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RESEARCH MEMORANDUM

EXPERIMENTAL PERFORMANCE OF A 5000-POUND-THRUST ROCKET CHAMBER USING A 20-PERCENT-FLUORINE - 80-PERCENT-OXYGEN MIXTURE WITH RP-1

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

April 24, 1957

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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EXPERIMENTAL PERFORMANCE OF A 5000-POUND-THRUST ROCKET CHAMBER USING A 20-PERCENT-FLUORINE - 80-PERCENT-OXYGEN MIXTURE WITH RP-1

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SUMMARY

The performance increase resulting from the addition of 20 percent fluorine to the oxygen - RP-1 propellant combination was evaluated experimentally in a 5000-pound-thrust rocket engine at a chamber pressure of 650 pounds per square inch absolute. Runs were made with the engine water cooled and regeneratively cooled.

At the volumetric oxidant-fuel ratio for peak performance of oxygen and RP-1, increases in specific impulse and characteristic velocity of 2.6 percent were obtained with fluorine addition for the water-cooled runs. The specific impulse was 248 pound-seconds per pound with fluorine added and 241 pound-seconds per pound with the oxygen - RP-1 combination, and the corresponding characteristic velocities were 5530 and 5390 feet per second. Heat rejection was slightly lower with fluorine added at the same volumetric oxidant-fuel ratio than with oxygen and RP-1 (1.10 compared to 1.25 Btu/(sq in.)(sec)).

The runs made with the engine regeneratively cooled indicated a specific impulse of 248 pound-seconds per pound and a characteristic velocity of 5380 feet per second for oxygen and RP-1. The heat rejection at peak specific impulse was approximately 1.10 Btu per square inch per second.

INTRODUCTION

An oxidant mixture of fluorine and oxygen will produce an increase in specific impulse of up to 14 percent over that for oxygen alone when hydrocarbons are used as the fuel (ref. 1). The advantage of adding fluorine to oxygen as a means of boosting the performance of the Vanguard first-stage engine, developed to use oxygen and RP-1, is discussed in references 2 and 3. Reference 3 points out the further advantage of adding unsymmetrical dimethylhydrazine (UDMH) to the fuel to preserve the volumetric flow ratio and still approximate the optimum weight ratio for high performance.

In cooperation with the Naval Research Laboratory and the General Electric Company, an experimental investigation was made at the Lewis laboratory to determine the performance gains and the change in heat rejection resulting from adding 20 percent fluorine to oxygen used with RP-1 as a fuel in a 5000-pound-thrust engine.

APPARATUS

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Engine

The thrust chambers (figs. 1 and 2(a)) used were supplied by the General Electric Company and produced 5000 pounds thrust at a chamber pressure of 600 pounds per square inch absolute with RP-1 fuel and liquid oxygen. The chambers, as originally supplied, were designed for regenerative cooling. This was accomplished by flowing the fuel through spiral passages surrounding the inner shell. These chambers were modified during the course of the experiments by extending the spiral cooling passages and adding a collector shroud (fig. 2(b)).

The injector (fig. 3) consisted of alternate rings of fuel and oxidant like-on-like sets of spray holes. There were 55 sets of 0.0465-inch-diameter fuel holes arranged in four rings and 51 sets of 0.0595-inch-diameter oxidant holes in three rings. Of this basic design there were two variations, the only difference between the two being the groove depth between adjacent rings. The two depths used were 1/64 and 7/64 inch. During the experiments, both types of injectors were modified by the drilling of 26 fuel holes (0.0225-in.-diam.) equally spaced between impinging fuel sets in the outermost ring.

Because of sealing difficulties with the large flared fitting used for an oxidant connection on the injector, this seal was changed to a flange type connection for the last series of runs.

Test Installation

The thrust stand consisted of a horizontal bedplate suspended from flexure plates. The engine was mounted directly on the bedplate. Propellants were supplied to the engine from pressurized tanks, flow rates being controlled by the tank pressure. The oxidant tank and the flow line up to the fire valve were surrounded by liquid nitrogen.

Propellants

The fuel used was RP-1 (MIL-F-25576). Oxygen was obtained as a liquid of 99.5-percent purity. Fluorine was obtained as a gas of at least 98-percent purity in commercial cylinders.

The fluorine-oxygen mixture was prepared in a propellant tank surrounded by liquid nitrogen. A known weight of oxygen was loaded first, then enough fluorine to make the mixture 20 percent fluorine by weight was added. The gaseous fluorine condensed upon entering the cooled tank. Helium was then bubbled through the oxidant to ensure a homogeneous mixture.

Instrumentation

Thrust was measured with a strain gage and recorded on an oscillograph recorder. The strain gage was calibrated before each series of runs; calibrations were made with the oxidant line cooled as during operation. The probable error in measurement was approximately ±1.5 percent.

Fuel and oxidant flows were measured by both turbine-type and differential-pressure flowmeters. The turbine-type flowmeter recorded directly on the oscillograph. The pressure drop across the differential-pressure flowmeter was sensed by a strain-gage transducer and the output recorded on the oscillograph. The oxidant turbine and Venturi meters were calibrated with both water and liquid oxygen. The fuel meters were calibrated with water. The flow calibrations indicated that the probable error in flow measurement was ±1.5 percent.

Chamber pressure was measured by a strain-gage pressure transducer, the output of which was recorded on an oscillograph, and by a recording Bourdon tube meter. Propellant feed pressures were measured by strain-gage pressure pickups recording on the oscillograph. The pressure instrumentation was calibrated with precision gages before each series of runs. Probable error in all pressure measurements was approximately ±3 pounds per square inch.

