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RESEARCH MEMORANDUM

ALTITUDE PERFORMANCE OF PENTABORANE - JP-4 FUEL BLENDS IN A MODIFIED J47 COMBUSTOR

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
April 17, 1957

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ALTITUDE PERFORMANCE OF PENTABORANE - JP-4 FUEL BLENDS IN A MODIFIED J47 COMBUSTOR

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SUMMARY

The combustion characteristics of several pentaborane - JP-4 (MIL-F-5624A) fuel blends in a turbojet combustor were investigated at simulated flight conditions of 100-percent rated engine speed and altitudes of 44,000, 48,000, and 61,000 feet. The combustor consisted of a standard J47 combustor housing and liner, and was fitted with a dual-fuel injector that permitted variation of the fuel composition in the combustor. The combustion performance of JP-4 fuel and blends of 27 and 66.8 percent pentaborane by weight was examined.

Combustion efficiency with the blends was from 6 percent higher to 2 percent lower than for JP-4 alone.

Relatively large quantities of boron oxide were deposited on the combustor walls for the short test durations. These deposits did not appear to have reached an equilibrium thickness. Only small amounts of the deposits were removed by subsequent operation on JP-4 over periods of 30 minutes at combustor outlet temperatures of 1550° F.

Despite the performance deficiencies noted, the combustor appeared suitable for the purpose for which it was developed; namely, to permit a short-duration test of a J47 engine employing this type combustor and fuel of various pentaborane - JP-4 blends.

INTRODUCTION

Special fuels that show promise of extending the range, thrust, and operational limits of jet-propelled aircraft are being investigated at the NACA Lewis laboratory. Certain applications exist for turbojet-powered aircraft that can operate on both conventional and special high-energy fuels. Aircraft-carrier operation, for instance, may dictate the use of conventional fuel for takeoff and landing and special fuel for cruise and combat.

Fuels of current interest include diborane, pentaborane, and pentaborane-hydrocarbon blends. These fuels possess desirable heating values and chemical reactivity; however, a special problem exists in preventing or controlling solid and liquid boron oxide in the combustion products from depositing on the combustor hardware. In addition, pentaborane introduces special handling problems because of its spontaneously inflammable nature at room temperatures (ref. 1).

Experimental investigations of the combustion characteristics of diborane, pentaborane, and pentaborane-hydrocarbon blends in modified turbojet combustors have been conducted at this laboratory at the request of the Bureau of Aeronautics, Department of the Navy, as part of Project Zip. Results of these single-combustor tests are presented in references 2 to 5. 3380

A combustor liner 4 inches shorter than the standard J47 liner, with most of its area air-filmed through the employment of porous wire cloth, was developed (ref. 5) for use with pentaborane. This combustor liner was relatively free of oxide deposits for the limited test conditions and short durations investigated.

The decreased length, extensive air-filming, and reduced recirculation limited the wire-cloth combustor liner to high-flame-speed, highly reactive fuels such as pentaborane. A dual-fuel combustor that would permit efficient combustion of both petroleum fuels and boron-hydride-type fuels appeared desirable from the aforementioned tactical application and for full-scale-engine research purposes. More economical use of the presently limited production of boron hydride fuels can be achieved on full-scale-engine research by bringing the engine to test conditions with conventional fuel, then crossing over to operation on the special fuel for the brief test period. A further advantage with this method of operation exists with boron hydride fuels, inasmuch as the engine parts exposed to the molten oxide can be preheated above the melting point of the oxide and thereby prevent a rough layer of solid oxide from forming during the initial stages of warm-up. In addition, the ability of a full-scale research combustor to operate on various fractions of pentaborane - JP-4 fuel is desirable, since the influence of different concentrations of boron oxide on engine performance can be determined.

The best research design would then be a combustor that exhibited consistently high combustion efficiency, flat outlet temperature profile, and general freedom from combustion deposits over a range of pentaborane concentration in JP-4. Some hope for achieving this design was indicated in reference 4, where improved fuel atomization reduced oxide deposition in a standard type turbojet combustor.

The objective of this investigation was to develop a fuel injector and combustor that would meet the immediate requirements for full-scale-engine research and indicate the design features desirable for more general engine application. Data are presented on combustion efficiency, combustor outlet temperature profile, and oxide deposition for 0, 27, and 67 percent pentaborane - JP-4 fuel blends in a dual-fuel combustor at simulated altitudes of 44,000 and 61,000 feet, 100-percent rated engine speed, and flight Mach number of 0.6. Data are also presented for the simulated flight condition and fuel program typical of a full-scale-engine test: altitude, 48,000 feet; engine speed, 95 percent; and flight Mach number, 0.8.

FUELS

Source. - The pentaborane used in this investigation was obtained through the cooperation of the Bureau of Aeronautics, Department of the Navy. The pentaborane component of the blend fuel was 99 percent pure. The hydrocarbon component was JP-4 (MIL-F-5624A) fuel.

Properties. - Values of some of the physical properties of the blends and the pentaborane component are as follows:

Physical property	Pentaborane[a]	27 Percent pentaborane and 73 percent JP-4 by weight	66.8 Percent pentaborane and 33.2 percent JP-4 by weight
Formula weight	63.17		
Melting point, ^{o}F	-52		
Boiling point, ^{o}F at 760 mm Hg	136		
Heat of combustion, Btu/lb	[b,c]29,127	21,497	25,657
Heat of combustion, Btu/cu ft	[d]1,170,000	[e]997,500	[e]1,100,000
Stoichiometric fuel-air ratio	0.07365	0.06992	0.07327

[a]Pure.

[b]Based on H_2O in gaseous phase.

[c]Value used in this report. Most recent value is 29,100.

[d]Specific gravity of pentaborane taken as 0.644 at 0^{o} C.

[e]Specific gravity of blend at 0^{o} C.

The melting points of the two forms of boron oxide B_2O_3 are as follows:

Crystalline, ^{o}F 842
Vitreous, ^{o}F 1070

Values of some of the physical properties of the hydrocarbon component are given in table I.

FUEL SYSTEM

The fuel system used for the two fuels is shown on figure 1. The blend fuel system was purged with helium for approximately 1 minute before the fuel-tank valves were opened. Both fuel tanks were pressurized with helium by means of remote-controlled pressure regulators. Helium from a separate source was supplied to that part of the blend fuel line entering the combustor immediately preceding and immediately following the use of blend fuel. Fuel flows were started and stopped by remote-controlled pressure-operated piston valves. The flow rates were controlled by remote-operated throttle valves. Atomizing air-flow rate was governed by a remote-controlled pressure regulator and a rotameter. The blend fuel system was flushed with dry JP-4 after each run.

The dual-fuel air-atomizing injector shown schematically on figure 2 permitted warm-up on JP-4 fuel and variation of the combustor blend composition during the runs. The center nozzle is identical to that of reference 5. A blend of 66.8 percent pentaborane was fed through the center passage to the nozzle and injected into the combustor in a solid cone. Air at room temperature from the central laboratory supply was conducted through a concentric passage to provide cooling and atomization of the blend fuel and also atomization of the JP-4 fuel. The JP-4 fuel was admitted to the outside passage and entered the combustor through the small holes aligned with the three holes drilled into the atomizing-air tube. The atomizing air had a pressure on the order of 15 pounds per square inch gage on entering the injector and a flow rate of about 0.007 pound per second for all runs. Approximately 25 percent of the atomizing air flow was distributed to atomize the JP-4 fuel.

