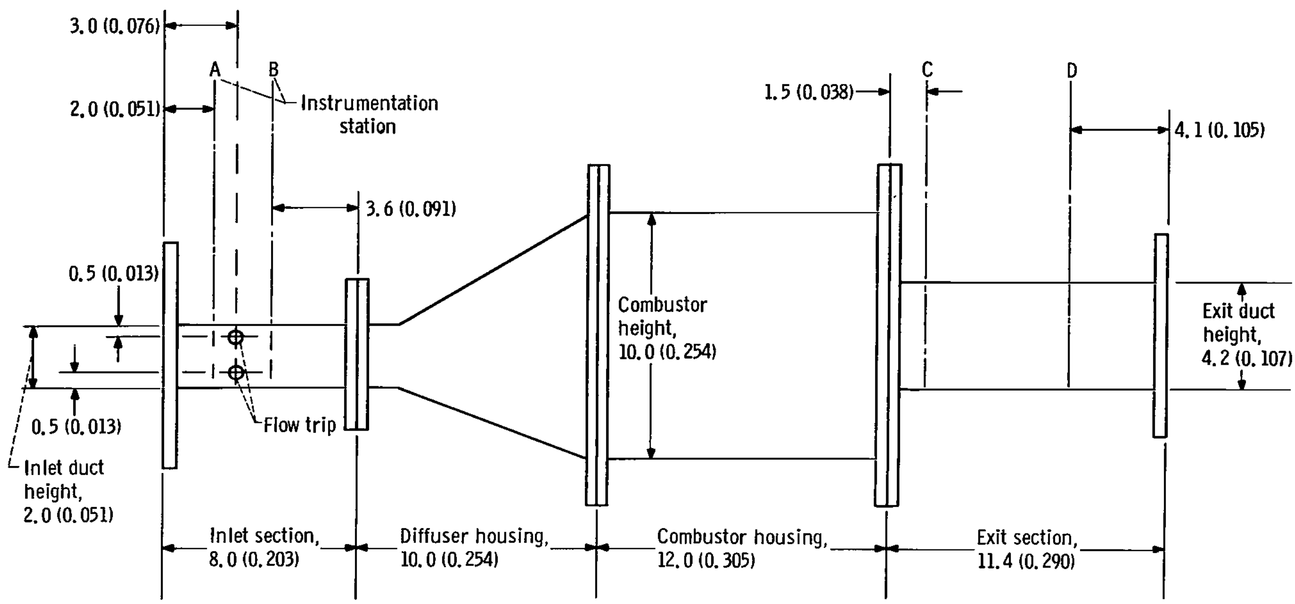


Figure 2. - Test sections and instrumentation stations. Dimensions are in inches (m).

(1.422 m) in length. A cone having a 120° included angle at the apex and a 24-inch (0.610-m) diameter at the base was mounted within the plenum chamber to aid mixing. Square-mesh wire fabric was installed at the exit of the plenum chamber to get nominal 3/16-inch (0.005-m) openings to aid in obtaining uniform inlet velocity profiles.

The rectangular test section assembly and the inlet and exit ducts shown in figure 2 were 15 inches (0.381 m) wide. The inlet section was 2 inches (0.051 m) in height and provided mounts for inlet total pressure rakes, thermocouple probes, and flow trip devices. To obtain a hub-peaked or tip-peaked inlet velocity profile, a 1/2-inch (0.013-m) diameter rod was installed across the duct at the appropriate flow trip location. The exit section was 4.2 inches (0.107 m) in height and provided mounts for exit temperature and pressure rakes. Water sprays downstream of the exit section quenched the combustion products before they were exhausted to the atmosphere. A vertical exhaust pipe enabled use of a viewing window for observation of combustor configurations during operation.

Instrumentation

Airflow rates were determined from a sharp-edged orifice installed according to ASME specifications. The orifice differential pressure was measured by a strain-gage-type pressure transducer whose output was read on a digital voltmeter. Upstream orifice pressure was measured with a Bourdon-tube-type direct indicating gage, and orifice

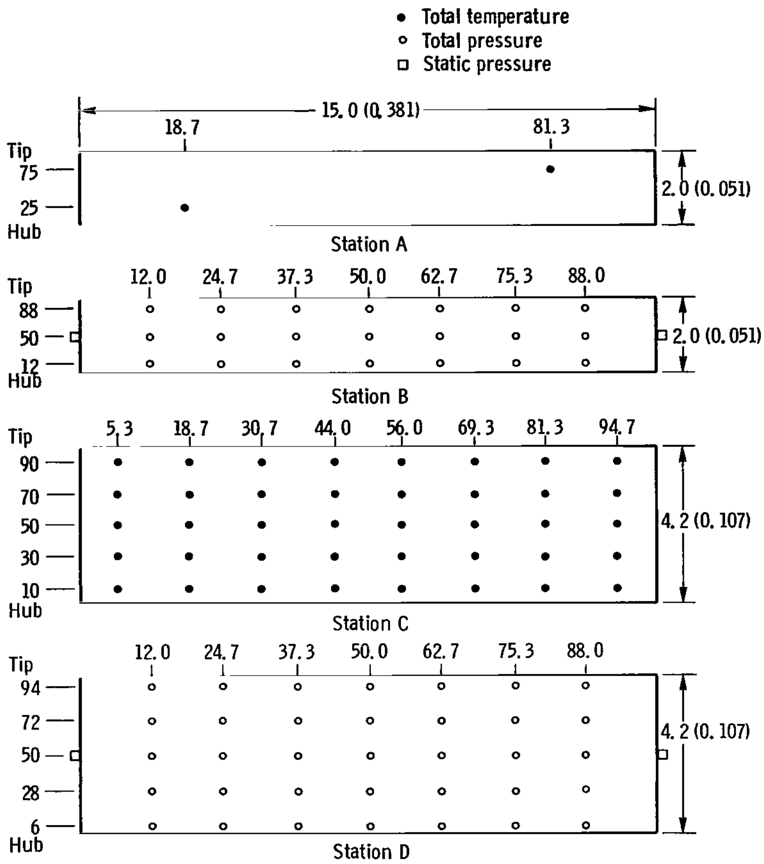
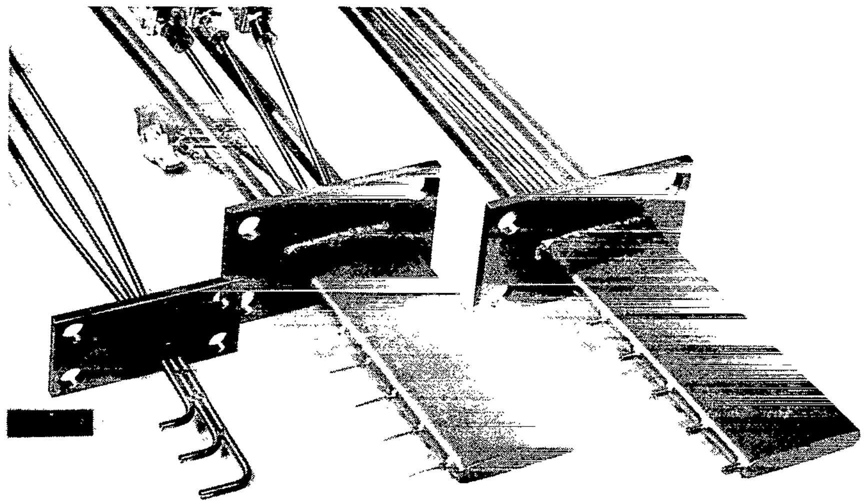


Figure 3. - Location of temperature and pressure probes in percentage of duct height and and width. Dimensions are in inches (m). Views are looking downstream. See figure 2 for station locations.

inlet temperature was measured with an iron-constantan thermocouple probe. Fuel flow rates were measured by turbine type flowmeters, with the output connected to a digital counter.

The location of the combustor inlet and exit instrumentation stations is shown in figure 2, and the details at these stations are shown in figure 3. At station A, two iron-constantan thermocouple probes provided a measurement of inlet temperature. At station B, seven rakes, each having three total pressure sensing points, provided measurement of inlet total pressure. At station C, eight water-cooled thermocouple rakes, each having five temperature sensing points, were installed to measure the combustor exit temperature distribution. The thermocouple wire was 24-gage platinum-13-percent-rhodium/platinum (ISA calibration R). These thermocouples were the exposed junction type having 0.5-inch (0.013-m) extension of bare wire from the support tubing to minimize conduction errors. At station D, seven water-cooled total pressure rakes, each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(a) Inlet total pressure, P_3. (b) Exit total temperature, T_4. (c) Exit total pressure, P_4.

Figure 4. - Instrumentation rakes.

having five total pressure sensing points, provided measurement of exit total pressure. The instrumentation rakes are shown in figure 4.

The iron-constantan thermocouples were read from an indicating-type, continuous balance potentiometer. The platinum-13-percent-rhodium/platinum thermocouples were read from a multipoint strip-chart-recording continuous balance potentiometer. Pressures were connected to banks of manometers referenced to atmospheric pressure. The manometer tubes were filled with a dibutyl phthalate fluid having a specific gravity of 1.04. Manometer board photographs were used to record the pressures.

In addition, a temperature sensitive paint was sometimes applied to the combustor parts to get an indication of local hot spots. This also helped to determine the internal flow characteristics of the combustor.

Probable accuracy of exit thermocouple readings was $\pm 20^{\circ}$ F (11.1 K) prior to any adjustment for radiation. The temperature adjustment for radiation was based on the method of reference 5. An unshielded-wedge-type exit thermocouple probe and a platinum wire emissivity of 0.3 were assumed. The typical adjustment amounted to 115° F (64 K) at an exit temperature reading of 2081° F (1412 K) and an exit Mach number of 0.22. Probable accuracy of inlet temperature readings was $\pm 10^{\circ}$ F (5.6 K). Pressures were read to the nearest 0.1 inch (0.0025 m) of displacement.

Combustor Design

The experimental combustor was designed to be installed in a rectangular housing 15 inches (0.381 m) wide and 10 inches (0.254 m) high. The rectangular shape was chosen to simplify fabrication of the combustor and instrumentation sections. The rectangular segment simulated a sector of an annular-type combustor housing having the same size and orientation of the diffuser inlet and the combustor exit as for the combustor described in reference 6. Thus the diffuser inlet height was 2 inches (0.051 m), and the combustor exit height was 4.2 inches (0.107 m). The length of the combustor test section was 22 inches (0.559 m). A view of the final combustor configuration is shown in figure 5, and a longitudinal cross section is shown in figure 6. Details of preliminary combustor configurations are presented in the appendix.