The oxidant tank, which was immersed in liquid nitrogen, was suspended from a strain gage load cell. The tank weight system was calibrated before each series of runs. The load cell temperature was maintained at $67^{\circ} \pm 2^{\circ}$ F. The content weight was determined to ±5 pounds.

PROCEDURE

The same starting procedure was used for the regeneratively cooled and water-cooled tests with RP-1 and liquid oxygen. First, propane and gaseous oxygen, introduced through the main flow lines into the engine, were ignited by an external torch. Low propellant flows (about 25 percent of full thrust flows) at an oxidant-fuel weight ratio of about 1.7 were then introduced and ignited by the propane-oxygen flame. As soon as low-flow combustion was assured (about 1.0 sec), the engine was brought up to full thrust.

In starting the fluorine-oxygen mixture, the gas flow step was eliminated, since at the fluorine concentration used the propellants ignited spontaneously. Again, when the low flows were burning properly, the engine was brought up to full thrust.

In all tests a fuel lead and an override of 0.1 to 0.2 seconds were used. Run duration varied from 5 to 15 seconds. Runs of 15-second duration were made with both oxygen and fluorine-oxygen mixtures.

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RESULTS

Experimental results are presented in table I and figures 4 to 7.

Oxygen with RP-1. - Figure 4 shows the performance obtained with RP-1 and oxygen during the first three series of runs when the engine was regeneratively cooled with the fuel. The specific impulse was about 248 pound-seconds per pound at an oxidant-fuel ratio of 2.2. Heat rejection at peak performance was approximately 1.10 Btu per square inch per second. The characteristic velocity was 5380 feet per second, and the thrust coefficient varied from 1.47 to 1.53. Each of the three series of runs resulted in damage to the engine (see table I and fig. 8). Prior to series 3, 26 holes (0.0225-in.-diam.) were drilled in the outer ring of the injector to provide a more fuel-rich atmosphere at the wall.

Figure 5 shows the performance obtained with RP-1 and oxygen during run series 4 and 6. The engine was modified to allow more uniform velocity distribution near the injector end (fig. 2(b)), and water cooling was employed. As before, the injector was provided with additional fuel holes. Peak specific impulse was 241 pound-seconds per pound at an oxidant-fuel ratio of 2.2. Heat rejection at peak performance was 1.25 Btu per square inch per second. Characteristic velocity was approximately 5390 feet per second, and thrust coefficient 1.44.

Fluorine-oxygen mixture with RP-1. - Series 5 was made with fluorine added to the oxidant. For this series, the exact percent of fluorine was uncertain because of trouble in the oxidant weight system, but it was approximately 10 percent. The run was made at a low oxidant-fuel ratio to avoid engine damage during disposal of the uncertain oxidant mixture. The injector was somewhat eroded during this run (fig. 9).

Figure 6 shows the performance obtained with RP-1 and a 20-percent-fluorine - 80-percent-oxygen mixture. During these runs (series 7, 8, and 9), as during series 4 and 6, the injector had added fuel holes in the outer ring and the engine was modified and water cooled. Specific impulse was 248 pound-seconds per pound at an oxidant-fuel ratio of 2.40. At this ratio, the heat rejection was 1.24 Btu per square inch per second. The characteristic velocity and thrust coefficient were 5540 feet

per second and 1.44, respectively. The performance was just slightly lower at an oxidant-fuel ratio of 2.32 (volumetrically equivalent to an oxidant-fuel ratio of 2.20 with oxygen and RP-1 at the normal boiling point for each oxidant). The specific impulse was about 248 pound-seconds per pound, the heat rejection approximately 1.10 Btu per square inch per second, the characteristic velocity 5530 feet per second, and the thrust coefficient 1.44. Heat rejection increased rapidly with increasing oxidant-fuel ratio. The engines and injectors used were damaged
4459 during some of the fluorine runs. The damage is described in table I and shown in figures 10 to 12.

The performance curves of figures 5 and 6 are summarized in figure 7. At constant volumetric oxidant-fuel ratio, approximately 2.6-percent increases in specific impulse and characteristic velocity were obtained. The heat rejection was less with fluorine added than for oxygen and RP-1 alone at the oxidant-fuel ratios considered. The thrust coefficients are equal in the region of interest. At peak performance with fluorine, the specific impulse was 2.7 percent higher than at the peak with oxygen and RP-1. The heat transfer with 20 percent fluorine at peak performance was equivalent to that obtained at peak performance with oxygen and RP-1.

DISCUSSION

The 2.6-percent increase in specific impulse resulting from addition of 20 percent fluorine at the volumetric oxidant-fuel ratio for peak performance of oxygen and RP-1 is that predicted in reference 3. However, the peak performance increase of 2.7 percent is less than the 4.0 percent increase predicted in reference 3. Furthermore, the experimental peak occurred at an oxidant-fuel ratio of 2.4, rather than the predicted 2.7. The engine burnouts encountered during operations at high oxidant-fuel ratios limited data obtained in this region; this, in turn, limited the accuracy of the performance curve at these high oxidant-fuel ratios.

The apparent slight decrease in heat rejection with fluorine addition at the same oxidant-fuel ratio is somewhat surprising and contrary to the prediction of reference 3. Scatter in the data may account for some of the difference. However, the data indicate no substantial difference in the oxidant-fuel-ratio region of interest. The heat transfer differences cannot be explained by temperature alone, since the theoretical temperature was the same at an oxidant-fuel ratio of 2.1 and slightly higher at higher ratios. The differences, then, were caused by other factors such as gas composition or wall deposits.