A thermocouple imbedded in the outside surface of the blend fuel tube (fig. 2) for runs 2 and 5 indicated a wall temperature on the order of 500° F just prior to initiating the blend fuel flow.

APPARATUS

Combustor installation. - Figure 3 shows a diagram of the combustor installation. Combustion air from the central laboratory supply was controlled by a remote-operated valve. The combustor inlet-air temperature was regulated by a heat exchanger. Combustion products were discharged into an exhaust plenum, cooled and exhausted to a header that was valved to provide either 1-atmosphere or 1/2-atmosphere exhaust pressure.

A standard J47 combustor housing and liner were used. The cooling-air passage between housing and liner at the rear of the combustor was blocked to provide higher transition-section wall temperatures. The crossover ports on the liner were capped. The sparkplug electrodes were lengthened 3/4 inch. Only one sparkplug was used. The combustor inlet and outlet transitions were segments of the corresponding sections of a complete engine. The outlet transition section was covered with a 2-inch blanket of insulation.

Instrumentation. - The combustion air flow was metered by an ASME orifice. The pressure upstream of the orifice and the fuel-tank pressures were indicated by calibrated gages. Orifice differential pressure and total-pressure drop across the combustor were measured by water-filled manometers. Combustor inlet, outlet, and exhaust pressures were read from mercury manometers. The outlet total-pressure probe was kept free of oxides by a continuous bleed of air through the tube. The bleed air-flow rate was sufficiently low that friction pressure losses within the tube were considered negligible.

The fuel-flow rate was recorded continuously by means of a rotating-vane flowmeter (fig. 1) and a self-balancing strip-chart potentiometer. The flowmeter measures volume flow rate and was calibrated with gasoline before each group of runs. The weight-flow rate of the test fuels was determined from the gasoline calibration and a density correction.

The location of the thermocouples at the combustor inlet and outlet is shown in figure 4. Two parallel couples indicated combustor inlet-air temperature; single couples indicated combustion-air temperature at the orifice, fuel temperature at the flowmeters, and the outlet transition wall temperature at station D. Closed-end thermocouples were used to measure outlet gas temperature. Twenty-three of the thermocouples at station D were wired individually, and the remaining twelve were wired parallel in groups of three. Nine thermocouples at station D' were wired parallel in groups of three to provide a check on the average combustor outlet gas temperature computed from the thermocouples at station D. All the temperatures measured by individual thermocouples were recorded at regular intervals on self-balancing strip-chart potentiometers. Temperatures averaged by the paralleled thermocouples were recorded manually from self-balancing indicating potentiometers.

PROCEDURE

Test conditions. - The following table lists the target test conditions. Conditions B and D are identical to those of reference 5.

Test condition	Combustor inlet total pressure, in. Hg abs	Combustor inlet temperature, °F	Air flow[a], lb/sec sq ft	Combustor temperature rise, °F	Simulated flight condition[b]	
					Altitude, ft	Percent rated speed
B	34	368	5.35	1182	44,000	100
D	15	368	2.38	1182	61,000	100
F	32	440	5.00	1200	48,000	95

[a]Air flow per unit of maximum cross-sectional area of combustor housing, 0.48 sq ft.

[b]Simulating a flight Mach number of 0.6 for conditions B and D and 0.8 for condition F, for a typical turbojet having a 5.2 compressor pressure ratio at sea-level rated rpm.

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For each series of runs at conditions B and D, the combustor and outlet transition section were warmed up on JP-4 for a period of 15 minutes (runs 1, 4, 7, and 10 in table II). Then, while maintaining a constant combustor outlet temperature, JP-4 and blend fuel-flow rates were adjusted to obtain the desired blend compositions within the combustor (runs 2, 5, 8, and 11 in table II). The combustor was then photographed, reassembled, and subjected to a 30-minute run on JP-4 at a combustor outlet temperature of 1550° F (runs 3, 6, 9, and 12 in table II) in an attempt to remove the oxide deposits.

Run 13, condition F, had a similar warm-up period; however, for this run the pentaborane concentration was varied in steps from 0 to 36.8 percent, and the clean-up period on JP-4 fuel followed without cooling the combustor. Run 13 simulated the conditions planned for the full-scale-engine operation.

Calculations. - Time intervals of 1 minute on blend runs and 3 or 5 minutes on JP-4 runs were chosen for analysis. Combustion efficiencies were computed from the following relation:

$$\eta_b = \frac{\text{Equivalence ratio theoretically required for measured temperature rise}}{\text{Actual equivalence ratio}} \times 100$$

The theoretically required equivalence ratio for a measured temperature rise was determined from unpublished results by the methods and assumptions described in reference 6.

The average combustor outlet gas temperature was computed as the arithmetic mean of the 35 outlet thermocouple indications. This was achieved by assuming that each of the thermocouples in a paralleled group sensed a temperature equal to the temperature recorded for the paralleled group. No correction was made for velocity or radiation effects on the thermocouples.

The total-pressure loss through the combustor was computed as the dimensionless ratio of the measured total-pressure drop $P_A - P_C$ to the calculated reference dynamic pressure q_r. The value of q_r was computed from the combustor inlet density, the air-flow rate, and the maximum cross-sectional area of the combustor housing, 0.48 square foot.

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RESULTS AND DISCUSSION

The results of all tests are presented in chronological order in table II. Because of similarity of results, some of the data points for the JP-4 runs have been omitted.

A synopsis of the data of table II is given below:

Test condition	Combustor inlet total pressure, in. Hg abs	Combustor inlet temperature, °F	Air flow, lb/(sec)(sq ft)	Combustor temperature rise, °F	Pentaborane concentration, percent	Combustion efficiency, percent
B	32.8	359	5.30	1204	0	94
B	32.7	352	5.33	1181	27	96
B	32.5	367	5.31	1291	67	96
D	14.2	382	2.41	1254	0	81
D	14.2	382	2.41	1217	26	80
D	14.1	372	2.39	1306	67	85
F	30.1	408	4.95	1267	18-37	95-100

Accuracy and reproducibility. - The accuracy of the combustion-efficiency data was affected by the deposition of solid products of combustion. The accuracy of the data was also limited to the accuracy of the temperature measurements and fuel-flow measurements. The combustion efficiencies are estimated to be within ±3 percent for the conditions where the wall temperature at the outlet thermocouple station had approached equilibrium. Figure 5 shows the increase in combustion efficiency with increasing wall temperature. This effect is attributed to the decreasing thermocouple error associated with increasing wall temperature. The data for combustor operation with pentaborane blends were recorded at times in excess of 15 minutes, where wall temperatures had essentially reached equilibrium. Reproducibility of the data is illustrated (fig. 5) by the close agreement of combustion-efficiency data obtained with JP-4 at condition B at intervals during the program.