As shown in figure 5, individual inlet chutes are positioned between fuel nozzle locations. These chutes supply airflow for film cooling of the firewall and lower liner as well

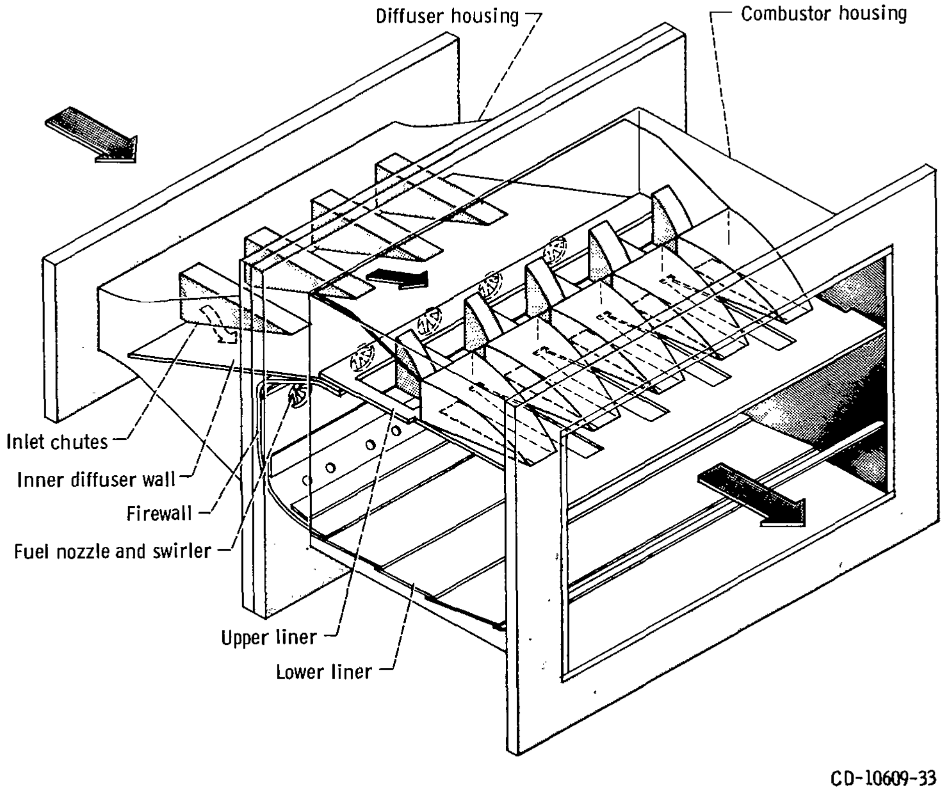


Figure 5. - Final model rectangular combustor and housing; liner II-9-F.

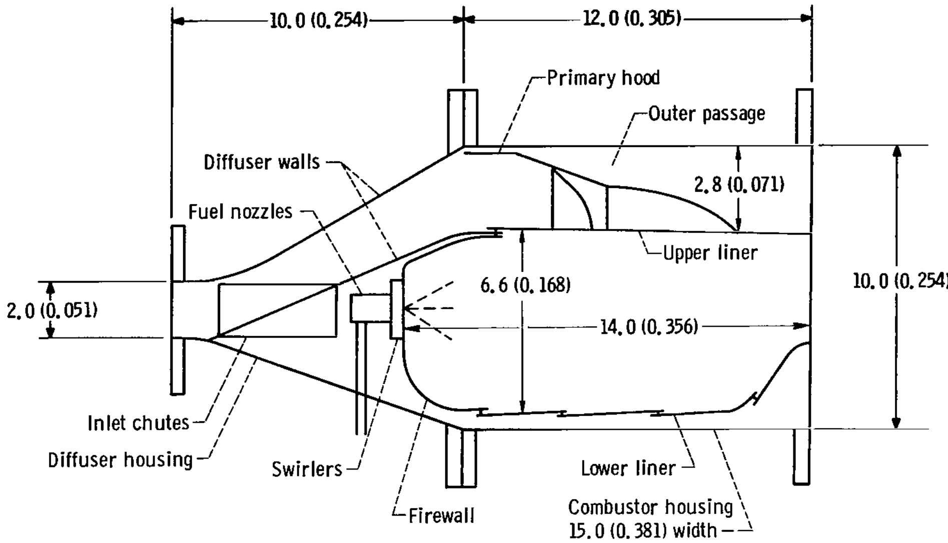


Figure 6. - Combustor test section: liner II-9-F. Dimensions are in inches (m).

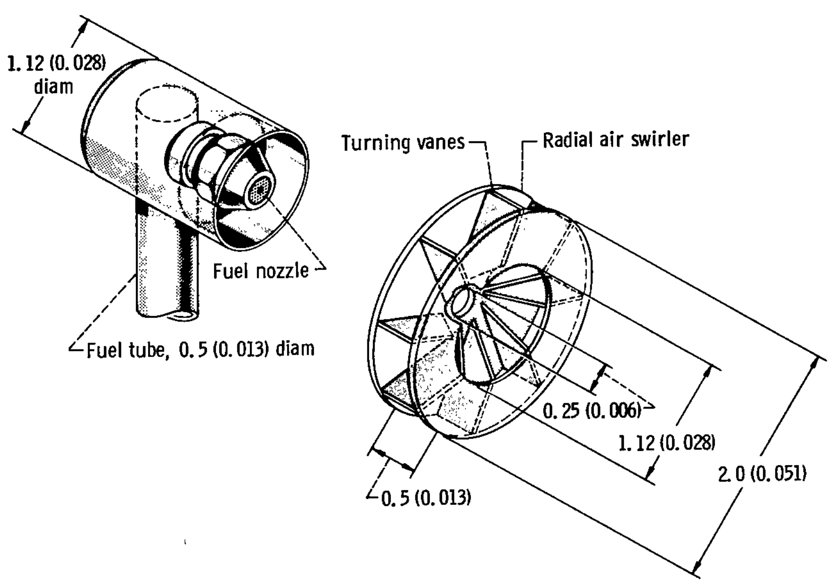


Figure 7. - Fuel nozzle holder and radial swirler assembly. Dimensions are in inches (m).

as sufficient air for the swirlers. The fuel nozzle and swirler assembly is shown in figure 7. The swirlers were a radial type having eight vanes indexed to give a 55° radial swirl angle. Five fuel nozzle locations were provided on the basis of 32 for a full annulus. Thus, the spacing between fuel nozzle centerlines was 3.0 inches (0.076 m). The fuel nozzles were a simplex type having a spray angle of 90°. The upper liner consisted of primary scoops to provide the air fraction required for stoichiometric combustion and secondary scoops to increase penetration and mixing to control the exit temperature profile. The final assembly of upper and lower liners to the firewall as installed in the diffuser housing is shown in figure 8. This view also shows the fuel nozzle locations, provisions for film cooling of the firewall, and the lower liner arrangement.

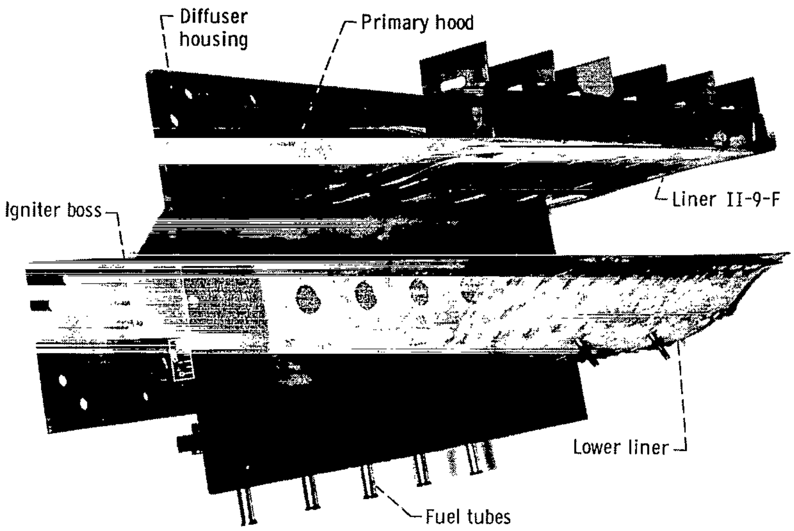
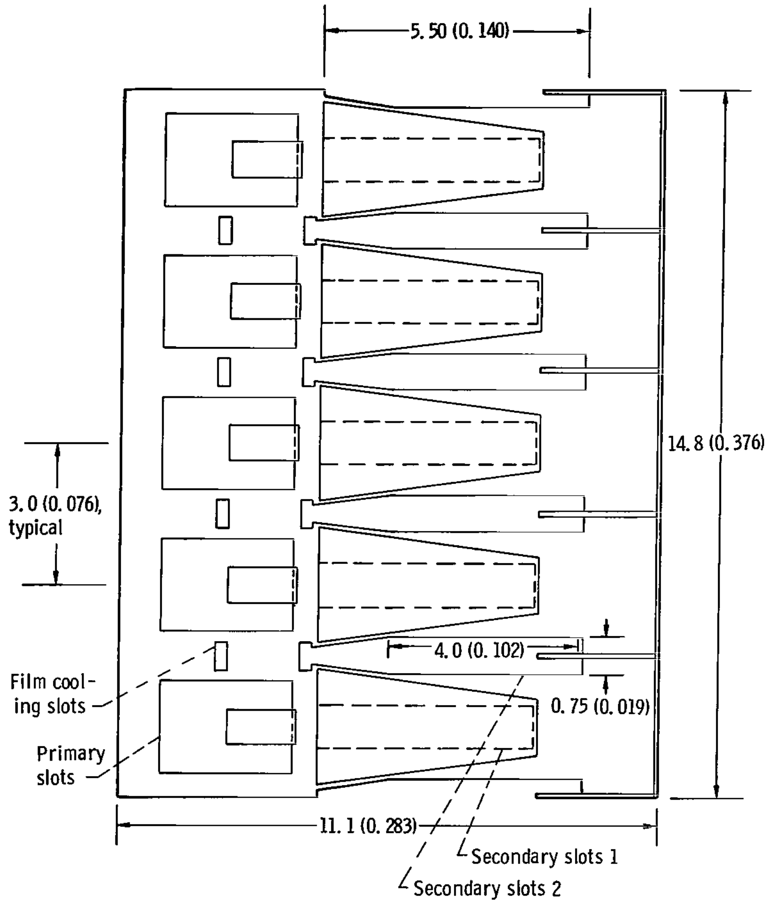
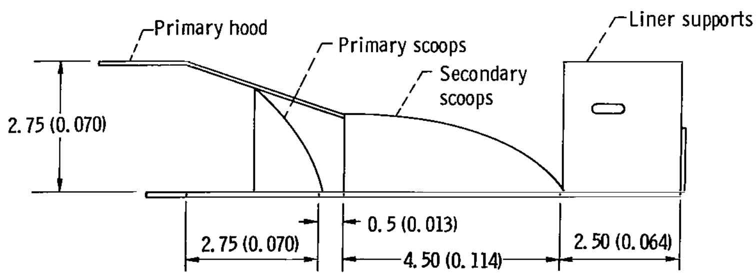


Figure 8. - Final combustor assembly: liner II-9-F.

Final liner configuration. - The final liner configuration designated II-9-F is shown in figure 9. Its design was based on an assumed overall air split of 15 percent to the inlet chutes and 85 percent to the outer liner (fig. 10). The primary scoops were sized to capture approximately one-fourth of the annulus air, or 21.2 percent. About 3.8 percent was estimated for film cooling so that secondary air was 60 percent. The secondary air was further subdivided for hub cooling and tip cooling. Hub cooling was accomplished by deep penetration of the dilution jets which are supplied with the aid of the secondary scoops attached to slots 1. Tip cooling is accomplished by shallow penetration of the set of dilution jets which are supplied by the flush slots 2. However, the gap between the



(a) Top view without hood.



(b) Side view.

Item	Width		Length		Height	
	in.	m	in.	m	in.	m
Primary slot	2.00	0.051	2.75	0.070	----	-----
Secondary slot 1	.87	.022	4.50	.114	----	-----
Secondary slot 2	.75	.019	5.50	.140	----	-----
Film cooling slots	.62	.016	.25	.006	----	-----
Primary scoop	.75	.019	1.38	.035	2.12	0.054
Secondary scoop	2.50	.064	4.50	.114	1.62	.041

Figure 9. - Liner II-9-F slot and scoop arrangement. Dimensions are in inches (m).