Series 4 and 6 for oxygen and RP-1 indicate two different sets of values for both characteristic velocity and thrust coefficient. However, the best average line drawn through all the points agrees closely with the thrust-coefficient data obtained from the fluorine runs. A possible

answer to the scatter may be found in the different average chamber pressures for each series. Series 4 (oxygen and RP-1) was made at a mean chamber pressure of 626 pounds per square inch absolute, series 6 at a mean pressure of 673 pounds per square inch absolute, and the 20-percent-fluorine runs at a mean pressure of 651 pounds per square inch absolute. Changes in the chamber pressure, and hence the mass flow through the engine, may have affected the gas velocity in the acceleration or reaction zone near the injector. Since the chamber pressure tap in this case was in the reaction zone as indicated by chamber heat marks, velocity changes could occur that would affect the measurement of static pressure. For 4459
the contraction ratio of this engine, a static pressure 7 to 8 percent lower than the total pressure may occur at the beginning of the convergent section. Shifting the flame front downstream with increased mass flow would reduce velocity at the chamber-pressure tap and consequently raise static pressure.

The engine appeared to be marginally cooled. With either oxygen or the 20-percent-fluorine - 80-percent-oxygen mixture operation was apparently safe below an oxidant-fuel ratio of about 2.5. Above this ratio burnouts occurred almost invariably. The bubbled cadmium plating found in the engine cooling passages after series 3, for example, indicated an inner-wall temperature of over 624° F. This was evidently well over the anticipated inner-wall temperature.

The difference in specific impulse between the regeneratively cooled and water-cooled runs may have been caused by a systematic error in thrust, since both characteristic velocities are the same. The reason for this error is not known. Previous experience indicates that the level of specific impulse obtained for the regeneratively cooled runs is more nearly the true level (see ref. 3), while the value for water-cooled runs is probably low. However, data from the water-cooled runs with and without fluorine appear consistent, because the percent increase in specific impulse and characteristic velocity are the same.

In summary, a 20-percent-fluorine - 80-percent-oxygen mixture with RP-1 gives a 2.6-percent increase in performance at the volumetric oxidant-fuel ratio corresponding to peak performance with oxygen and RP-1. In addition, the engine appeared to be unharmed by the addition of fluorine. The heat rejection was actually lower with fluorine in the region considered, and burnouts appeared to be no more of a problem.

SUMMARY OF RESULTS

The performance resulting from the addition of 20 percent fluorine to the oxygen - RP-1 propellant combination was evaluated experimentally at a chamber pressure of 650 pounds per square inch absolute in a 5000-pound-thrust engine similar to the Vanguard first-stage engine. The following results were obtained:

1. Specific impulse was increased 2.6 percent, from 241 to 248 pound-seconds per pound at the volumetric oxidant-fuel ratio for peak performance of oxygen and RP-1.

2. Characteristic velocity was increased 2.6 percent, from 5390 to 5530 feet per second at the same volumetric oxidant-fuel ratio.

3. Heat transfer decreased from 1.25 to 1.10 Btu per square inch per second with fluorine added at the same volumetric oxidant-fuel ratio.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, February 18, 1957

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1. Gordon, Sanford, and Wilkins, Roger L.: Theoretical Maximum Performance of Liquid Fluorine - Liquid Oxygen Mixtures with JP-4 Fuel as Rocket Propellants. NACA RM E54H09, 1954.

2. Stehling, K. R., and Escher, W. J. D.: A Method of Improving the Performance of the Vanguard First-Stage Powerplant by Adding Fluorine to the Liquid Oxygen Oxidizer. NRL Memo. 582, Vehicles Branch, Project Vanguard, Naval Res. Lab., Apr. 4, 1956.

3. Tomazic, William A., Schmidt, Harold W., and Tischler, Adelbert O.: Analysis of Fluorine Addition to the Vanguard First Stage. NACA RM E56K28, 1957.

TABLE I. - SUMMARY OF DATA

Oxidant-fuel ratio	Specific impulse, lb-sec/lb	Over-all heat rejection, Btu/(sq in.)(sec)	Chamber pressure, lb/sq in. abs	Characteristic velocity, ft/sec	Thrust coefficient	Full thrust duration, sec	Remarks
Series 1: Oxygen and RP-1; regenerative cooling.							
2.51	225.2	1.04	598	4893	1.482	2.0	Engine burned out at injector end and at throat.
2.20	-----	----	644	5393	-----	5.5	
2.21	248.2	1.20	625	5335	1.498	5.6	
2.31	249.2	1.16	636	5351	1.499	5.8	
2.32	-----	1.17	631	5329	-----	5.8	
2.68	-----	1.44	674	5175	-----	5.5	
2.67	-----	1.38	671	5009	-----	5.5	Low characteristic velocities (last three) indicate that the first burn-out occurred during previous run.
2.05	-----	1.30	671	4941	-----	17.4	
1.94	-----	1.36	677	4930	-----	16.0	
Series 2: Oxygen and RP-1; regenerative cooling.							
----	-------	----	---	----	-----	6.1	Gouge marks in chamber at injector end.
Series 3: Oxygen and RP-1; regenerative cooling.							
2.17	250.0	1.07	633	5370	1.528	5.1	Twenty-six 0.0225-in.-diam. holes added in outer ring of injector; screens installed in fuel and oxidant lines before injector; start and shutdown more fuel-rich. Engine burned out at injector (fig. 8) and cadmium plating in coolant passages bubbled.
2.18	248.9	1.16	632	5329	1.534	5.3	
2.21	246.6	.95	635	5354	1.512	5.3	
2.24	249.1	.96	639	5355	1.527	7.0	
2.37	247.0	.90	647	5381	1.472	9.3	
2.35	247.4	.93	645	5372	1.476	9.2	
2.32	247.6	.94	645	5400	1.470	9.3	
2.42	247.0	.92	645	5400	1.467	9.7	
2.50	246.8	.85	637	5341	1.481	10.0	
2.51	247.7	.95	645	5387	1.474	9.8	
Series 4: Oxygen and RP-1; water cooling.							
2.44	240.8	1.52	627	5240	1.478	9.6	Engine modified at injector end to give more even distribution of coolant (fig. 2(b)). Water flow more than twice fuel flow.
1.86	241.1	1.19	635	5269	1.472	9.5	
1.84	242.9	1.15	637	5288	1.477	9.5	
1.74	235.7	1.07	640	5176	1.465	9.4	
2.05	239.8	1.09	620	5252	1.469	6.7	
2.22	240.1	1.09	613	5251	1.471	6.7	
2.07	240.0	1.10	624	5301	1.456	6.8	
2.14	240.5	1.19	623	5321	1.454	6.8	
2.29	240.8	1.19	614	5323	1.455	6.5	
Series 5: 10%-Fluorine - 90%-oxygen mixture and RP-1; water cooling.							
1.16	211.4	----	519	4834	1.407	5.7	Injector somewhat scored (fig. 9).