Combustion efficiency. - Combustion-efficiency values with JP-4 taken just prior to throttling in the blend fuel were 94 percent for condition B and 80 to 83 percent for condition D. Corresponding values for combustor fuel blends of approximately 27 and 66.8 percent pentaborane at condition B were 95 to 97 percent. Combustion efficiencies for the blends at condition D were 80 percent for a blend of approximately 27 percent pentaborane and 85 percent for the 66.8 percent pentaborane blend. Run 13 gave combustion-efficiency values generally in agreement with those at condition B. Because of a limited fuel quantity, some difficulty was encountered in varying the combustor blend composition rapidly between data points on run 13. Thermocouple values appeared to lag changes in fuel flow by 10 to 15 seconds, which accounts for the variation of combustion efficiency for the 31 and 30 percent pentaborane data for this run. 3380

Figure 6 shows values of combustion efficiency obtained with JP-4 fuel and with blends of 27 and 66.8 percent pentaborane. Also included in figure 6 are curves from reference 5 showing the performance of the combustor employing a liner of porous wire cloth. For comparable fuel blends the combustion efficiencies of the combustor of reference 5 are 4 or 5 percent higher than the combustion efficiencies obtained with the standard combustor liner. The combustor of reference 5 employed the same fuel nozzle as that used herein for injection of the blend fuel, but the recirculatory flow in the upstream end of the porous wire-cloth liner was considerably less than that obtained with the standard liner. This recirculatory flow may account for the lower combustion efficiencies obtained with the standard liner as follows: It is hypothesized that the pentaborane component of the blend fuel may react with oxygen of the air in the recirculatory region within the combustor where the over-all fuel-air ratio is much too high to permit complete oxidation of the fuel. This rich oxidation may result in relatively unreactive products that do not burn completely in passing through the combustor. Such a process would be somewhat analogous to the formation of smoke in turbojet combustors using petroleum fuels (ref. 7). This phenomenon would also account for the fact that the combustion efficiency of the 27 percent pentaborane blend is lower than that obtained with JP-4 fuel.

Temperature profiles. - With JP-4 fuel, the temperature spread at the combustor outlet was approximately 280° F at condition B and increased to about 360° F for the reduced combustor pressure at condition D (based on JP-4 reference runs 1, 4, 7, and 10). Temperature spread was increased when blend fuel was injected through the center nozzle. A maximum spread of 550° F (fig. 7) resulted at condition D from injecting all the fuel through the blend nozzle. Reference 5 reports a spread of 650° F for approximately the same blend in the shortened wire-cloth combustor at condition D for an outlet temperature of 1540° F. However, at condition B, with all the fuel injected through the center nozzle, the temperature spread was on the order of 850° F for the wire-cloth combustor liner compared with 400° F for the standard combustor liner. The temperature spread of 550° F obtained with the high pentaborane concentration would be considered marginal in many current engines; however, this temperature profile seems satisfactory for the intended application of this combustor in a short-duration test of an engine.

Oxide deposition. - Since the combustor outlet temperature was on the order of 1600° F for all runs, the oxide was a thin film of the brittle, transparent, glassy type in the liner and transition section. The dome deposits, however, were a thin layer of the white powder type. The material was thickest at the bottom of the liner and indicated that the oxide flowed downward as well as axially through the liner. The downstream side of the liner thimbles collected a large portion of the deposit. The ratio of the weight of boron oxide deposited on the liner walls to the weight of boron oxide formed in the combustion products (assuming 100 percent combustion efficiency) was 0.0096 for both runs at condition B and 0.015 for both runs at condition D. The additional weight of deposit for the longer duration of run 13 indicates that deposition did not reach an equilibrium condition during the short runs. At condition B, this ratio was only 0.0033 for the wire-cloth liner (ref. 5), and 90 percent of this deposit was on the metal tailpiece of the liner. Furthermore, deposition appeared to have reached an equilibrium thickness for the wire-cloth liner.

Deposits in the liner and transition before and after a "clean-up" run on JP-4 fuel are shown on figures 8 and 9. Only 9 grams of the oxide were removed from the liner walls during 30 minutes operation on JP-4 at outlet temperatures of 1500° to 1600° F. Removal of deposits by continuing operation on petroleum fuel would appear to require a long duration and very high outlet temperatures.

SUMMARY OF RESULTS

The results obtained in this investigation of the combustion of pentaborane - JP-4 fuel blends in a modified J47 turbojet combustor are summarized as follows:

1. Combustion efficiencies of 94 percent with JP-4 and 95 to 100 percent with the blends were obtained at a combustor pressure of 1 atmosphere. At a combustor pressure of 1/2 atmosphere efficiency values were 80 to 82 percent for both JP-4 and 27 percent pentaborane blend and 85 percent for the 66.8 percent pentaborane blend.

2. The combustion efficiencies obtained with the standard combustor liner were 4 to 5 percent below those reported in reference 5 for the combustor using a porous wire-cloth liner. It is hypothesized that the somewhat lower combustion efficiencies may be the result of rich

oxidation of the pentaborane into relatively unreactive products due to the strong recirculation in the primary zone of this combustor.

3. The combustor outlet temperature profile was satisfactory for the intended application of the combustor. The difference between the maximum and the minimum temperature at the combustor outlet was from 100° to 450° F less than that for the combustor of reference 5 employing a liner of porous wire cloth.

4. Deposition of boron oxide did not appear to have reached equilibrium thickness for the short durations of the tests. More than twice as much oxide was collected on the liner walls than was collected for the same test duration on the wire-cloth liner of the combustor of reference 5, where deposit thickness did reach equilibrium. 3380

5. Removal of all deposits from the combustor-liner walls by continuing operation on conventional fuel does not appear promising at normal combustor outlet temperatures.

6. Despite the performance deficiencies noted, the combustor appeared suitable for the purpose for which it was developed; namely, to permit a short-duration test of a J47 engine employing this type combustor and fuel of various pentaborane - JP-4 blends.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 16, 1954

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TABLE I. - ANALYSIS OF HYDROCARBON COMPONENT OF BLEND

FUEL, MIL-F-5624A GRADE JP-4

Initial boiling point, °F	136
Percent evaporated	
5	180
10	243
20	292
30	316
40	331
50	341
60	355
70	371
80	390
90	421
95	447
Final boiling point, °F	480
Residue, percent	1.0
Loss, percent	1.0
Reid vapor pressure, lb/sq in.	2.4
Specific gravity, 60° F/60° F	0.778
Hydrogen-carbon ratio	0.168
Net heat of combustion, Btu/lb	18,675