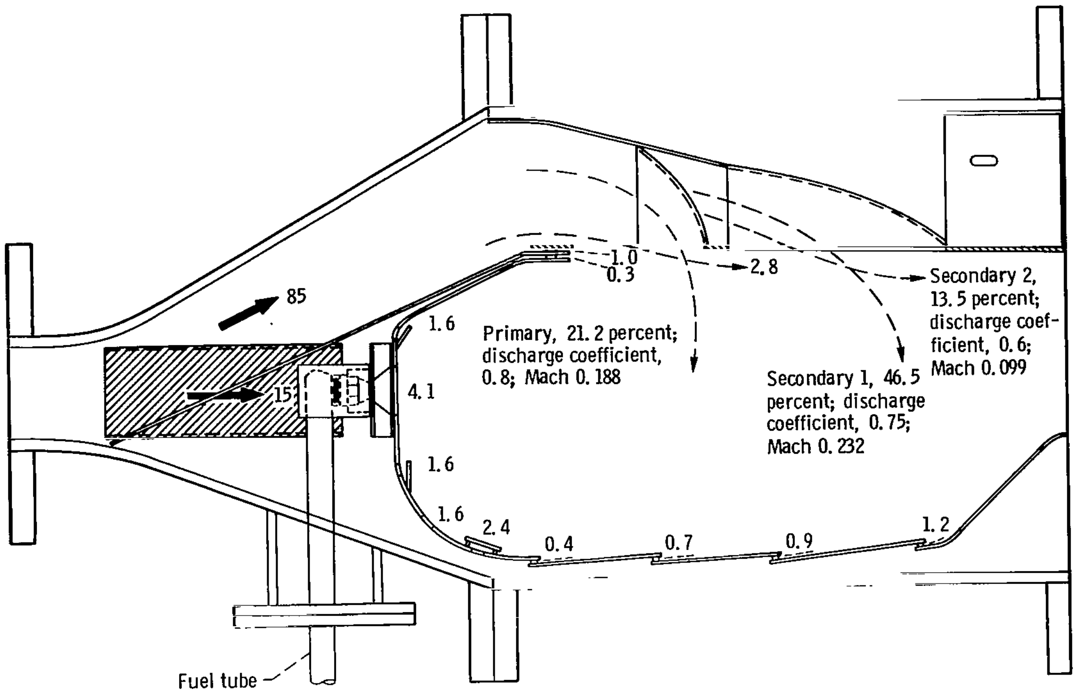


Figure 10. - Final combustor flow distribution: liner II-9-F. Numbers given are values of airflow in percent.

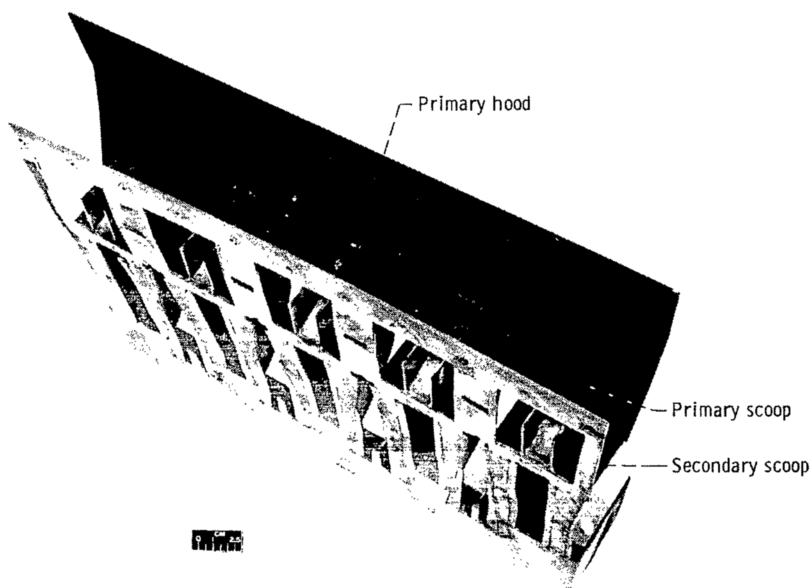


Figure 11. - Final outer liner configuration: liner II-9-F.

secondary scoops limited the flow to slots 2. Assuming that this gap area has a discharge coefficient of 1.0, the secondary air was subdivided to provide 46.5 percent through slots 1 and 13.5 percent through slots 2. From assumed discharge coefficients for each of these slots, dilution jet Mach numbers were calculated. These are included with the results of the calculated air split determination shown in figure 10. The final liner configuration is shown in figure 11.

Test Conditions

The data obtained to determine the performance of combustor configurations included exit temperature distribution, total pressure loss, and combustion efficiency. Two nominal test conditions, one at an inlet Mach number of 0.24 and another at a Mach number of 0.30 at an inlet temperature of 600° F (589 K) were used. Fuel-air ratios were set to approach design objective average exit temperatures of 2200° F (1478 K). The test conditions are listed in table I.

TABLE I. - NOMINAL TEST CONDITIONS

[Nominal inlet temperature, 600° F (589 K).]

Test condition	Diffuser inlet Mach number, M_3	Inlet total pressure, P_3		Airflow rate, W		Reference velocity[a], V_R		Combustor reference Mach number, M_R
		psia	N/m^2	lb/sec	kg/sec	ft/sec	m/sec	
A	0.24	16.0	1.103×10^5	3.17	1.44	77.8	23.7	0.049
B	.30	17.0	1.172	4.12	1.87	97.4	29.7	.061

[a]Computed from airflow rate, diffuser inlet static pressure and temperature, and maximum cross-sectional area of combustor housing (1.04 ft^2, 0.097 m^2).

Uniform inlet velocity profiles were used for general evaluation of combustor modifications. Whenever inlet flow distortion was to be simulated, a 1/2-inch (0.013-m) diameter rod was installed in the inlet duct at the locations provided, as shown in figure 2. To obtain a tip-peaked velocity profile, the rod was inserted at the lower position; for a hub-peaked velocity profile, the rod was inserted at the upper position. The inlet velocity profiles were established from the ratio of average inlet static pressure to average inlet total pressure at the three inlet radial height positions. The average inlet static pressure was determined from the inlet Mach number, which was calculated by the compressible flow expression using the average inlet total pressure and the measured total airflow. This method was chosen because the static pressures measured with the sidewall taps shown in figure 3 are sensitive to local static pressure variations occurring with distorted inlet velocity profiles.

A jet-type fuel conforming to ASTM A-1 specifications was used throughout the tests. The 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). A capacitor-type igniter with an energy of 20 joules was used. The igniter boss was located on a side wall of the diffuser housing.

RESULTS AND DISCUSSION

A turbojet combustor segment was designed with scoops in one annulus to obtain in-

TABLE II. - COMBUSTOR PERFORMANCE DATA: LINER II-9-F

Run	Inlet velocity profile	Diffuser inlet Mach number, M_3	Inlet total pressure, P_3			Airflow rate, W		Inlet total temperature, T_3		Total pressure loss, $\Delta P/P_3$, percent
			psia	N/m^2	atm[a]	lb/sec	kg/sec	$^{\circ}$F	K	
1	Uniform	0.241	15.84	1.092×10^5	1.086	3.11	1.41	598	588	5.34
2	Tip peaked	.236	16.04	1.106	1.097	3.09	1.40	595	586	6.06
3	Hub peaked	.236	16.22	1.118	1.110	3.12	1.42	595	586	6.95
4	Uniform	.299	16.64	1.147	1.141	3.92	1.78	600	589	8.22
5	Tip peaked	.290	16.85	1.162	1.152	3.92	1.78	595	586	9.03
6	Hub peaked	.285	17.04	1.175	1.166	3.90	1.77	595	586	10.06

Run	Reference velocity, V_R		Average exit temperature[b], T_4		Exit temperature profile quality factors			Average exit temperature[c], T_4'		Combustion efficiency, η, percent
	ft/sec	m/sec	$^{\circ}$F	K	$\bar{\delta}$ eq. (1)	δ_{stator} eq. (2)	δ_{rotor} eq. (3)	$^{\circ}$F	K	
1	77.0	23.5	2229	1494	0.27	0.30	0.05	2196	1476	97.5
2	77.0	23.5	2281	1522	.25	.31	.05	2194	1474	92.3
3	77.0	23.5	2294	1530	.32	.29	.08	2204	1480	93.0
4	94.4	28.8	2223	1490	.26	.26	.05	2172	1462	94.6
5	94.4	28.8	2227	1492	.25	.29	.05	2118	1432	93.0
6	94.0	28.7	2275	1520	.30	.26	.07	2160	1455	94.0

[a]Based on local barometric pressure.
[b]Based on central 30 exit temperatures individually adjusted for radiation and used to calculate the exit temperature profile factors δ_{stator}, δ_{rotor}, and $\bar{\delta}$.
[c]Based on entire 40 exit temperatures individually adjusted for radiation.

TABLE III. - SUPPLEMENTARY PERFORMANCE DATA: LINER II-9-F

Run	Diffuser inlet Mach number, M_3	Inlet total pressure, P_3			Airflow rate, W		Inlet total temperature, T_3		Total pressure loss, $\Delta P/P_3$, percent	Reference velocity, V_R		Average exit temperature[a], T_4'		Combustion efficiency, η, percent	Exit to inlet temperature ratio, T_4'/T_3	Fuel-air ratio, f/a	Pattern factor, $\bar{\delta}$ eq. (1)	Fuel nozzle supply pressure	
		psia	N/m^2	atm[b]	lb/sec	kg/sec	°F	K		ft/sec	m/sec	°F	K					psig	N/m^2 (gage)
1	0.244	15.67	1.081×10^5	1.096	3.09	1.40	605	592	5.67	77.8	23.7	2288	1526	88.2	2.58	0.0307	0.27	260	1.79×10^6
2	.246	15.56	1.073	1.088	↓	↓	611	595	5.75	----	----	1915	1320	90.1	2.22	.0224	----	135	9.30×10^5
3	.247	15.37	1.059	1.075	↓	↓	593	585	5.05	----	----	1443	1057	85.5	1.81	.0147	----	55	3.79×10^5
4	.248	15.28	1.053	1.068	↓	↓	587	582	4.81	----	----	1057	843	78.0	1.45	.0085	----	18	1.24×10^5
5	.250	15.26	1.052	1.067	3.08	↓	601	590	4.87	----	----	882	746	72.6	1.27	.0053	----	0	0
6	.251	15.17	1.046	1.061	3.10	1.41	595	586	4.67	----	----	----	----	----	1.0	------	----	---	--------
7	.245	15.40	1.062	1.056	3.07	1.39	593	585	4.36	77.8	23.7	----	----	----	1.0	------	----	---	--------
8	.310	16.51	1.138	1.154	4.04	1.83	610	594	8.87	99.4	30.3	2230	1494	88.6	2.51	.0292	.28	415	2.86×10^6
9	.312	16.44	1.133	1.156	4.07	1.85	607	593	9.23	----	----	2204	1480	92.5	2.50	.0274	----	365	2.52×10^6
10	.311	16.31	1.125	1.147	↓	↓	580	578	8.92	----	----	1862	1291	93.5	2.23	.0210	----	210	1.45×10^6
11	.318	16.13	1.112	1.134	↓	↓	600	589	8.54	----	----	1461	1067	89.5	1.81	.0142	----	90	6.20×10^5
12	.322	15.95	1.100	1.121	↓	↓	597	587	8.28	----	----	1052	840	82.6	1.43	.0078	----	25	1.72×10^5
13	.324	15.86	1.094	1.115	↓	↓	601	590	8.13	----	----	866	737	78.2	1.25	.0046	----	10	6.90×10^4
14	.326	15.80	1.089	1.110	↓	↓	604	591	8.20	----	----	----	----	----	1.0	------	----	---	--------

[a]Based on average of 40 exit temperatures adjusted for radiation.
[b]Based on local barometric pressure.

variant liner airflow distributions when inlet flow distortions occur. The results obtained with preliminary combustor configurations are presented in the appendix. Data for the final combustor configuration with uniform and distorted inlet velocity profiles are presented in table II. Supplemental performance data with uniform inlet velocity profiles are presented in table III. These data are discussed in the following paragraphs.