TABLE I. - Concluded. SUMMARY OF DATA

Oxidant-fuel ratio	Specific impulse, lb-sec/lb	Over-all heat rejection, Btu/(sq in.)(sec)	Chamber pressure, lb/sq in. abs	Characteristic velocity, ft/sec	Thrust coefficient	Full thrust duration, sec	Remarks
Series 6: Oxygen and RP-1; water cooling.							
1.87	239.5	0.59	665	5425	1.420	4.8	Same conditions as series 4. Injector changed because of face erosion during series 5.
1.98	243.7	----	671	5456	1.437	5.0	
2.05	242.3	1.25	669	5418	1.438	5.0	
2.23	242.4	1.38	672	5459	1.428	5.1	
2.32	238.5	1.40	673	5396	1.422	5.0	
2.43	239.2	1.42	669	5401	1.425	4.9	
2.06	239.6	1.38	672	5412	1.424	4.8	
2.05	239.6	1.33	675	5422	1.422	5.9	
1.89	237.4	1.34	683	5399	1.414	6.0	
2.07	242.8	1.29	676	5532	1.411	6.0	
2.12	242.3	1.32	671	5461	1.427	5.9	
2.04	241.7	1.36	676	5492	1.415	5.8	
2.27	243.5	1.41	677	5490	1.427	5.9	
2.12	242.1	1.35	673	5467	1.424	5.9	
2.08	241.6	1.39	---	----	-----	3.8	
Series 7: 20.4%-Fluorine - 79.6%-oxygen mixture and RP-1; water cooling.							
2.32	241.9	1.08	647	5445	1.429	4.7	Engine damaged, probably during high-oxidant-fuel-ratio run (second last). Burnt near injector and near throat.
2.36	245.9	1.06	645	5514	1.435	6.0	
2.26	248.2	.69	635	5502	1.451	14.5	
2.38	249.5	1.05	657	5584	1.437	11.5	
2.58	244.5	1.34	664	5466	1.438	10.9	
2.34	241.7	1.24	644	5497	1.414	13.9	
Series 8: 19.9%-Fluorine - 80.1%-oxygen mixture and RP-1; water cooling.							
2.47	248.1	1.577	657	5520	1.445	3.9	Engine scored badly in three places (fig. 10).
Series 9: 19.9%-Fluorine - 80.1%-oxygen mixture and RP-1; water cooling.							
2.38	253.4	----	658	5619	1.450	3.6	Repaired engine from series 7 used. Injector ring burnt through (fig. 11), resulting oxidant stream burnt engine (fig. 12).