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TABLE II. - OPERATING CONDITIONS AND RESULTS

Run	Test condition	Duration of combustion, min	Time data recorded, min	Combustor inlet temperature, °F	Combustor inlet total pressure, in. Hg abs	Air flow,[a] lb/(sec)(sq ft)	Total fuel flow, lb/sec	Pentaborane in combustor blend, percent	Equivalence ratio	Combustion efficiency, percent	Atomizing air flow, lb/sec	Combustor velocity, ft/sec	Average combustor outlet temperature, °F	Maximum individual outlet temperature, °F	Minimum individual outlet temperature, °F	Wall temperature at station D, °F	Pressure loss across combustor, $\frac{P_A - P_C}{q_r}$	Deposit remaining after run, g
1	B	17	0	357	30.8	5.33	------	----	-----	------	------	103	----	----	----	----	10.2	None
			3.0	363	32.7	5.27	0.0493	0	0.286	90.5	0.0083	100	1566	1722	1418	----	11.2	
			6.0	355	32.8	5.38	.0478	0	.271	91.4	.0083	101	1520	1666	1365	----	11.2	
			9.0	362	32.8	5.33	.0480	0	.276	92.1	.0083	101	1548	1694	1392	----	11.1	
			12.0	368	32.8	5.27	.0478	0	.277	93.4	.0083	100	1572	1712	1410	----	11.1	
			15.0	359	32.8	5.30	.0478	0	.276	93.6	.0083	100	1563	1695	1402	----	11.2	
			17.0	Throttled in blend fuel														
2	B	4	18.0	352	32.7	5.33	0.0401	27.0	0.223	96.3	0.0083	100	1533	1683	1300	----	11.5	
			19.0	354	32.8	5.32	.0414	28.4	.230	94.5	.0083	100	1556	1710	1352	----	11.5	
			20.0	356	32.8	5.31	.0405	28.0	.226	95.7	.0083	100	1552	1731	1316	----	11.4	
			21.0	Weighed deposit														32
3	B	31	6.0	365	32.4	5.32	0.0472	0	0.271	91.4	0.0081	102	1527	1725	1345	1205	12.5	
			30.0	357	32.6	5.52	.0479	0	.266	96.0	.0081	105	1548	1745	1363	1375	12.3	
			31.0	Weighed deposit														23
4	B	14	3.0	373	32.3	5.23	0.0495	0	0.289	89.9	0.0074	102	1582	1721	1469	----	12.3	None
			9.0	363	32.3	5.34	.0483	0	.277	92.7	.0074	102	1562	1692	1433	1270	12.1	
			14.0	Throttled in blend fuel														
5	B	4	15.0	368	32.6	5.44	0.0368	66.8	0.191	97.1	0.0074	104	1628	1845	1405	----	13.9	
			16.0	367	32.5	5.31	.0376	66.8	.200	96.0	.0074	102	1658	1889	1567	----	14.0	
			17.0	367	32.4	5.27	.0380	66.8	.205	95.6	.0074	101	1676	1888	1477	----	13.4	
			18.0	Weighed deposit														71
6	B	31	5.0	370	32.2	5.37	0.0501	0	0.285	90.5	0.0069	104	1569	1716	1378	1216	11.2	
			10.0	370	32.2	5.48	.0495	0	.276	92.7	.0069	106	1567	1704	1389	1310	11.0	
			15.0	373	32.2	5.33	.0494	0	.284	92.8	.0069	104	1592	1706	1392	1327	11.1	
			20.0	378	32.2	5.37	.0493	0	.281	94.5	.0069	105	1606	1758	1440	1405	10.9	
			25.0	372	32.3	5.54	.0493	0	.272	95.9	.0069	108	1582	1732	1411	1400	10.9	
			30.0	367	32.3	5.46	.0493	0	.276	95.2	.0069	105	1590	1724	1409	1399	11.0	
			31.0	Weighed deposit														62
7	D	15.7	0	349	13.6	2.43	------	----	-----	-----	------	109	----	----	----	----	----	None
			3.0	366	14.3	2.41	0.0286	0	0.364	73.1	0.0070	105	1599	1810	1424	1047	----	
			6.0	375	14.2	2.36	.0266	0	.344	76.7	.0070	105	1596	1768	1446	1174	----	
			9.0	380	14.2	2.34	.0276	0	.361	76.0	.0070	104	1649	1827	1494	1235	----	
			12.0	381	14.1	2.34	.0256	0	.334	78.2	.0070	105	1592	1773	1459	1260	----	
			15.0	382	14.2	2.41	.0265	0	.336	80.9	.0070	108	1636	1802	1490	1308	----	
			15.7	Throttled in blend fuel														
8	D	3.5	16.5	382	14.2	2.41	0.0229	25.9	0.283	80.0	0.0070	108	1599	1788	1364	1353	----	
			17.5	379	14.2	2.41	.0219	25.3	.271	81.3	.0070	108	1565	1764	1328	1345	----	
			18.5	378	14.2	2.43	.0229	27.4	.280	79.3	.0070	108	1582	1788	1338	1349	----	
			19.2	Weighed deposit														29
9	D	31	5.0	364	13.9	2.39	0.0251	0	0.322	78.0	0.0068	107	1535	1728	1360	1072	----	
			30.0	369	14.1	2.39	.0259	0	.332	82.0	.0068	106	1629	1811	1419	1330	----	
			31.0	Weighed deposit														19
10	D	16	3.0	368	14.0	2.41	0.0255	0	0.324	78.3	0.0069	108	1551	1765	1359	990	----	None
			15.0	369	14.0	2.41	.0249	0	.317	82.8	.0069	108	1590	1793	1388	1225	----	
			16.0	Throttled in blend fuel														
11	D	3.6	17.0	372	14.1	2.39	0.0195	66.8	0.232	84.5	0.0059	106	1678	1900	1348	1369	----	
			18.0	372	14.1	2.39	.0191	66.8	.226	85.8	.0059	106	1662	1879	1338	1410	----	
			19.0	372	14.1	2.39	.0192	66.8	.228	84.2	.0059	106	1660	1872	1320	1426	----	
			19.6	Weighed deposit														56
12	D	31	5.0	374	14.4	2.41	0.0253	0	0.322	77.4	0.0076	105	1537	1689	1425	1085	----	
			30.0	368	14.4	2.43	.0242	0	.305	82.3	.0076	105	1541	1684	1437	1246	----	
			31.0	Weighed deposit														53
13	F	56	0	410	31.2	5.01	------	----	-----	----	------	106	----	----	----	----	11.3	None
			3.0	405	32.1	5.03	0.0476	0	0.289	89.6	0.0061	102	1606	1735	1491	1212	12.2	
			15.0	402	30.1	4.95	.0485	0	.288	93.4	.0061	107	1690	1836	1574	1460	11.5	
			15.8	401	30.1	4.97	.0428	18.2	.259	95.5	.0061	107	1668	1800	1455	1470	12.0	
			17.5	408	30.1	4.94	.0425	24.8	.256	95.5	.0061	107	1686	1823	1480	1460	11.8	
			19.0	408	30.1	4.95	.0376	31.3	.224	100.0	.0061	108	1650	1770	1436	1460	11.9	
			21.1	409	30.1	4.96	.0385	36.8	.228	98.3	.0061	108	1676	1819	1467	1490	12.0	
			22.7	406	32.2	4.95	.0416	30.3	.248	94.6	.0061	101	1696	1850	1471	1510	13.0	
			24.0	404	32.2	4.98	.0414	25.8	.247	97.6	.0061	101	1684	1800	1495	1514	12.8	
			33.0	409	32.1	5.08	.0440	0	.265	95.0	.0061	104	1582	1721	1461	1412	12.2	
			47.0	354	32.3	5.27	.0472	0	.274	95.5	.0061	100	1575	1730	1412	1400	12.9	
			56.0	Weighed deposit														93

[a]Air flow per unit maximum cross-sectional area of combustor housing, 0.48 sq ft.