Exit Temperature Profiles

An important requirement of a combustor is that it provide the radial exit temperature profile required by the turbine. The design temperature profile in an actual engine combustor is determined from stress and structural considerations in the first-stage turbine stator and rotor. The design profile used for the tests reported herein is typical of ones required in advanced high-temperature engines. The goal of the tests was to not exceed the design profile by more than 100° F (55.6 K). The measured radial profile is established from the circumferential average of the temperatures at each radial position and is plotted as a deviation from average exit temperature against radial position. To eliminate any sidewall effects, the end-wall thermocouple readings were deleted from profile calculations.

To detect temperature nonuniformities which may not be evident in the average radial profiles, three temperature profile quality factors were calculated. The temperature pattern factor $\bar{\delta}$ is a ratio which reflects the magnitude of nonuniformity caused by the maximum local temperature. This factor is calculated as follows:

$$\bar{\delta} = \frac{T_{max} - T_{av}}{T_{av} - T_{in}} \tag{1}$$

where T_{max} is the maximum individual temperature at any point, T_{av} is the average exit temperature, and T_{in} is the average inlet temperature.

The factor δ_{stator} is a measure of the magnitude of temperature nonuniformity which affects turbine stator blades. This factor is calculated as follows:

$$\delta_{stator} = \frac{\left(T_{R,local} - T_{R,design}\right)_{max}}{\Delta T_{av}} \tag{2}$$

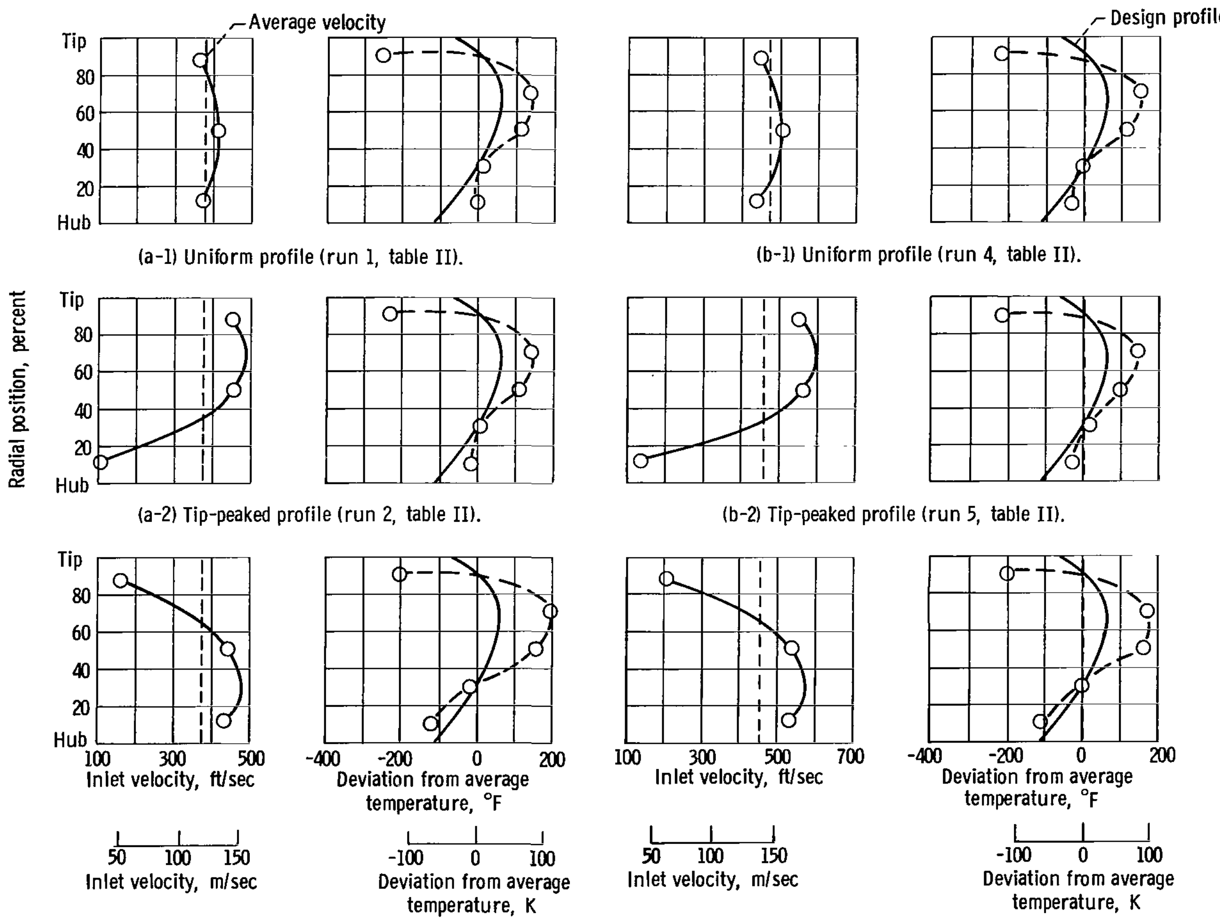
where $T_{R,local}$ is the individual temperature at a particular radial height which yields the maximum positive temperature difference with respect to the design temperature $T_{R,design}$ at that radial height, and ΔT_{av} is the temperature difference between the average exit temperature and the average inlet temperature.

The factor δ_{rotor} is a measure of the magnitude of temperature nonuniformity which affects turbine rotor blades. This factor is calculated as follows:

$$\delta_{rotor} = \frac{\left(T_{R,av} - T_{R,design}\right)_{max}}{\Delta T_{av}} \quad (3)$$

where $T_{R,av}$ is the average radial temperature at a particular radial height which yields the maximum positive temperature difference with respect to the design average radial temperature at the respective radial height position.

Measured temperatures were adjusted for the error due to radiation prior to calculating the profile quality factors. Low values for these factors are desirable as this in-



(a-3) Hub-peaked profile (run 3, table II).

(b-3) Hub-peaked profile (run 6, table II).

(a) Nominal inlet Mach number, 0.24.

(b) Nominal inlet Mach number, 0.30.

Figure 12. - Effect of inlet velocity profile on exit radial temperature profile: liner II-9-F.

dicates a low level of temperature nonuniformity.

Achieving the desired performance levels for this side-entry combustor design required considerable development effort, as outlined in the appendix. The average radial temperature profiles obtained for the final combustor configuration with and without flow distortion are shown in figure 12. With uniform inlet velocity profiles, satisfactory radial exit temperature profiles were obtained. When the inlet airflow was tripped to simulate a tip-peaked compressor outlet profile, the combustor radial exit temperature profile did not vary. When the inlet airflow was tripped to simulate a hub-peaked compressor outlet profile, the combustor radial exit temperature profile did not shift significantly. Thus, the desired insensitivity of the combustor radial exit temperature profile to radially distorted inlet velocity profiles was satisfactorily demonstrated.

For the tests at inlet Mach numbers of 0.24 (table II), the pattern factor δ ranged from 0.25 to 0.32, while δ_{stator} ranged from 0.29 to 0.31 and δ_{rotor} ranged from

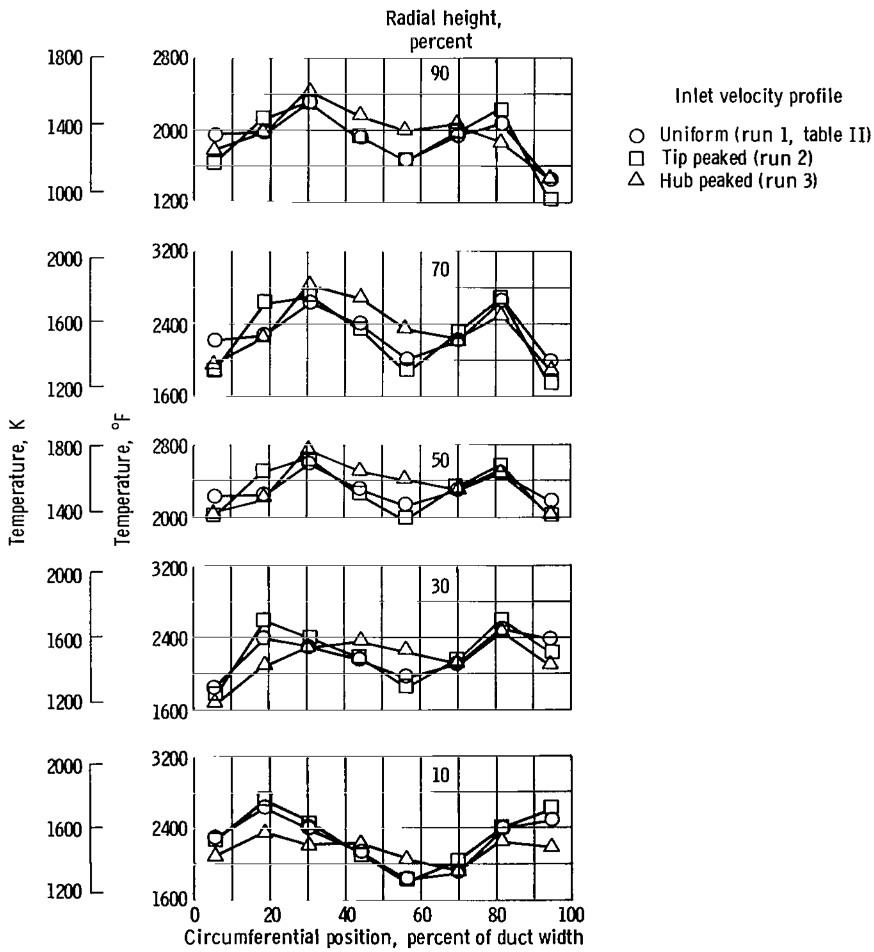


Figure 13. - Circumferential temperature distribution; liner II-9-F.

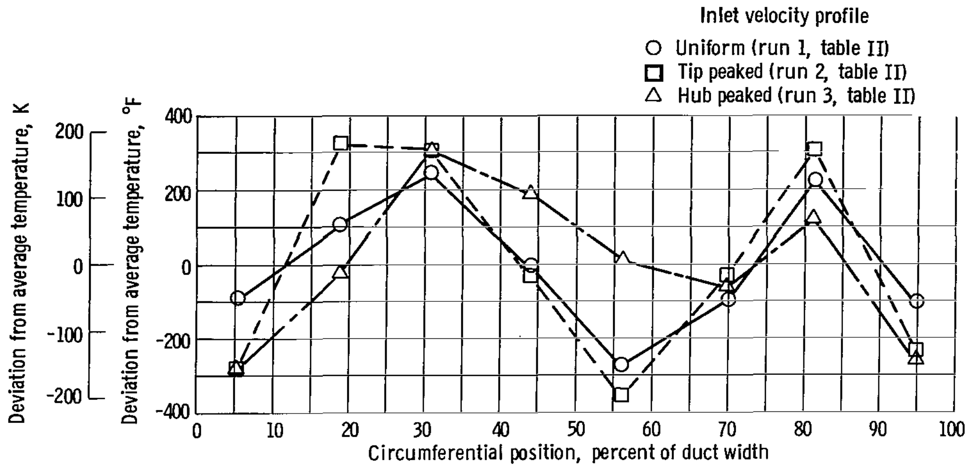


Figure 14. - Average circumferential temperature profiles: liner II-9-F.