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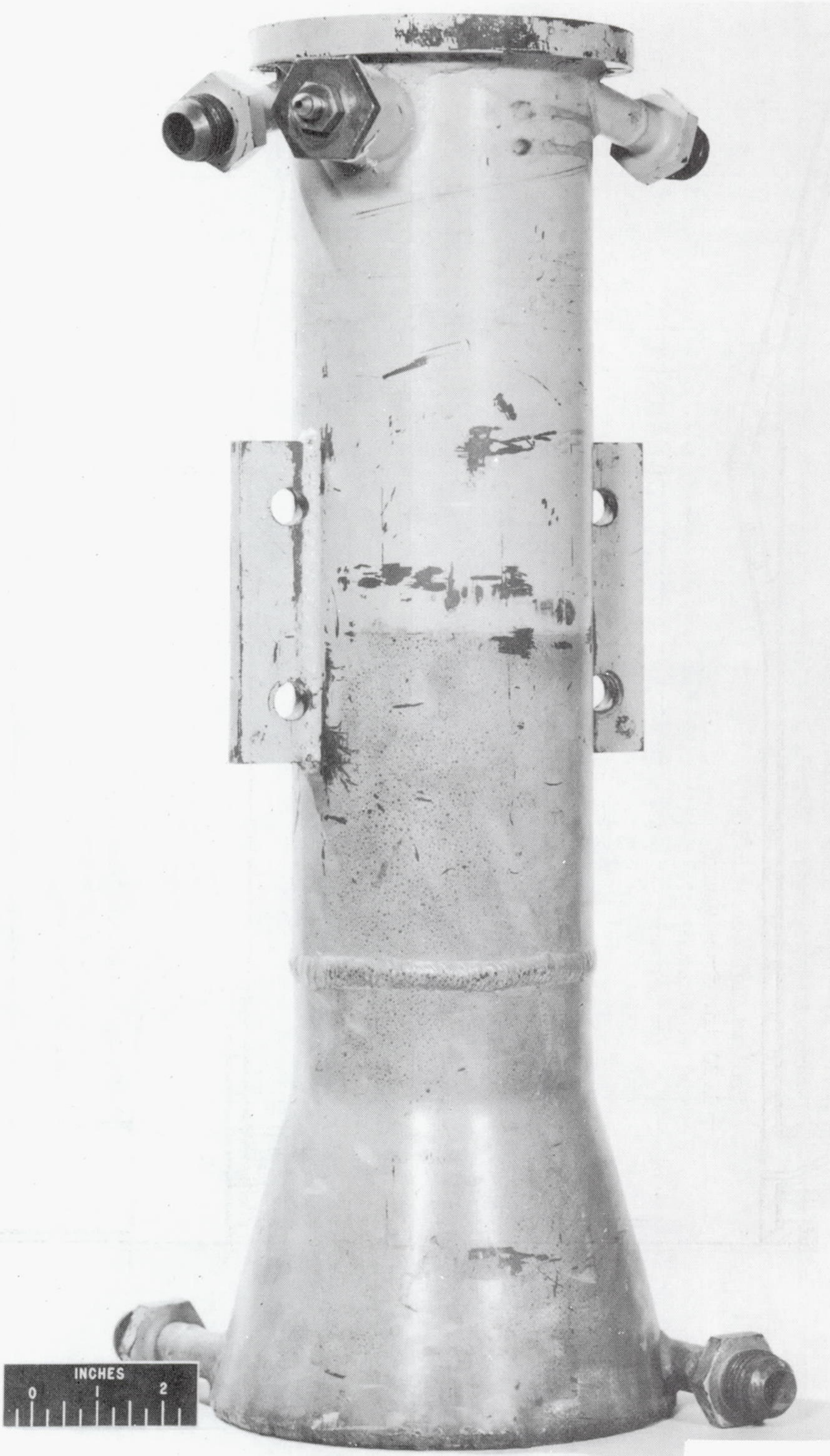

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Figure 1. - 5000-Pound-thrust chamber before alterations.

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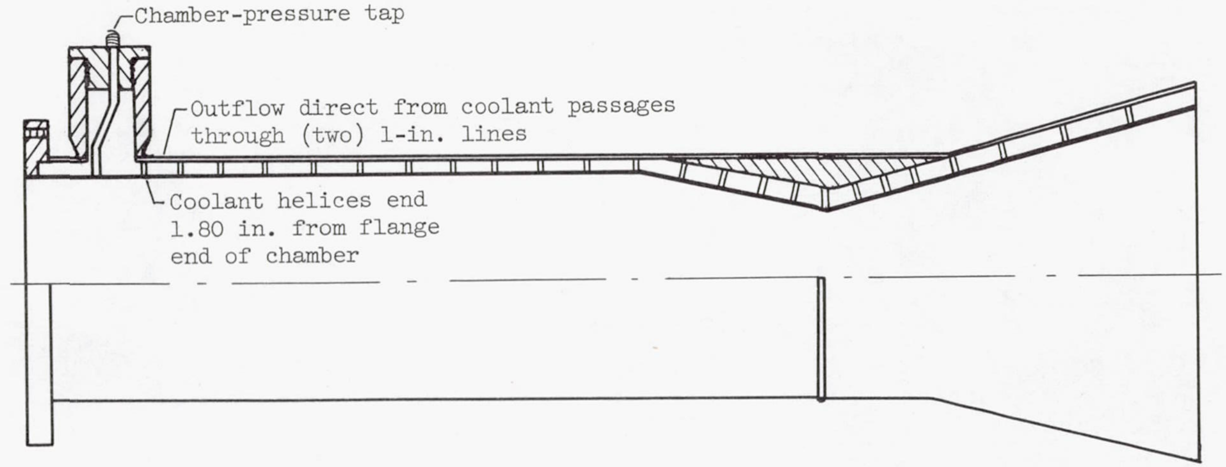
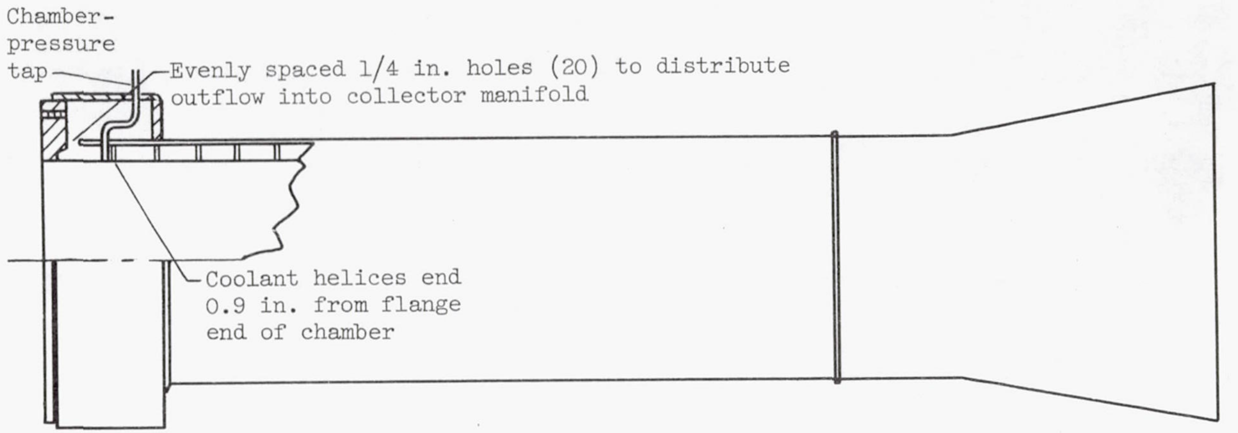


(a) Before alterations.