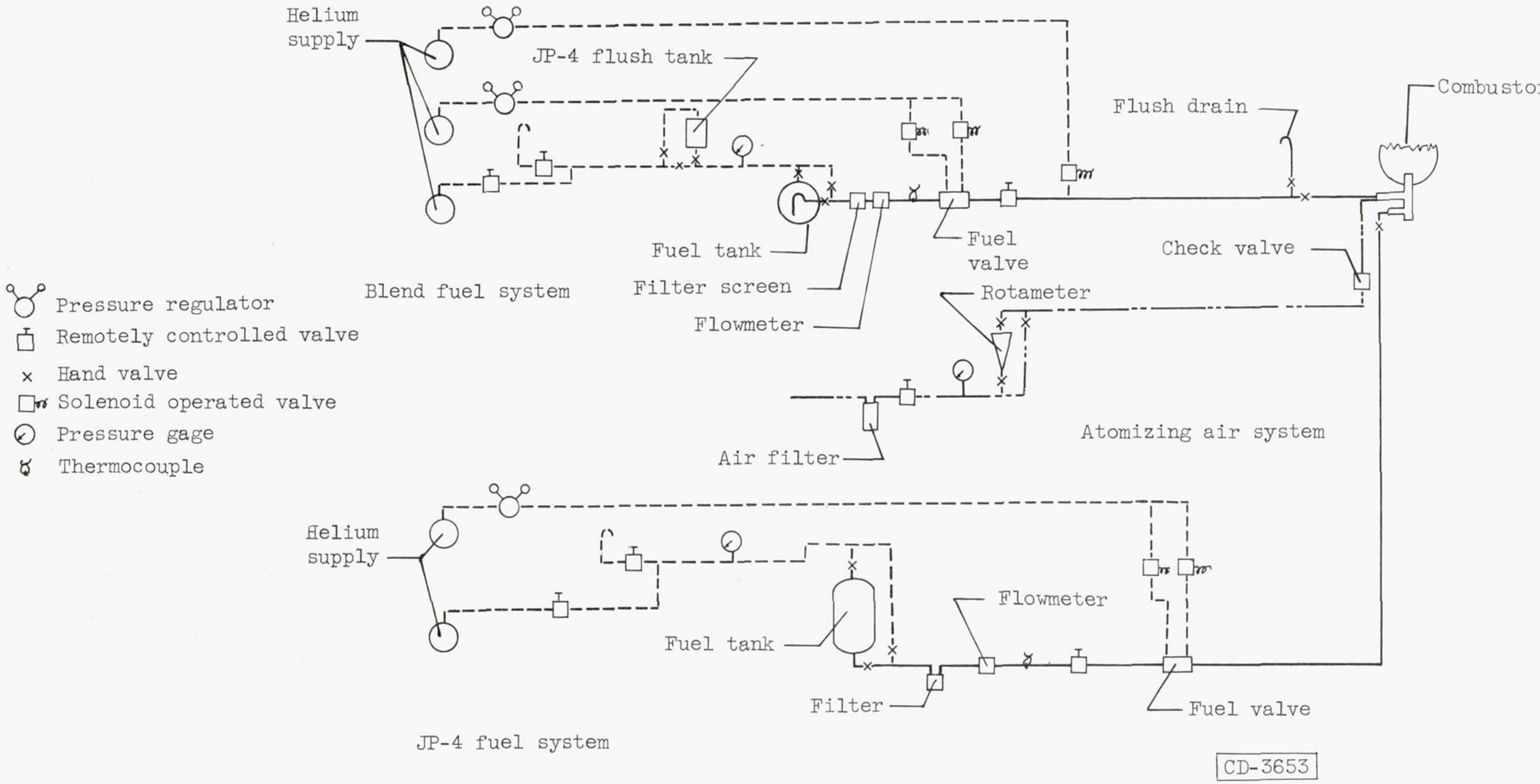

Figure 1. - Fuel system.

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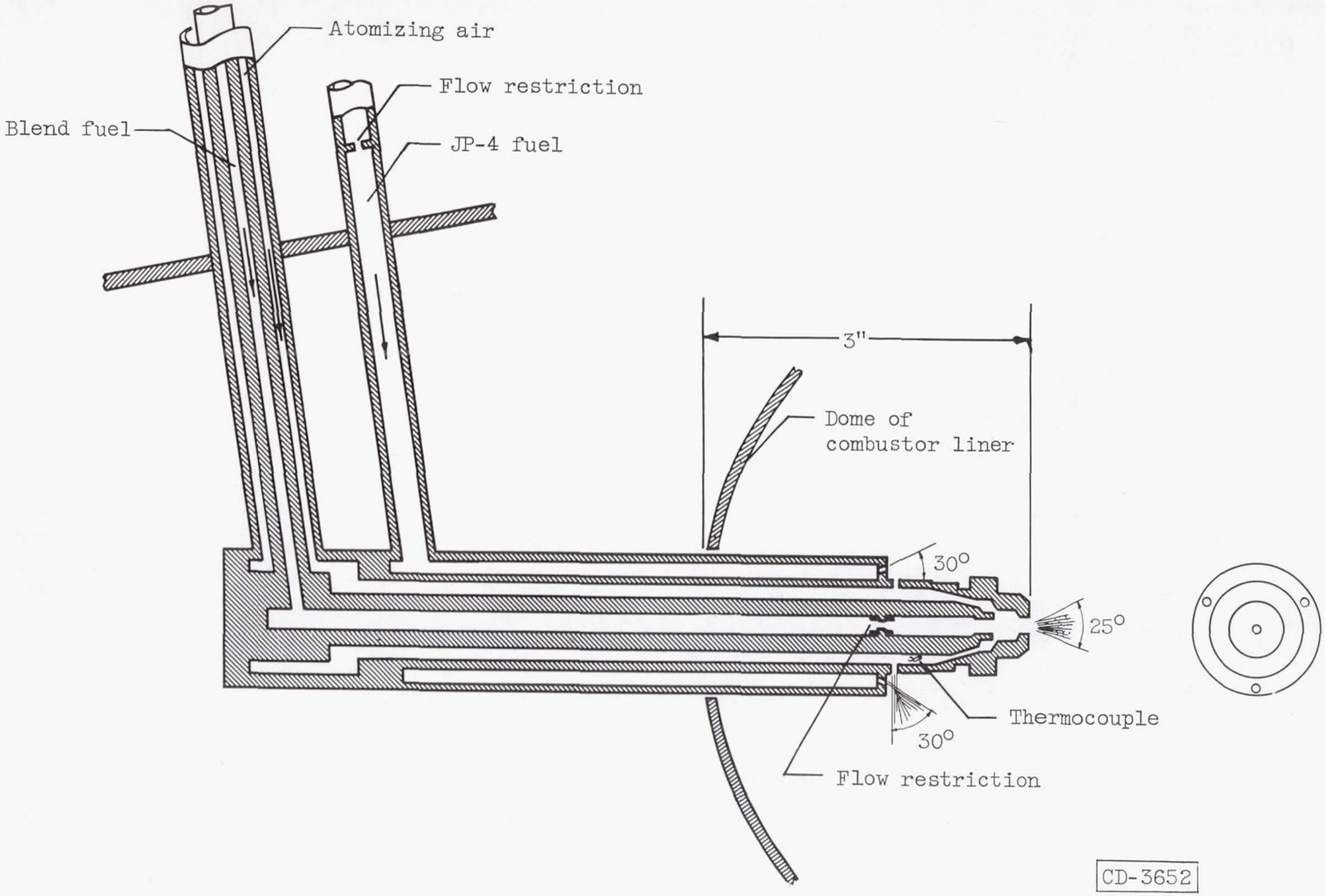

Figure 2. - Schematic diagram of dual-fuel injector.