0.05 to 0.08. For the tests at inlet Mach numbers of 0.30 (table II), the pattern factor $\bar{\delta}$ ranged from 0.25 to 0.30, δ_{stator} from 0.26 to 0.29, and δ_{rotor} from 0.05 to 0.07.

Any concentrated hot zones which may affect turbine stator blades are made evident by plotting the circumferential exit temperature profiles. Circumferential profiles showing the temperature variation at each radial height position are presented in figure 13 as typical for uniform and distorted inlet velocity profiles at inlet Mach numbers of 0.24. The corresponding average circumferential temperature profiles are shown in figure 14. Circumferential inlet airflow variations were less than 6 percent. Thus, the circumferential exit temperature profile peaks did not correspond to inlet velocity characteristics. Warpage of the combustor sheet metal was evident at the inner diffuser wall, and at the junction of the outer liner and the firewall. This warpage also did not appear to be related to the profile peaks.

Another characteristic of interest is the pattern of exit temperature isotherms. An exit temperature isotherm plot of run 1 (table II) is typical for all performance tests and is shown in figure 15. Two hot spots were noticeable, but did not appear to be related to the combustor geometry.

Total Pressure Loss

Combustor total pressure loss was defined by the following expression:

$$\frac{\Delta P}{P_3} = \frac{\text{(Average diffuser inlet total pressure) - (Average combustor exit total pressure)}}{\text{Average diffuser inlet total pressure}} \qquad (4)$$

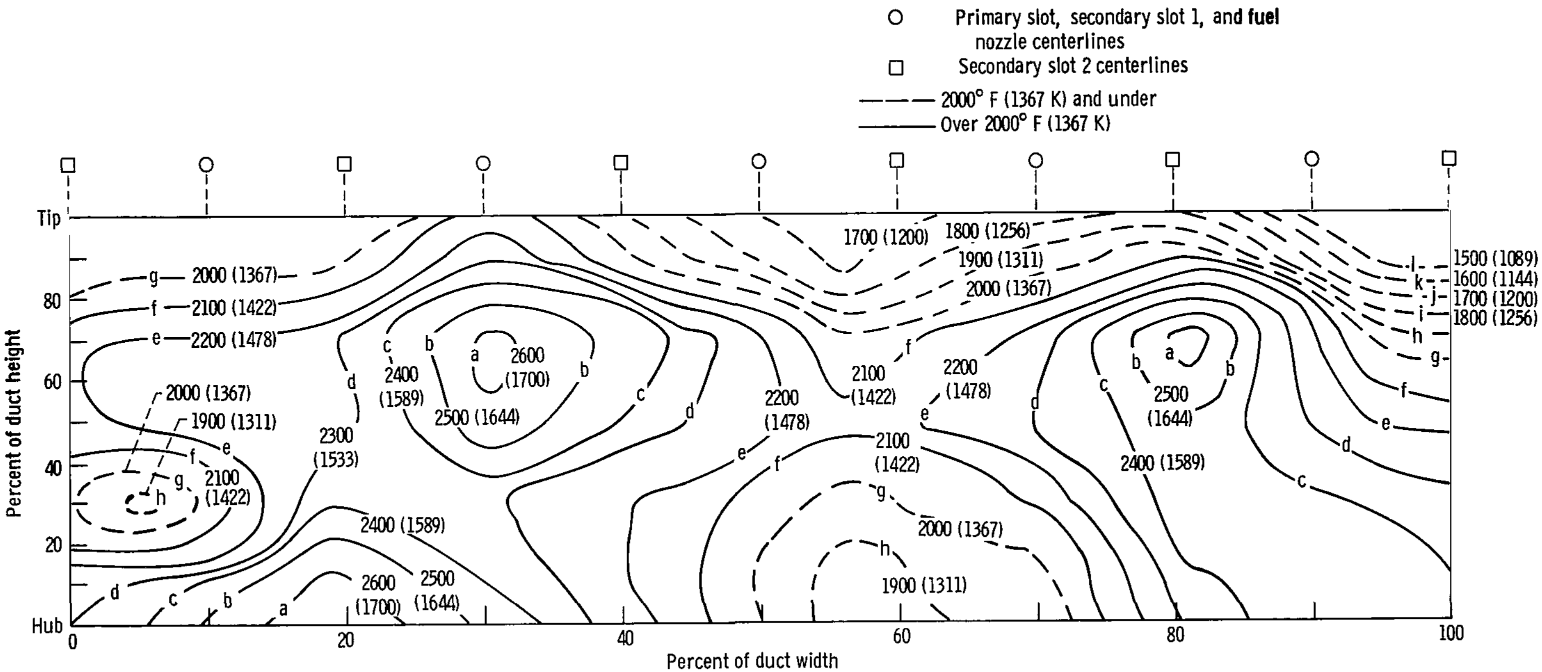


Figure 15. - Combustor outlet temperature distribution: liner II-9-F. Run 1 (table II); view looking downstream; temperatures are in °F (K).

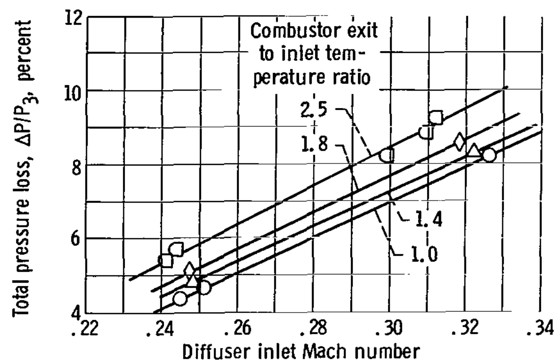


Figure 16. - Total pressure loss: liner II-9-F.

The pressure loss of the final combustor configuration is shown in figure 16 for various diffuser inlet Mach numbers and several ratios of combustor exit to inlet total temperature. Pressure loss, as expected, increases with increasing Mach number and increasing temperature ratio. At a diffuser inlet Mach number of 0.241 and temperature ratio of 2.5, the pressure loss was about 5.3 percent; for similar conditions at a Mach number of 0.299, the pressure loss was 8.22 percent. The amount of pressure loss with tip-peaked and hub-peaked inlet velocity profiles increased 0.72 and 1.61 percent, respectively, at test condition A, and 0.81 and 1.84 percent, respectively, for test condition B (table I). This was attributed to a degradation of diffuser performance with nonuniform inlet profiles. Detailed data are presented in table II.

Combustion Efficiency

Combustion efficiency was defined as the percentage ratio of actual enthalpy rise to theoretical enthalpy rise and was calculated by the method described in reference 7. The average exit temperature was first calculated using all 40 actual temperature readings. Then, a radiation adjustment based on the method of reference 5 and an estimate of the exit Mach number was used to obtain an adjusted exit temperature. Combustion efficiency was calculated using the enthalpy tables from reference 8 and standard enthalpy curves which account for the products of combustion. The accuracy of the combustion efficiency calculation is believed to be of the order of ±5 percent. Aspirating-type exit thermocouple probes (ref. 6) would have provided more reliable measurements. Since this program was preliminary in scope, the unshielded wedge-type probe was considered to be adequate. Additional data (table III) were taken to check the variation of combustion efficiency with fuel-air ratio. These results are shown in figure 17. Combustion efficiency was better at the higher reference velocity. At the design fuel-air ratio of 0.025 and nominal reference velocities of 77 and 100 feet per second, the combustion ef-

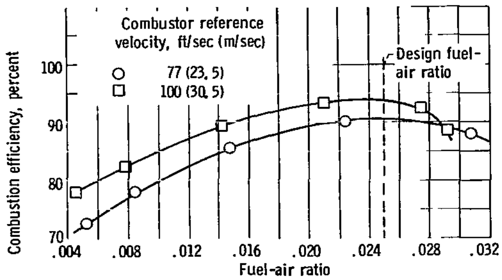


Figure 17. - Combustion efficiency: liner II-9-F.

ficiency was 90.5 and 93.7 percent, respectively. The fuel nozzle supply pressure was correspondingly higher for the higher reference velocity (table III). At low fuel-air ratios the fuel supply pressure was low and probably affected the fuel spray characteristics. No extensive effort was made to improve efficiency since the program was preliminary in scope.

SUMMARY OF RESULTS

A short length turbojet combustor, designed to be insensitive to variations in inlet radial velocity distribution, was tested with ASTM A-1 fuel at the following nominal conditions: combustor-inlet pressure, 1 atmosphere; combustor-inlet temperature, 600° F (589 K); combustor exit temperature, 2200° F (1478 K).

The final combustor configuration produced the following results:

1. Satisfactory exit temperature radial profiles were achieved and did not vary appreciably when the combustor inlet radial velocity profiles were purposely distorted to produce peak velocities at different radial positions.

2. At a diffuser inlet Mach number of 0.241 and temperature ratio of 2.5, the overall pressure loss (including diffuser) was about 5.3 percent; for similar conditions at a Mach number of 0.299, the pressure loss was 8.2 percent.

3. Temperature profile quality factors were reasonably low, indicating satisfactory temperature distribution. The pattern factor δ ranged from 0.25 to 0.32, while δ_{stator} ranged from 0.26 to 0.31 and δ_{rotor} ranged from 0.05 to 0.08.

4. At the design fuel-air ratio of 0.025 and nominal reference velocities of 77 and 100 feet per second, the combustion efficiency was 90.5 and 93.7 percent, respectively. No extensive effort was made to improve efficiency since the program was preliminary in scope.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 24, 1969,
720-03.

APPENDIX - PRELIMINARY DESIGN AND DEVELOPMENT

Two basic side-entry configurations were originally selected for design and fabrication; namely, Model I to simulate zero diffusion to the outer annulus and Model II to simulate 7^o diffusion to the outer annulus. A combustor burning length of 14 inches (0.356 m) was selected. This allowed for a primary zone length comparable to the height of the combustor and a secondary zone length compatible with previous experience with mixing zones. Initial designs were based on an air split of 10 percent to the inlet chutes and 90 percent to the outer annulus, which was subdivided into 40 percent for the primary and 50 percent for the secondary. A pressure loss of 8 percent for nonburning flow at an inlet Mach number of 0.244 and an inlet pressure of 17 psia (1.172×10^5 N/m^2) were used for design calculations.

To determine the required hole areas for these initial configurations, an average hole discharge coefficient of 0.75 was assumed for the primary zone and a coefficient of 0.6 for the secondary zone. The equation for flow through flame-tube holes given in references 9 and 10 was used together with calculated flow conditions in the diffuser passage and annulus. Dilution jet penetration and film cooling requirements were also calculated. Primary slots were initially aligned with the fuel nozzle locations, and the secondary slots were staggered. The resulting liner flow areas and pertinent dimensions are presented in table IV, and designated I-1-A and II-1-A, respectively. Performance characteristics are contained in table VIII. In order to reduce pressure loss, the slot flow areas were increased, as suggested in reference 11. This also led to subsequent outer liner designs, as outlined in tables IV to VIII. The basic liner design is designated by a numeral and the significant modifications by a letter in respective sequence.