(b) After alterations.

Figure 2. - Comparison of thrust chamber before and after alterations to coolant passages. Nozzle diameter, 6.22 inches; throat diameter, 2.65 inches; chamber diameter, 3.58 inches; over-all length, 21.71 inches; inner-chamber wall thickness, 0.12 inch.

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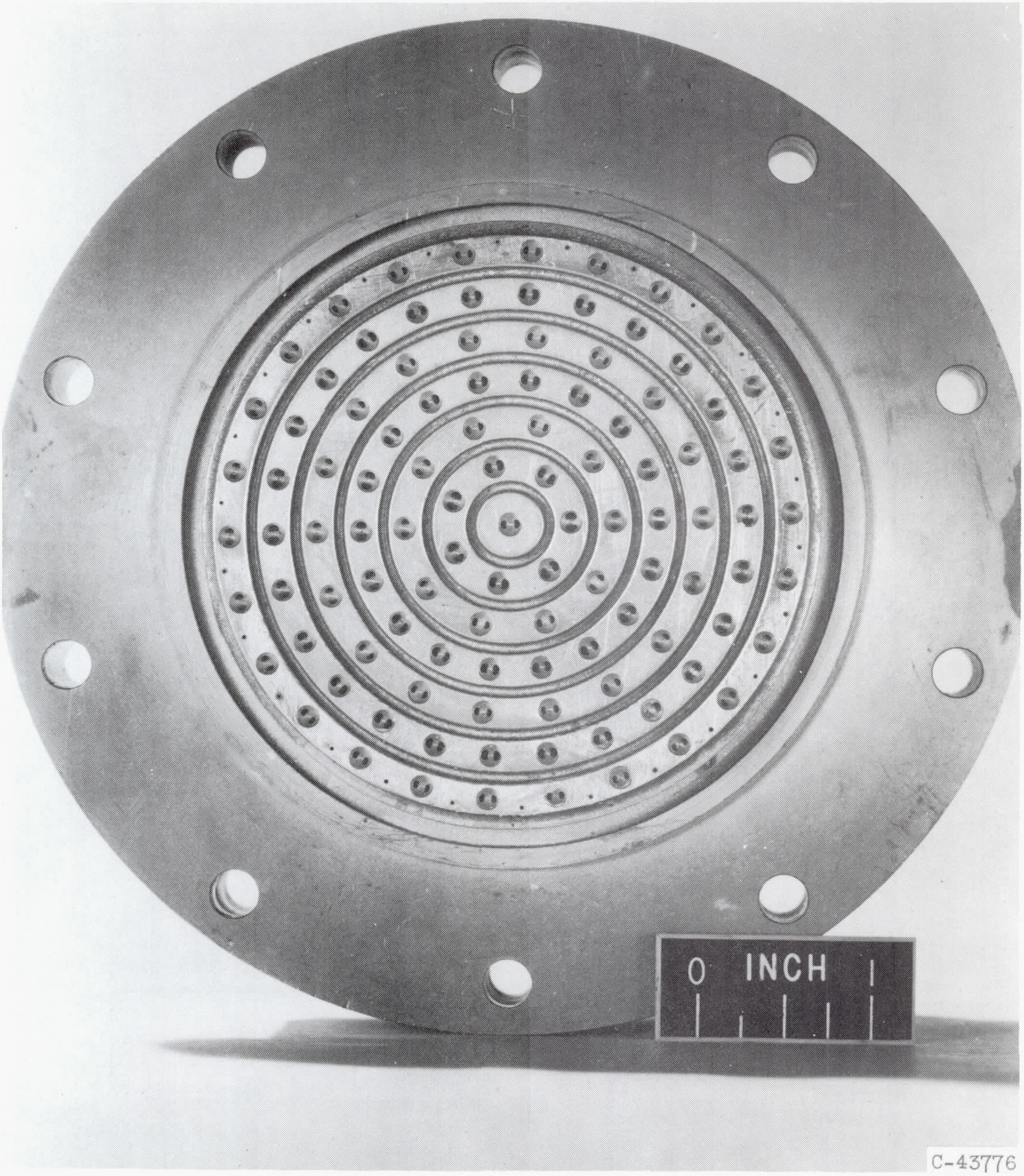

Figure 3. - Like-on-like injector for 5000-pound-thrust chamber after addition of film cooling holes.