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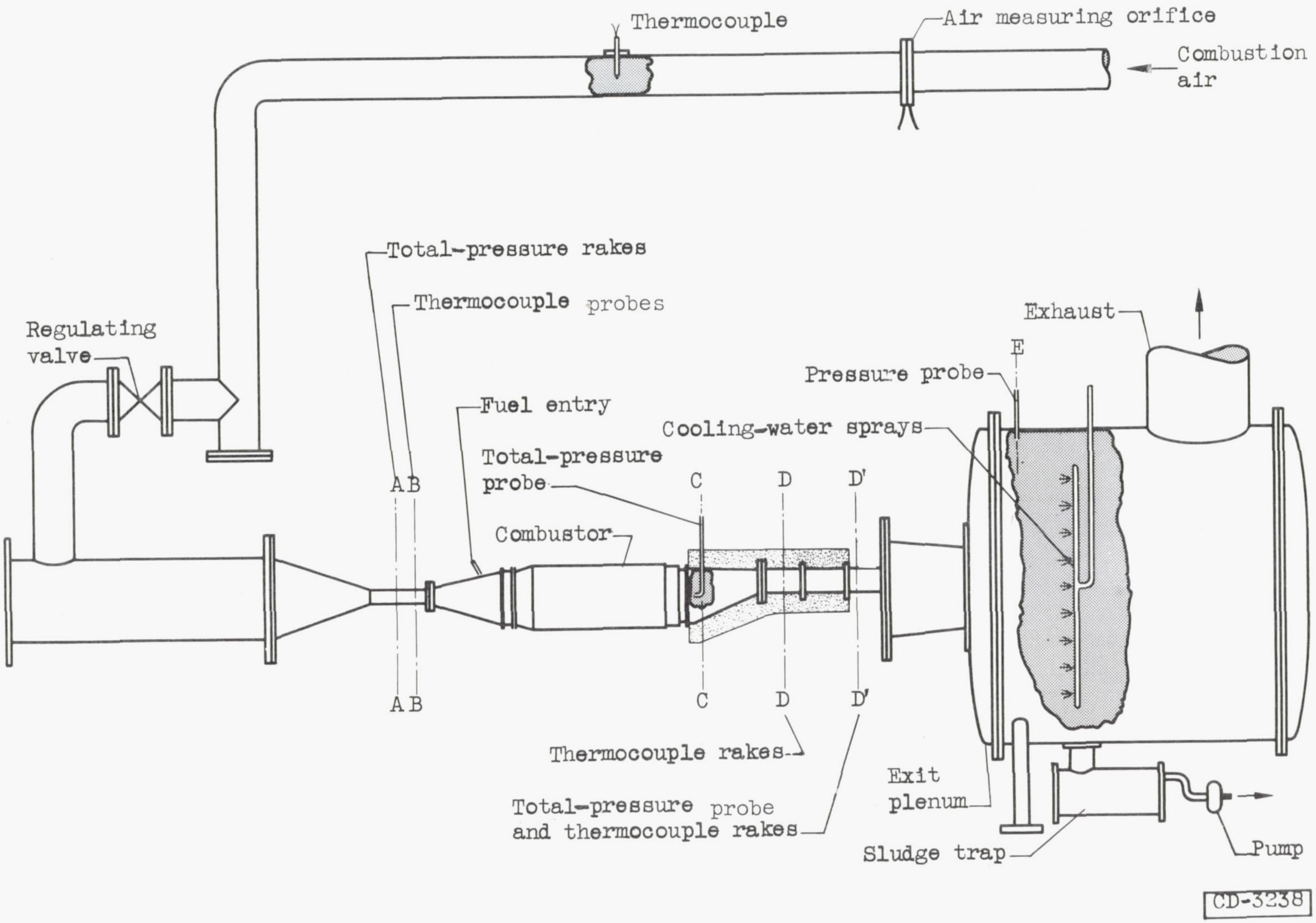

Figure 3. - J47 Combustor installation.

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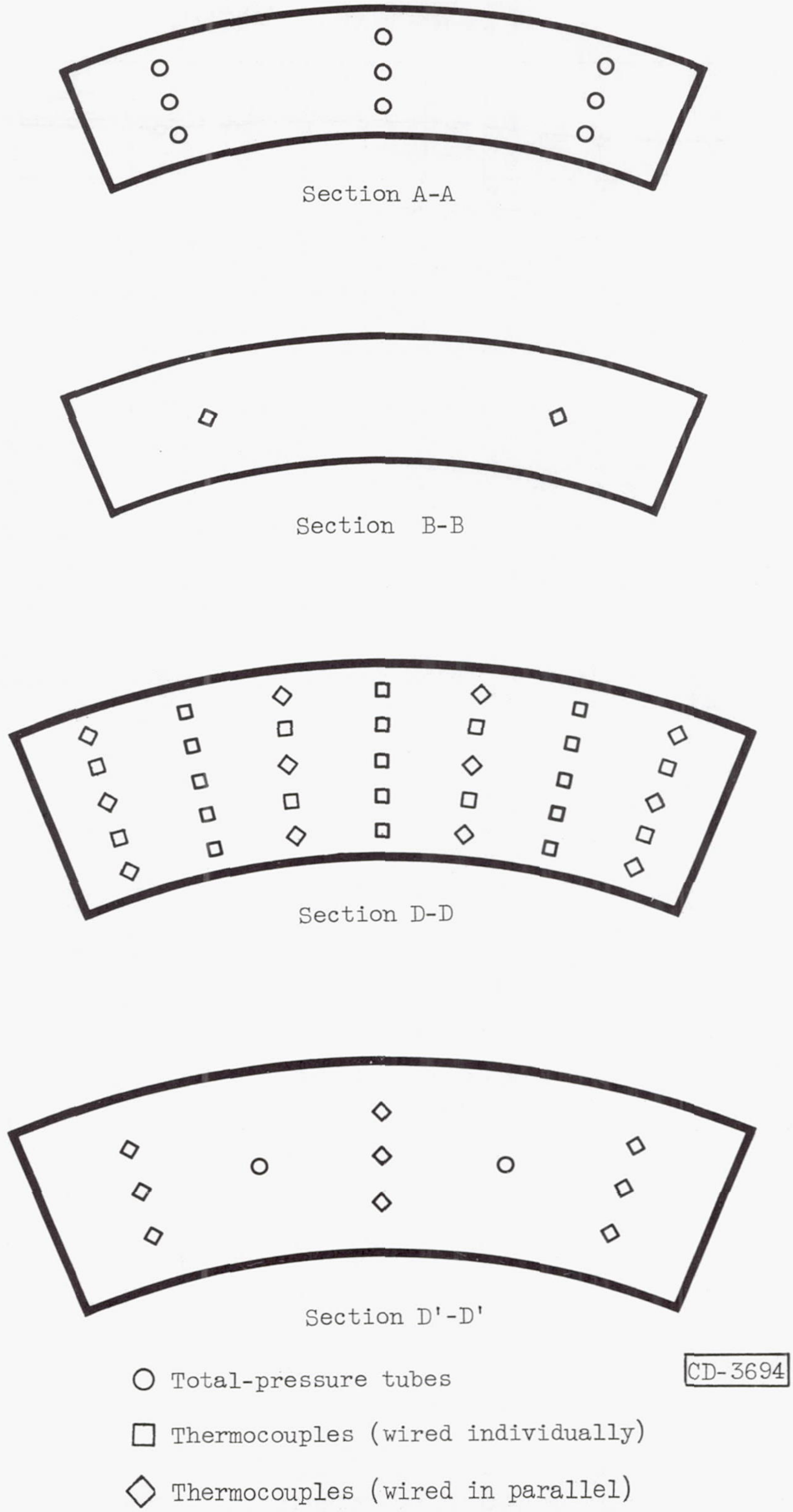


Figure 4. - Instrumentation sections.