To establish this combustor concept as practical, a pressure loss of less than 6 percent for test condition A (table I) was desired. In the course of achieving this, the development effort led to an assortment of exit temperature profiles and other performance variations. Of special interest was the profile characteristic produced with liner II-7-A(8), where the number in parentheses refers to an additional modification (see table VIII). The exit temperature profile was cold in the mid-span region. To account for such an effect, it was reasoned that the large secondary slot areas had reduced penetration. In addition, when wide secondary slots were used, a very close spacing of the dilution jets resulted. This actually caused a blockage in the combustor which prevented proper mixing. The dilution jets entered the combustor, spread, and coalesced, preventing mixing with the hot gases. By reducing the width of secondary slot 1, part of this blockage was removed, and the jets penetrated deeper. This was consistent with the results of the dilution jet mixing study (ref. 12), which showed that mixing was improved for flush holes of rectangular shape both with and without external scoops by increasing the hole spacing. Thus, the key modification (II-7-C(1)) was a reduction of the width of secondary slot 1 to achieve greater depth of jet penetration. The addition of flush secondary slots 2 provided shallow penetration and mixing to control hot tip temperatures.

Liner II-9-A was patterned from the results and analysis derived from liner II-7-C(1). The primary scoops were enlarged slightly to improve combustion efficiency. A few tests were necessary to determine the final tailoring of the slots to compensate for the change in the primary. The penetration and mixing technique developed with liner II-7-C(1) was sufficient to guide the modification procedure. The final liner configuration is shown in figure 9 and is designated II-9-F.

This investigation also revealed other effects of the various modifications. In particular, the inlet chutes did not cause any noticeable effect on pressure loss. The Model II diffuser contour produced lower pressure loss. The contour of the secondary scoops seemed significant in aiding penetration with a converging shape to maintain high air velocities. Comparisons of the exit temperature profiles for the various liner configurations indicated that the scoops were effective in controlling air splits and maintaining constant jet penetration with higher discharge coefficients.

The in-line scoop and slot arrangement (liner II-5-A) was based on the concept that in-line jets will aid and reinforce each other to effect better penetration (ref. 13). The final liner configuration utilized this technique, but also required additional flush secondary slots to be staggered to achieve the desired exit temperature profile and pressure loss.

TABLE IV. - LINER CONFIGURATIONS WITH STAGGERED PRIMARY AND SECONDARY SLOTS

Liner designation	Primary slots (5)			Secondary slots (5)			Primary scoops (5)				Secondary scoops (5)			
	Total area		Length-width ratio, L/W	Total area		Length-width ratio, L/W	Width		Height		Width		Height	
	in.^{2}	m^2		in.^{2}	m^2		in.	m	in.	m	in.	m	in.	m
I-1-A	11.3	0.729×10^{-2}	2.5	33.2	2.142×10^{-2}	2.5	1.4	0.036	1.7	0.043	1.6	0.041	2.1	0.053
I-1-B	16.4	1.058	1.7	33.2	2.142	2.5	↓	↓	↓	↓	↓	↓	↓	↓
I-1-C	11.9	.768	2.4	20.5	1.323	4.1	↓	↓	↓	↓	↓	↓	↓	↓
I-1-D	16.2	1.045	3.6	25.2	1.626	3.5	↓	↓	↓	↓	↓	↓	↓	↓
I-1-E	26.2	1.690	2.7	30.0	1.936	4.2	↓	↓	↓	↓	↓	↓	↓	↓
I-1-F	26.2	1.690	2.7	48.0	3.097	3.8	↓	↓	↓	↓	↓	↓	↓	↓
I-1-G	24.2	1.561	2.7	46.0	2.968	3.8	↓	↓	↓	↓	↓	↓	↓	↓
II-1-A	11.7	0.754×10^{-2}	2.7	18.7	1.207×10^{-2}	2.6	1.4	0.036	2.8	0.071	1.7	0.041	2.9	0.074
II-1-B	15.3	.987	3.5	24.6	1.587	3.4	↓	↓	↓	↓	↓	↓	↓	↓
II-1-C	20.8	1.342	3.4	34.8	2.245	2.4	↓	↓	↓	↓	↓	↓	↓	↓
II-1-D	25.5	1.645	2.8	34.8	2.245	2.4	↓	↓	↓	↓	↓	↓	↓	↓
II-1-E	20.4	1.316	2.2	34.8	2.245	2.4	↓	↓	↓	↓	↓	↓	↓	↓
II-1-F	20.8	1.342	3.3	34.8	2.245	2.4	↓	↓	↓	↓	↓	↓	↓	↓
II-2-A	15.3	0.987×10^{-2}	3.5	24.6	1.587×10^{-2}	3.4	0.9	0.023	2.8	0.071	1.9	0.048	2.9	0.074
II-3-A	15.3	0.987×10^{-2}	3.5	24.6	1.587×10^{-2}	3.4	1.4	0.036	2.8	0.071	1.5	0.038	2.9	0.074
II-3-B	11.7	.754	2.7	18.7	1.207	2.6	1.4	.036	2.8	.071	1.5	.038	2.9	.074
II-4-A	25.0	1.613×10^{-2}	4.0	31.2	2.012×10^{-2}	4.0	1.3	0.033	2.8	0.071	1.6	0.041	2.8	0.071
II-4-B	31.3	2.020	4.9	25.0	1.613	3.2	1.4	.036	↓	↓	1.3	.033	↓	↓
II-4-C	31.3	2.020	4.9	25.0	1.613	3.2	1.6	.041	↓	↓	1.3	.033	↓	↓
II-4-D	38.8	2.503	4.3	20.0	1.290	4.0	2.0	.051	↓	↓	.9	.023	↓	↓

TABLE V. - LINER CONFIGURATIONS WITH IN-LINE PRIMARY AND SECONDARY SLOTS

Liner designation	Primary slots (5)			Secondary slots (5)			Primary scoops (5)				Secondary scoops (5)			
	Total area		Length-width ratio, L/W	Total area		Length-width ratio, L/W	Width		Height		Width		Height	
	in.^{2}	m^2		in.^{2}	m^2		in.	m	in.	m	in.	m	in.	m
II-5-A	25.0	1.613×10^{-2}	3.0	31.2	2.012×10^{-2}	3.8	1.3	0.033	2.8	0.071	---	-----	---	-----
II-5-B	39.0	2.516	2.0	18.8	1.213	1.7	---	-----	---	-----	3.0	0.076	2.8	0.071
II-5-C	39.0	2.516	2.0	24.4	1.575	2.2	2.0	.051	2.8	.071	1.8	.046	2.8	.071
II-5-D	46.4	2.993	1.6	24.4	1.575	2.2	2.0	.051	2.8	.071	1.8	.046	2.8	.071
II-6-A	27.5	1.775×10^{-2}	1.4	33.8	2.180×10^{-2}	3.0	1.4	0.036	2.8	0.071	2.9	0.074	2.8	0.071
II-7-A	27.5	1.775×10^{-2}	1.4	33.8	2.180×10^{-2}	3.0	---	-----	---	-----	2.9	.074	1.6	0.041

TABLE VI. - LINER CONFIGURATIONS WITH IN-LINE AND STAGGERED SECONDARY SLOTS

Liner designation	Primary slots 1 (5)			Secondary slots 1 (5)			Secondary slots 2 (5)			Primary scoops (5)				Secondary scoops 1 (5)			
	Total area		Length-width ratio, L/W	Total area		Length-width ratio, L/W	Total area		Length-width ratio, L/W	Width		Height		Width		Height	
	in.^{2}	m^2		in.^{2}	m^2		in.^{2}	m^2		in.	m	in.	m	in.	m	in.	m
II-7-B	27.5	1.775×10^{-2}	1.4	33.8	2.180×10^{-2}	3.0	5.0	0.322×10^{-2}	4.0	0.5	0.013	2.1	0.053	2.9	0.074	1.6	0.041
II-7-C	27.5	1.775	1.4	28.1	1.813	3.6	7.5	.484	2.7	.5	.013	2.1	.053	2.9	.074	1.6	.041
II-9-A	27.5	1.775×10^{-2}	1.4	28.1	1.813×10^{-2}	3.6	8.0	0.516×10^{-2}	2.0	0.8	0.020	2.1	0.053	2.5	0.064	1.6	0.041
II-9-B	↓	↓	↓	23.8	1.535	4.2	12.4	.800	3.5	↓	↓	↓	↓	↓	↓	↓	↓
II-9-C				21.2	1.368	3.8	15.5	1.000	4.5								
II-9-D				19.7	1.271	5.1	19.4	1.252	4.5								
II-9-E				16.9	1.090	6.0	27.5	1.775	3.7								
II-9-F				16.9	1.090	6.0	19.5	1.258	7.3								

TABLE VII. - LINER CONFIGURATIONS WITH IN-LINE AND STAGGERED PRIMARY SLOTS

Liner designation	Primary slots 1 (5)			Primary slots 2 (5)			Secondary slots 1 (5)			Primary scoops (5)				Secondary scoops (5)			
	Total area		Length-width ratio, L/W	Total area		Length-width ratio, L/W	Total area		Length-width ratio, L/W	Width		Height		Width		Height	
	in.^{2}	m^2		in.^{2}	m^2		in.^{2}	m^2		in.	m	in.	m	in.	m	in.	m
II-8-A	13.8	0.890×10^{-2}	2.8	13.8	0.890×10^{-2}	2.8	33.8	2.180×10^{-2}	3.0	---	-----	---	-----	2.9	0.074	1.6	0.041
II-8-B	20.6	1.329	1.8	6.9	.445	5.5	33.8	2.180	3.0	---	-----	---	-----	2.9	.074	1.6	.041

TABLE VIII. - PRELIMINARY COMBUSTOR PERFORMANCE

Liner designation	Figure	Descriptive features	Performance characteristics
I-1-A(1)	18	Original design with staggered slots	Hot hub profiles; $\bar{\delta} = 0.4$ (approx); high pressure loss
I-1-A(2)	--	Row of firewall cooling holes	
I-1-A(3)	--	Additional firewall cooling holes	
I-1-B(1)	--	Secondary scoops deleted; primary slots enlarged; firewall cooling deflector	Hot hub profile; lower firewall temperatures, $\bar{\delta} = 0.5$ to 0.6 (approx)
I-1-B(2)	--	Secondary scoops with three turning vanes each	Increased firewall temperatures; $\bar{\delta} = 0.7$ (approx)
I-1-B(3)	--	Primary scoops with three turning vanes each	No significant improvement
I-1-B(4)	--	One-inch (0.025-m) internal extension of secondary scoops	Hot hub profile unchanged
I-1-C	--	Narrow primary and secondary slot widths, similar to II-1-A	Flat profile; $\bar{\delta} = 0.26$; $\Delta P/P_3 = 11.3$ percent at $M_3 = 0.26$ (approx)
I-1-D	--	Primary slots elongated	Fair profile; $\bar{\delta} = 0.5$ to 0.7 due to hot spot
I-1-E	--	Primary slots widened; secondary slots elongated	Hot hub profile; $\bar{\delta} = 0.9$ (approx)
I-1-F	--	Secondary slots enlarged; secondary scoop contour reduced	Hot hub profile; $\bar{\delta} = 0.5$ (approx); $\Delta P/P_3 = 8.1$ percent at $M_3 = 0.26$ (approx)
I-1-G	--	Lower liner contour revised	Hot hub profile; $\bar{\delta} = 0.9$ (approx)
II-1-A(1)	19	Original design with staggered slots	Ideal profile; $\bar{\delta} = 0.17$ to 0.20; $\Delta P/P_3 = 9.8$ percent at $M_3 = 0.264$
II-1-A(2)	20	Tests with flow trips	Insensitivity was demonstrated; $\bar{\delta} = 0.19$ to 0.23
II-1-B	--	Primary and secondary slots lengthened to reduce total pressure loss	Some profile shift to hot hub; $\bar{\delta} = 0.20$ to 0.24; $\Delta P/P_3 = 8.0$ percent at $M_3 = 0.27$; $\Delta P/P_3 = 13.0$ percent at $M_3 = 0.33$ (est.)
II-1-C(1)	--	Primary slots enlarged; secondary slots widened	Hot hub profile; $\bar{\delta} = 0.4$ to 0.5; $\Delta P/P_3 = 7.1$ percent at $M_3 = 0.27$ (est.)
II-1-C(2)	--	Inlet chutes enlarged; firewall cooling added	Hot hub profile; $\bar{\delta} = 0.4$ (approx); $\Delta P/P_3 = 6.8$ percent at $M_3 = 0.27$ (est.)
II-1-C(3)	--	Lower liner raised to reduce height in secondary zone	Extreme hot spot near hub; $\bar{\delta} = 1.33$; $\Delta P/P_3 = 7.6$ percent at $M_3 = 0.27$ (est.)
II-1-D	--	Primary slots widened	Hot hub profile; $\bar{\delta} = 0.7$ to 0.8; $\Delta P/P_3 = 5.5$ percent at $M_3 = 0.27$ (est.)