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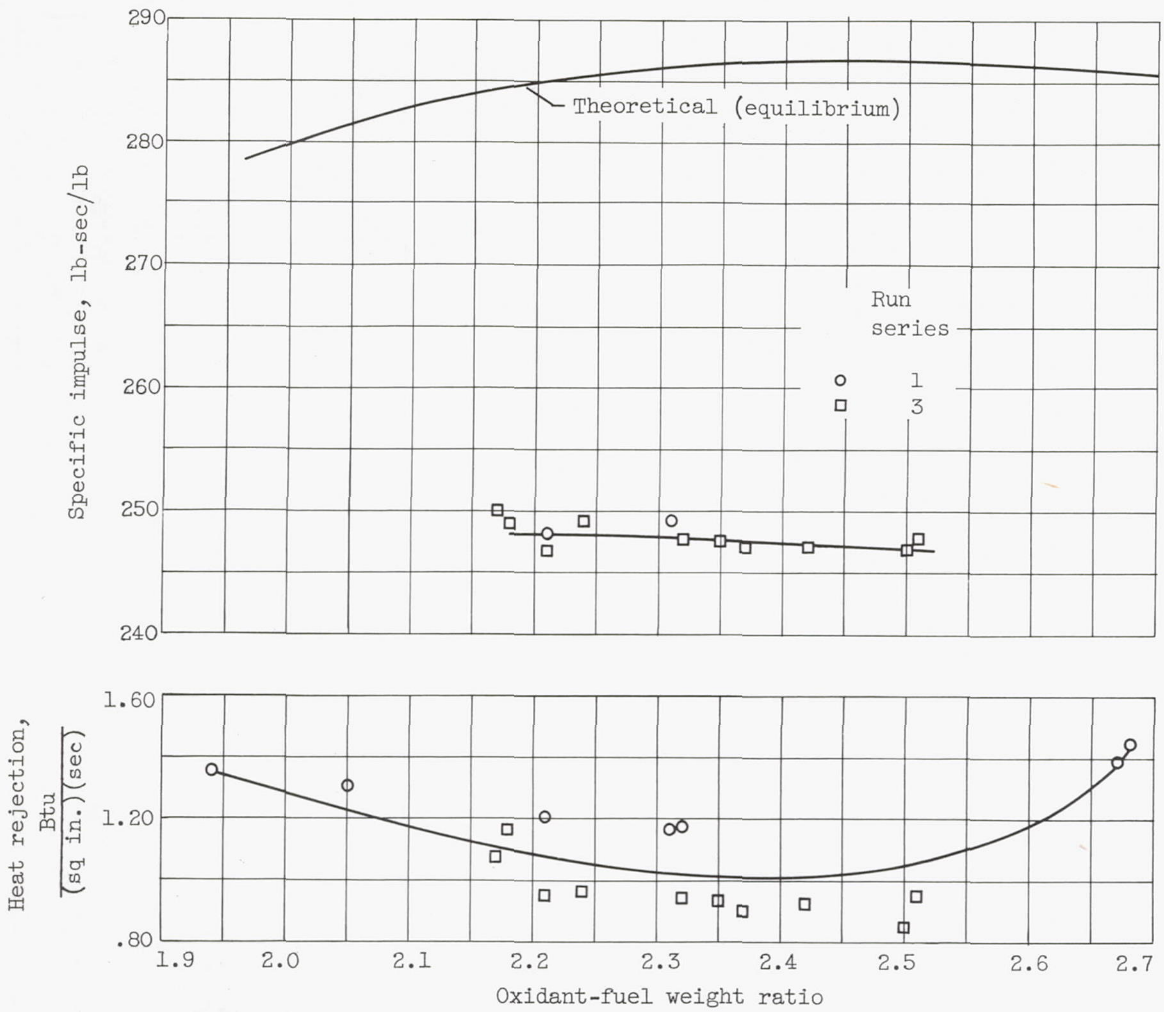

(a) Specific impulse and heat rejection.

Figure 4. - Theoretical and experimental performance of RP-1 and liquid oxygen in Vanguard 5000-pound-thrust engine (regeneratively cooled) at nominal chamber pressure of 650 pounds per square inch absolute.

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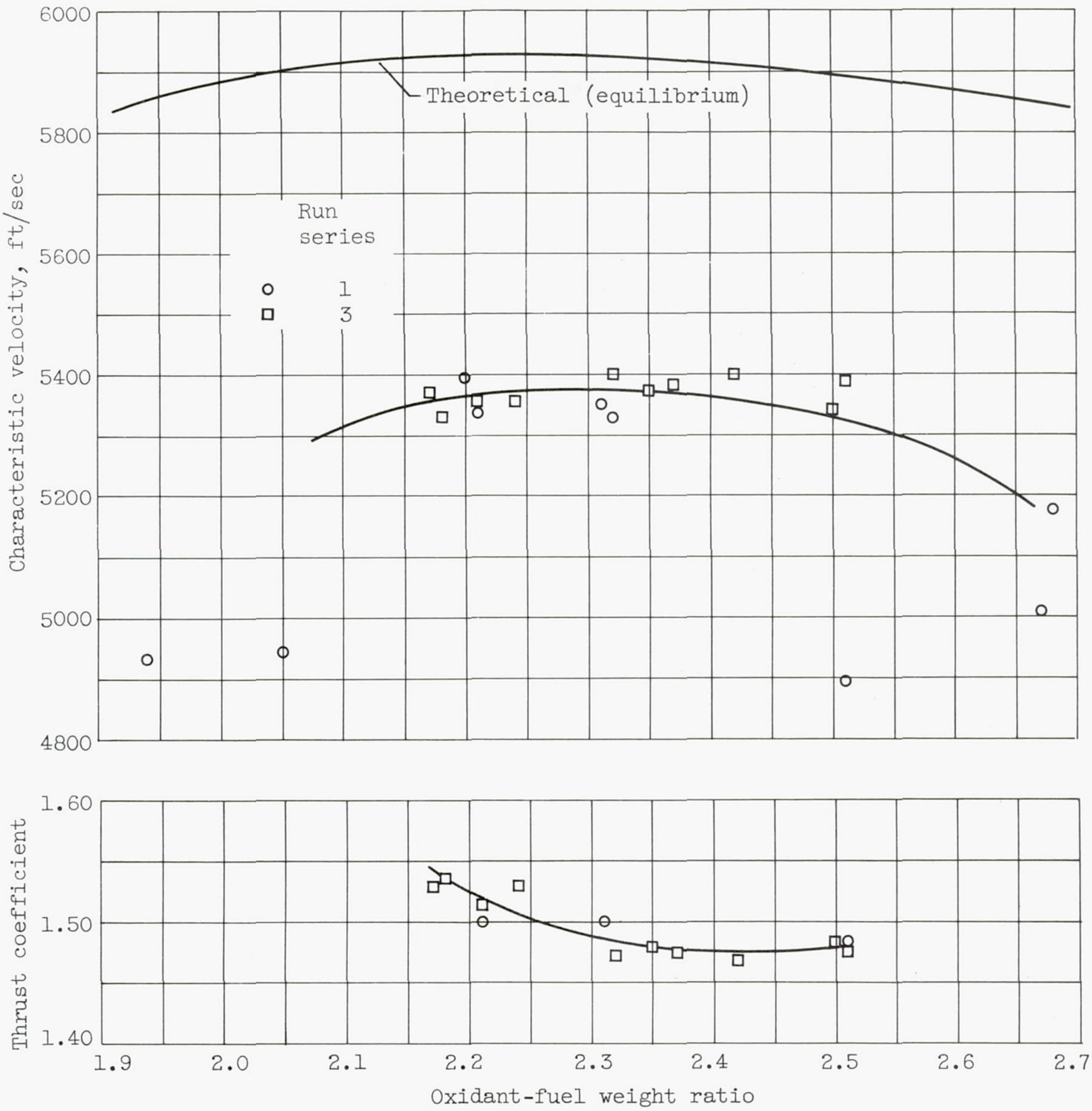