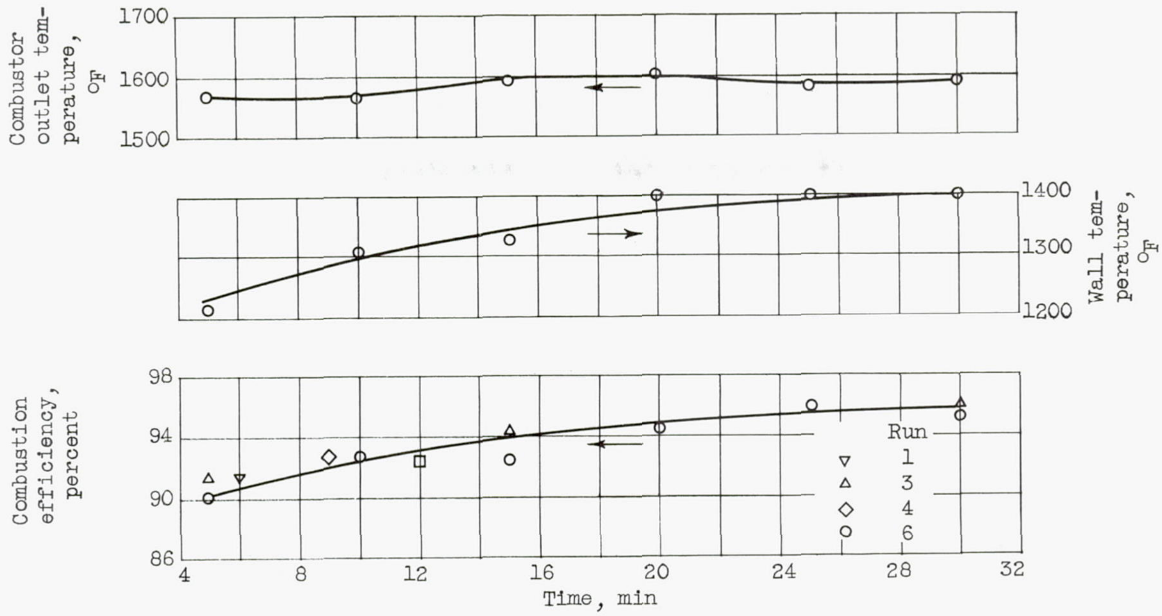


Figure 5. - Effect of thermocouple losses on computed combustion-efficiency values at condition B with JP-4, MIL-F-5624A, fuel.

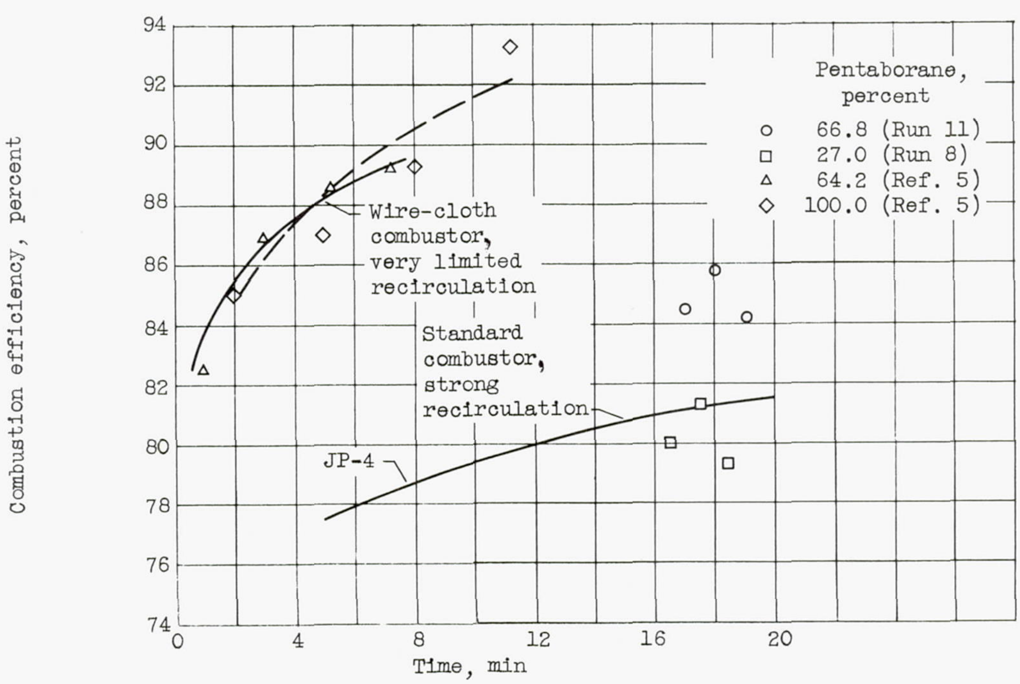
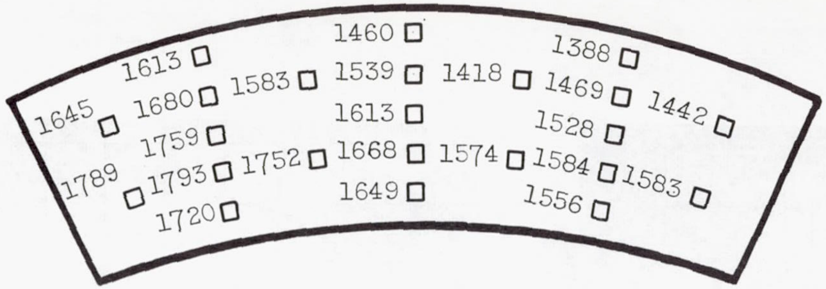
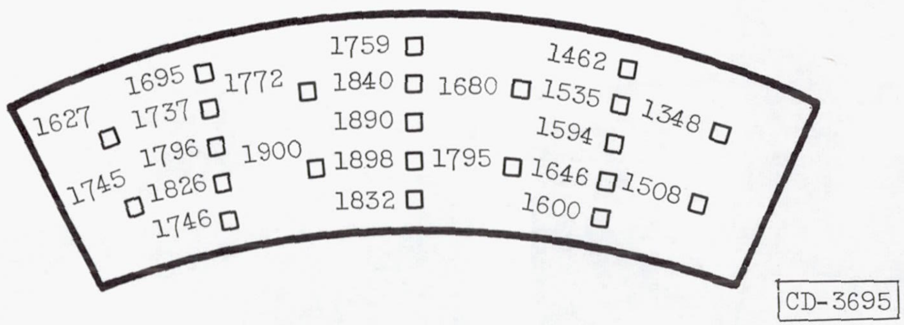


Figure 6. - Comparison of combustion efficiency of pentaborane and pentaborane blends at condition D with and without recirculation in combustion zone.

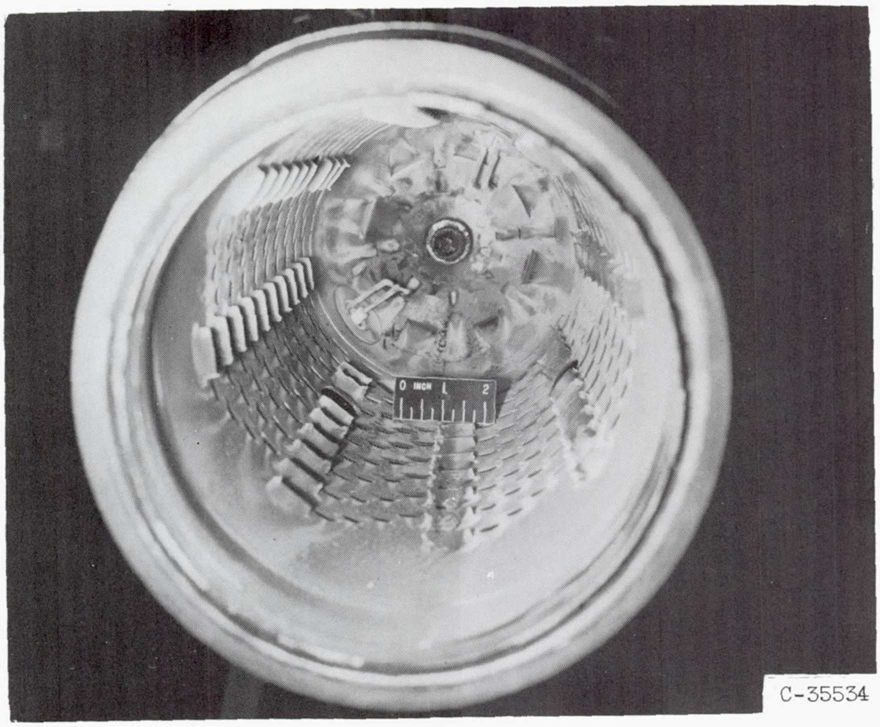


(a) Run 10; condition D; JP-4 fuel; outlet temperature, 1590° F; spread, 405° F.