TABLE VIII. - Continued. PRELIMINARY COMBUSTOR PERFORMANCE

Liner designation	Figure	Descriptive features	Performance characteristics
II-1-E	-----	Primary slot length reduced	Hot hub profile; no improvements
II-1-F	21(b)	Primary slots revised; 2-inch (0.051-m) internal extension of secondary scoops	Profile shifted to hot tip and cool center with hot hub; $\Delta P/P_3$ increased by approximately 2 percent
II-2-A	21(a), 21(c)	Channeled scoop arrangement to increase secondary air split	Hot hub profile; $\bar{\delta} = 0.91$; combustion efficiency, 48 percent; flames beyond combustor exit
II-3-A	-----	Slot sizes same as II-1-B; channeled scoop arrangement	Profile tapers to hot hub; $\bar{\delta} = 0.30$; $\Delta P/P_3 =$ 7.5 percent at $M_3 = 0.27$
II-3-B(1)	21(d)	Slot sizes same as II-1-A	Profile exhibited hot hub characteristics; $\bar{\delta} = 0.22$; $\Delta P/P_3 = 8.3$ percent at $M_3 = 0.25$ (est.)
II-3-B(2)	-----	Inlet chutes cut flush with inner diffuser wall to reduce total pressure loss	Profile unchanged; $\bar{\delta} = 0.25$; $\Delta P/P_3 =$ 8.1 percent at $M_3 = 0.25$ (est.)
II-4-A	-----	Long, narrow primary and secondary slots; changed air splits; channeled scoops	Hot hub profile; $\bar{\delta} = 0.8$; isothermal $\Delta P/P_3 =$ 4.8 percent at $M_3 = 0.26$ (est.)
II-4-B	-----	Primary slots lengthened; secondary slots shortened; primary air fraction increased to 44 percent	Hot hub profile; $\bar{\delta} = 0.4$ to 0.5; $\Delta P/P_3 =$ 6.1 percent at $M_3 = 0.26$ (est.)
II-4-C	-----	Primary scoop width increased; primary turning vane added in each scoop to improve efficiency	Efficiency improved approximately 10 percent to 93.3 percent with $\bar{\delta} = 0.5$ and $\Delta P/P_3 =$ 6.6 percent at $M_3 = 0.26$ (est.)
II-4-D	21(e)	Primary air fraction increased to approximately 60 percent; slots revised proportionately	Hot hub profile; $\bar{\delta} = 0.7$ to 0.8; $\Delta P/P_3 =$ 6.9 percent at $M_3 = 0.26$ (est.)
II-5-A	-----	Slots in-line; without secondary scoops	Hot hub profile; $\bar{\delta} = 0.7$; isothermal $\Delta P/P_3 =$ 5.5 percent at $M_3 = 0.26$ (est.)
II-5-B(1)	-----	Channeled scoop arrangement converging on secondary slot; flush primary slots sized for 60 percent primary air; secondary slots sized for 30 percent	Ideal profile characteristics with cool hub; $\bar{\delta} = 0.5$; poor burning stability
II-5-B(2)	-----	Two primary turning vanes	Hot hub profile; stability improved; $\bar{\delta} = 0.6$
II-5-B(3)	-----	One full-height primary turning vane 1.5 inches (0.038 m) wide at 2.5-inch (0.064-m) length of slot	Profile distorted with cool hub and hot peak at 30 percent radial position; $\bar{\delta} = 0.2$; $\Delta P/P_3 = 7.9$ percent at $M_3 = 0.26$ (est.); combustion efficiency improved

TABLE VIII. - Continued. PRELIMINARY COMBUSTOR PERFORMANCE

Liner designation	Figure	Descriptive features	Performance characteristics
II-5-C(1)	----	One full-height primary turning vane 1 inch (0.025 m) wide at 3-inch (0.076-m) length of slot; secondary slot elongated	Hot hub profile; $\bar{\delta} = 0.4$; $\Delta P/P_3 = 7.3$ percent at $M_3 = 0.26$ (est.); combustion efficiency reduced
II-5-C(2)	----	One full-height primary turning vane 2 inches (0.051 m) wide at 3.9-inch (0.099-m) length of slot	Cool hub profile; $\bar{\delta} = 0.5$; $\Delta P/P_3 = 6.9$ percent at $M_3 = 0.26$ (est.); combustion efficiency low
II-5-D(1)	----	Enlarged primary slots with trapezoidal shape; one full-height primary turning vane 0.75 inch (0.019 m) wide at 2.5-inch (0.064-m) length of slot added to vane for II-5-C(2)	Hot hub profile; $\bar{\delta} = 0.6$; $\Delta P/P_3 = 6.6$ percent at $M_3 = 0.26$ (est.); combustion efficiency low
II-5-D(2)	21(f)	One full-height primary turning vane 1.25 inch (0.032 m) wide at 2.5-inch (0.064-m) length of slot	Hot hub profile; $\bar{\delta} = 1.2$; combustion efficiency low
II-6-A	21(g)	Total slot area proportioned 4/9 primary, 5/9 secondary; one full-height primary turning vane 1.38 inch (0.035 m) wide	Hot hub profile; $\bar{\delta} = 0.6$; $\Delta P/P_3 = 6.9$ percent at $M_3 = 0.26$ (est.)
II-7-A(1)	----	Same slot sizes as II-6-A; height of secondary scoops reduced; no primary scoops	Very cool hub; $\bar{\delta} = 0.7$; low combustion efficiency; local hot spots
II-7-A(2)	----	Firewall holes added; fuel nozzles changed	Very cool hub; $\bar{\delta} = 0.9$; local hot spot
II-7-A(3)	----	Thumbnail film cooling slots added	Very cool hub; $\bar{\delta} = 1.0$; local hot spot
II-7-A(4)	----	One full-height primary turning vane 1.38 inch (0.035 m) wide	Cool hub, cold center; $\bar{\delta} = 0.5$; $\Delta P/P_3 = 7.2$ percent at $M_3 = 0.26$ (est.); local hot spot
II-7-A(5)	22	Chute fairings and annulus spacers added	Profile with cool center; $\bar{\delta} = 0.26$; $\Delta P/P_3 = 7.9$ percent at $M_3 = 0.26$ (est.)
II-7-A(6)	21(h)	Primary scoops 1 inch (0.025 m) wide	Profile with cool center; $\bar{\delta} = 0.3$; $\Delta P/P_3 = 7.0$ percent at $M_3 = 0.257$; combustion efficiency, 96 percent (est.)
II-7-A(7)	----	Diffuser contour adjusted; inlet chutes shortened	Hot hub, cool center profile; $\bar{\delta} = 0.25$; $\Delta P/P_3 = 6.9$ percent at $M_3 = 0.258$; combustion efficiency, 93 percent (est.)
II-7-A(8)	----	Primary scoops 0.5 inch (0.013 m) wide	Profile with hot tip, very cold center, and cool hub; $\bar{\delta} = 0.4$; $\Delta P/P_3 = 6.0$ percent at $M_3 = 0.261$; combustion efficiency, 92.5 percent
II-7-B	----	Small flush secondary slots 2 staggered for tip cooling	Tip temperatures reduced but still too hot; $\bar{\delta} = 0.27$; $\Delta P/P_3 = 5.9$ percent at $M_3 = 0.258$

TABLE VIII. - Concluded. PRELIMINARY COMBUSTOR PERFORMANCE

Liner designation	Figure	Descriptive features	Performance characteristics
II-7-C(1)	--	Width of secondary slots 1 reduced; secondary slots 2 enlarged	Ideal profile characteristics; local hot spot; $\bar{\delta} = 0.4$; $\Delta P/P_3 = 6.1$ percent at $M_3 = 0.254$; combustion efficiency, 89.0 percent
II-7-C(2)	--	Fuel nozzles interchanged; tests with flow trips	Profile insensitivity was demonstrated; $\bar{\delta} = 0.4$ to 0.5; combustion efficiency 85 to 88 percent
II-8-A	--	Flush primary slots, in line and staggered alternately for tip cooling	Hot hub profile; $\bar{\delta} = 0.65$; $\Delta P/P_3 = 6.2$ percent at $M_3 = 0.261$
II-8-B(1)	--	Primary slot areas reproportioned	Hot hub profile; $\bar{\delta} = 0.51$; $\Delta P/P_3 = 6.8$ percent at $M_3 = 0.267$
II-8-B(2)	--	Half-size inlet chutes deleted; ten 0.5-inch (0.013-m) firewall holes added	Hot hub profile; $\bar{\delta} = 0.36$; $\Delta P/P_3 = 6.8$ percent at $M_3 = 0.262$; combustion efficiency, 77.5 percent
II-9-A	--	Primary scoops 0.75-inch (0.019-m) wide to increase combustion efficiency	Distorted profile (hot hub and cold at 30 percent radial position; $\bar{\delta} = 0.3$; $\Delta P/P_3 = 5.9$ percent at $M_3 = 0.248$; combustion efficiency, 97 percent
II-9-B	--	Width of secondary slots 1 reduced to 1.06 inch (0.027 m); secondary slots 2 lengthened to 3.5 inches (0.089 m)	Profile with cool hub region and peak at 70 percent radial position; $\bar{\delta} = 0.36$; $\Delta P/P_3 = 5.96$ percent at $M_3 = 0.246$; combustion efficiency, 97.7 percent
II-9-C	--	Secondary slot 1 shortened to 4.0 inches (0.102 m); secondary slot 2 elongated to 4.5 inches (0.114 m)	Profile with cold zone at 30 percent radial position; $\bar{\delta} = 0.27$; $\Delta P/P_3 = 6.1$ percent at $M_3 = 0.25$ (est.); combustion efficiency, 96.4 percent
II-9-D	--	Secondary slots 1 changed to 0.87 inch (0.022 m) by 4.5 inch (0.114 m); half-size end slots 2 added to secondary	Profile with slight hot tail at hub; $\bar{\delta} = 0.18$; $\Delta P/P_3 = 6.5$ percent at $M_3 = 0.253$; combustion efficiency, 95.2 percent
II-9-E	--	Secondary slots 2 enlarged to trapezoidal shape with 5.5-inch (0.140-m) length	Profile near ideal with slight hot tail at hub; $\bar{\delta} = 0.19$; $\Delta P/P_3 = 6.75$ percent at $M_3 = 0.259$; combustion efficiency, 92.7 percent
II-9-F	9	Width of secondary slots 2 reduced to 0.75 inch (0.019 m); lower liner contour revised to get abrupt ramp at combustor exit; final configuration	As presented in tables II and III and discussed in main text

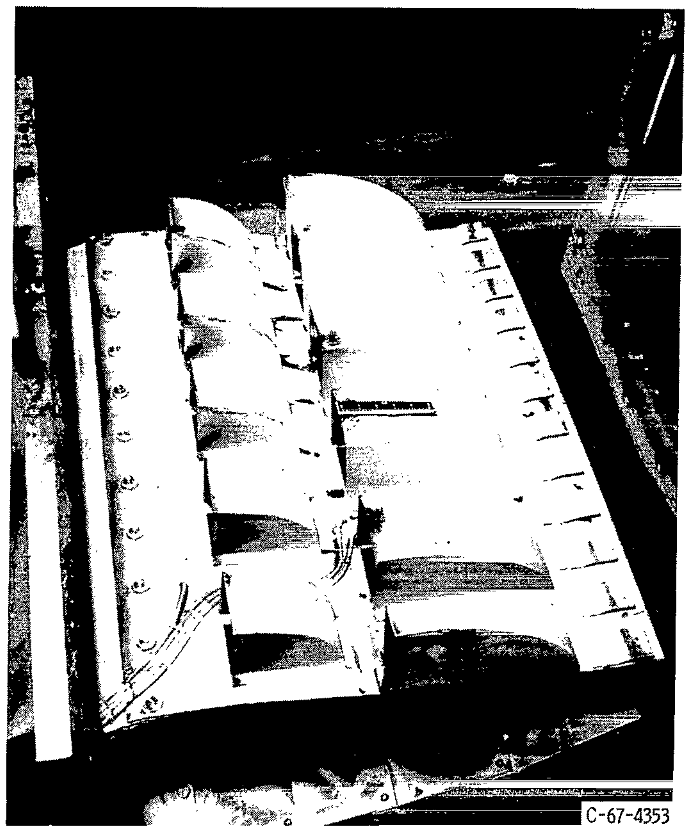


Figure 18. - Initial staggered slot configuration: liner I-1-A.

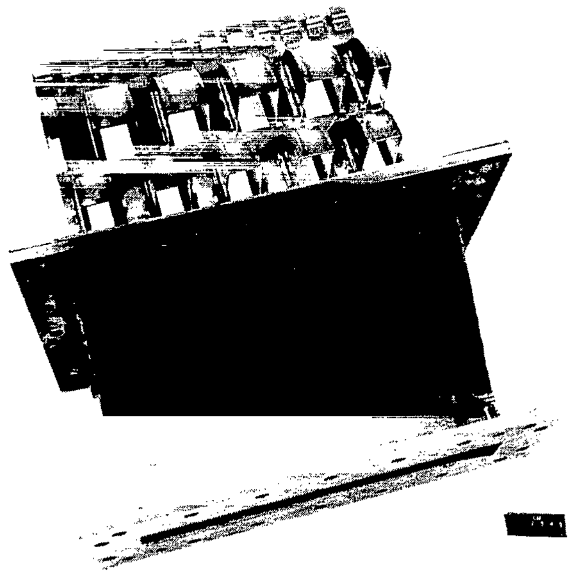


Figure 19. - Model II combustor assembly: liner II-1-A.

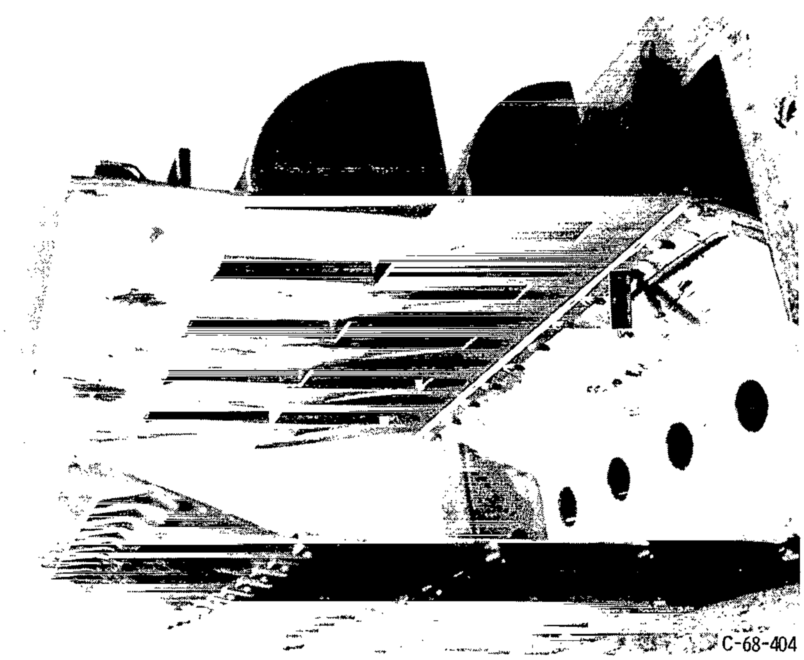
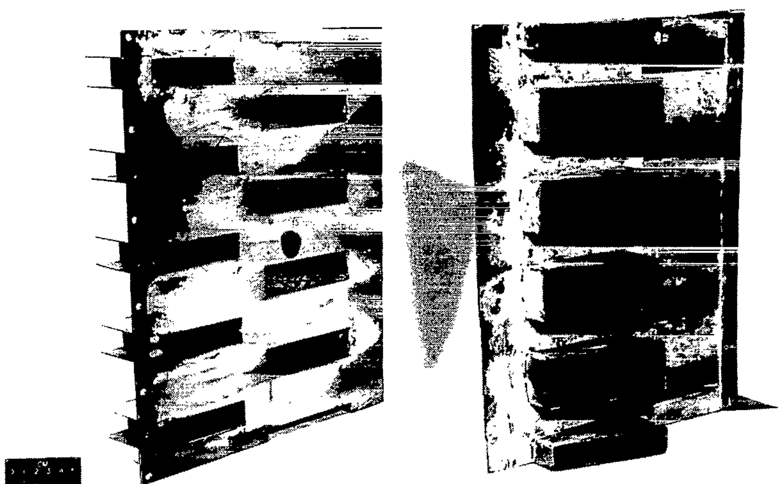


Figure 20. - Staggered primary and secondary slots: liner II-1-A.



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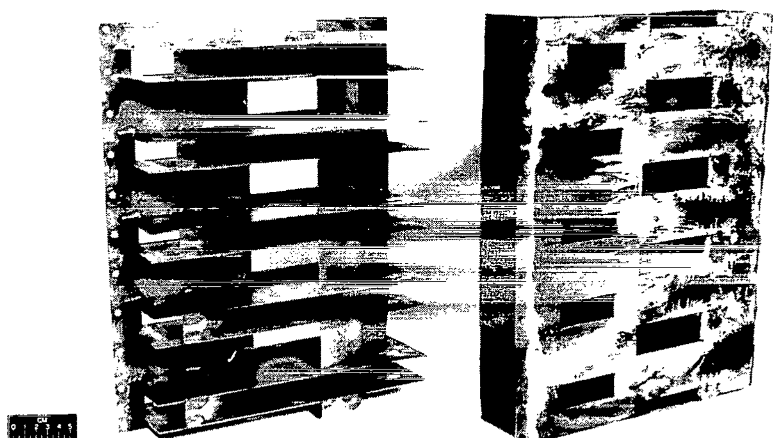
(a) Liner II-2-A. (b) Liner II-1-F.



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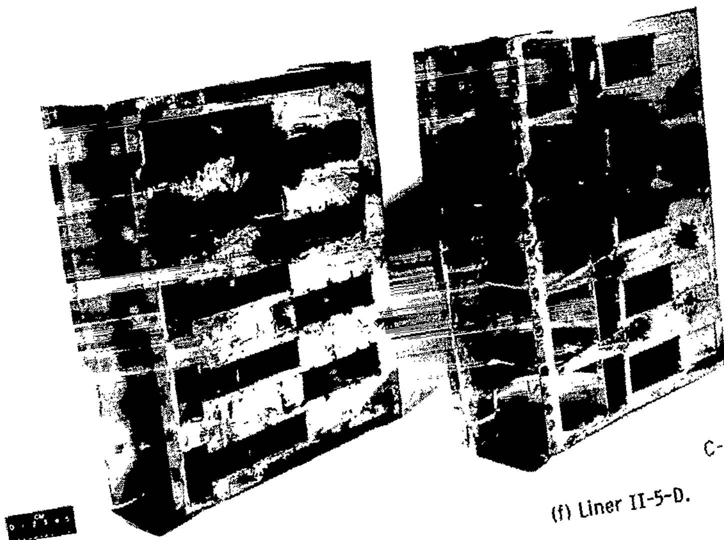
(c) Liner II-2-A. (d) Liner II-3-B.

Figure 21. - Liner configurations (refer to table VIII for details).



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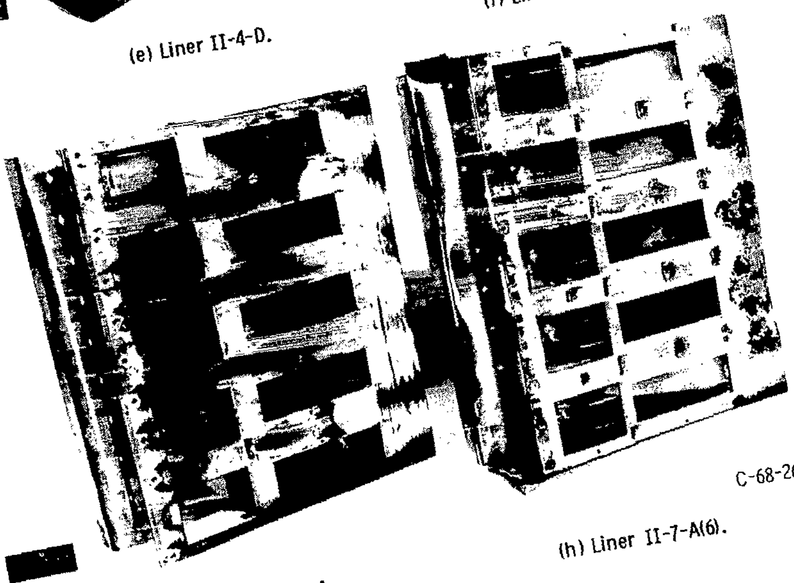
(e) Liner II-4-D.

(f) Liner II-5-D.



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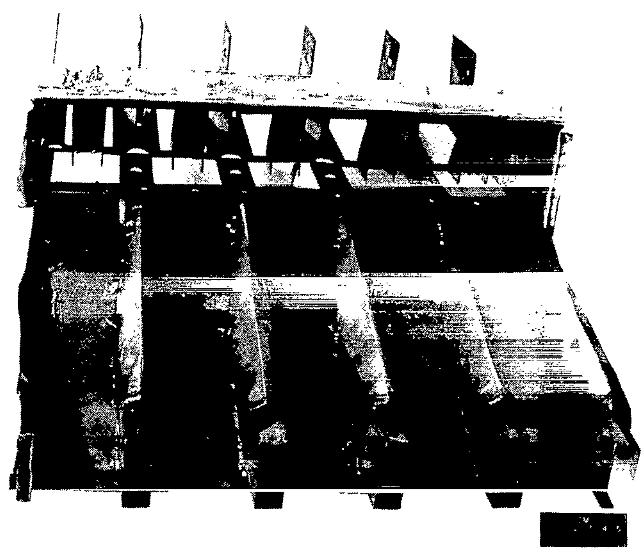
(g) Liner II-6-A.

(h) Liner II-7-A(6).

Figure 21. - Concluded.



C-68-2688

Figure 22. - Model II combustor assembly: liner II-7-A(6).

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