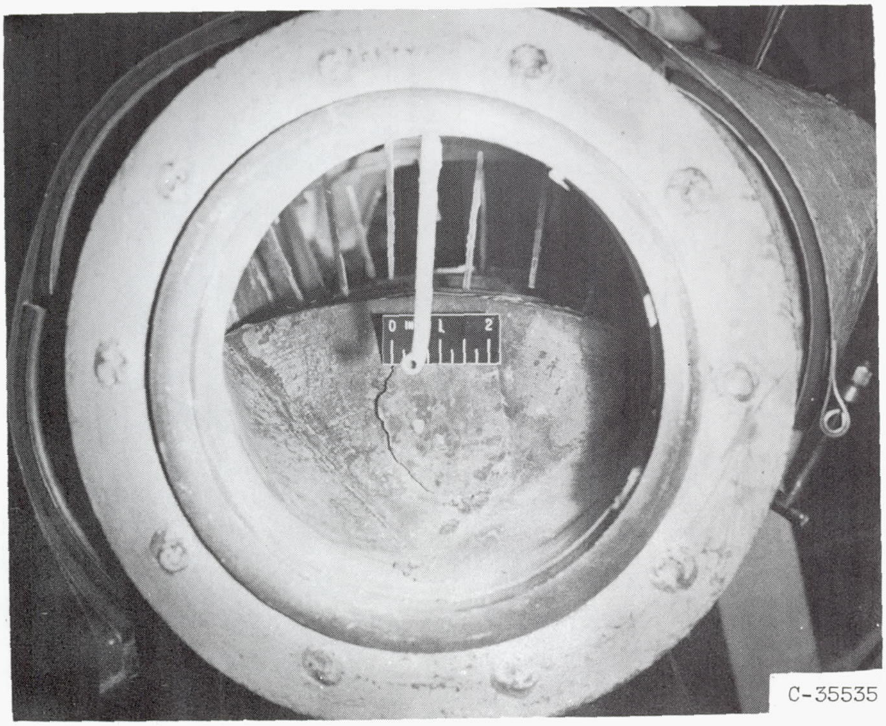


(b) Run 11; condition D; 66.8 percent pentaborane; outlet temperature, 1678° F; spread, 552° F.

Figure 7. - Combustor outlet temperature profiles.

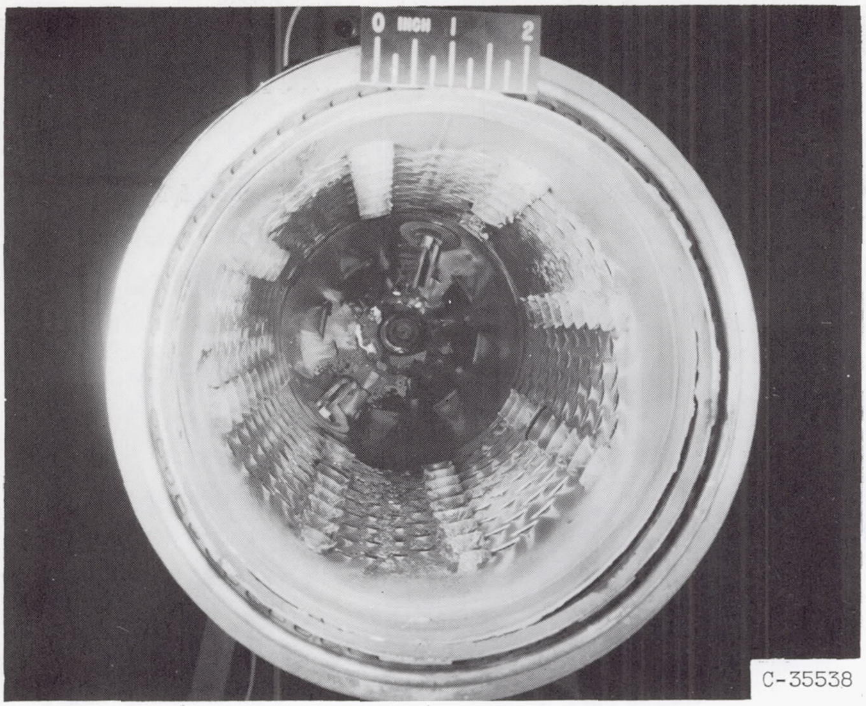


(a) Combustor.

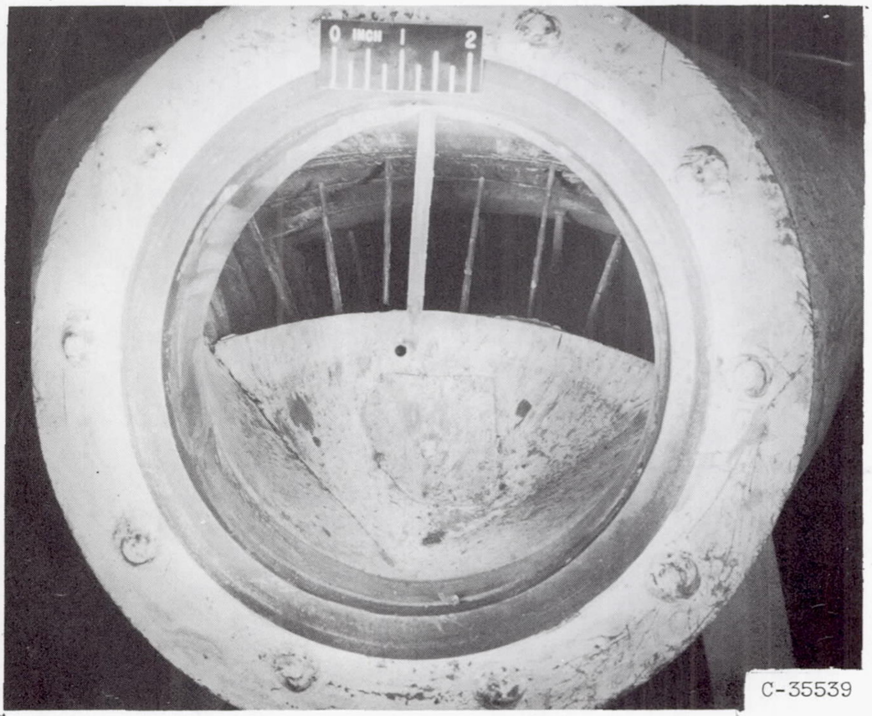


(b) Transition section.

Figure 8. - Deposits from combustion of a blend containing 66.8 percent pentaborane in JP-4. Condition B; run 5; test duration, 4 minutes; deposit weight, 71 grams.



(a) Combustor.



(b) Transition section.

Figure 9. - Deposits remaining after 30 minutes of operation with JP-4. Condition B; run 6; deposit weight, 62 grams.

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