(b) Characteristic velocity and thrust coefficient.

Figure 4. - Concluded. Theoretical and experimental performance of RP-1 and liquid oxygen in Vanguard 5000-pound-thrust engine (regeneratively cooled) at nominal chamber pressure of 650 pounds per square inch absolute.

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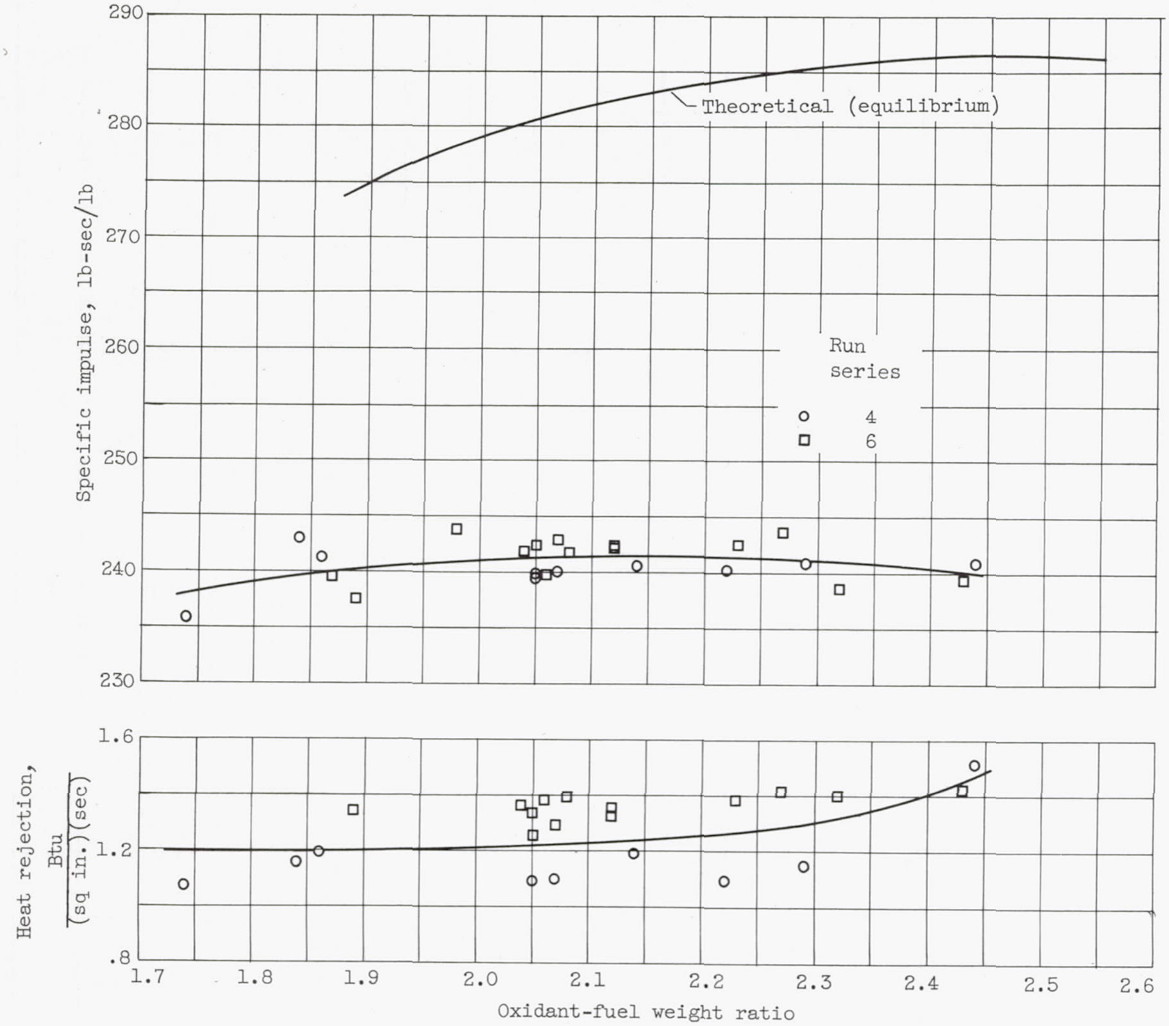

(a) Specific impulse and heat rejection.

Figure 5. - Theoretical and experimental performance of RP-1 and liquid oxygen in Vanguard 5000-pound-thrust engine (water-cooled) at nominal chamber pressure of 650 pounds per square inch absolute.

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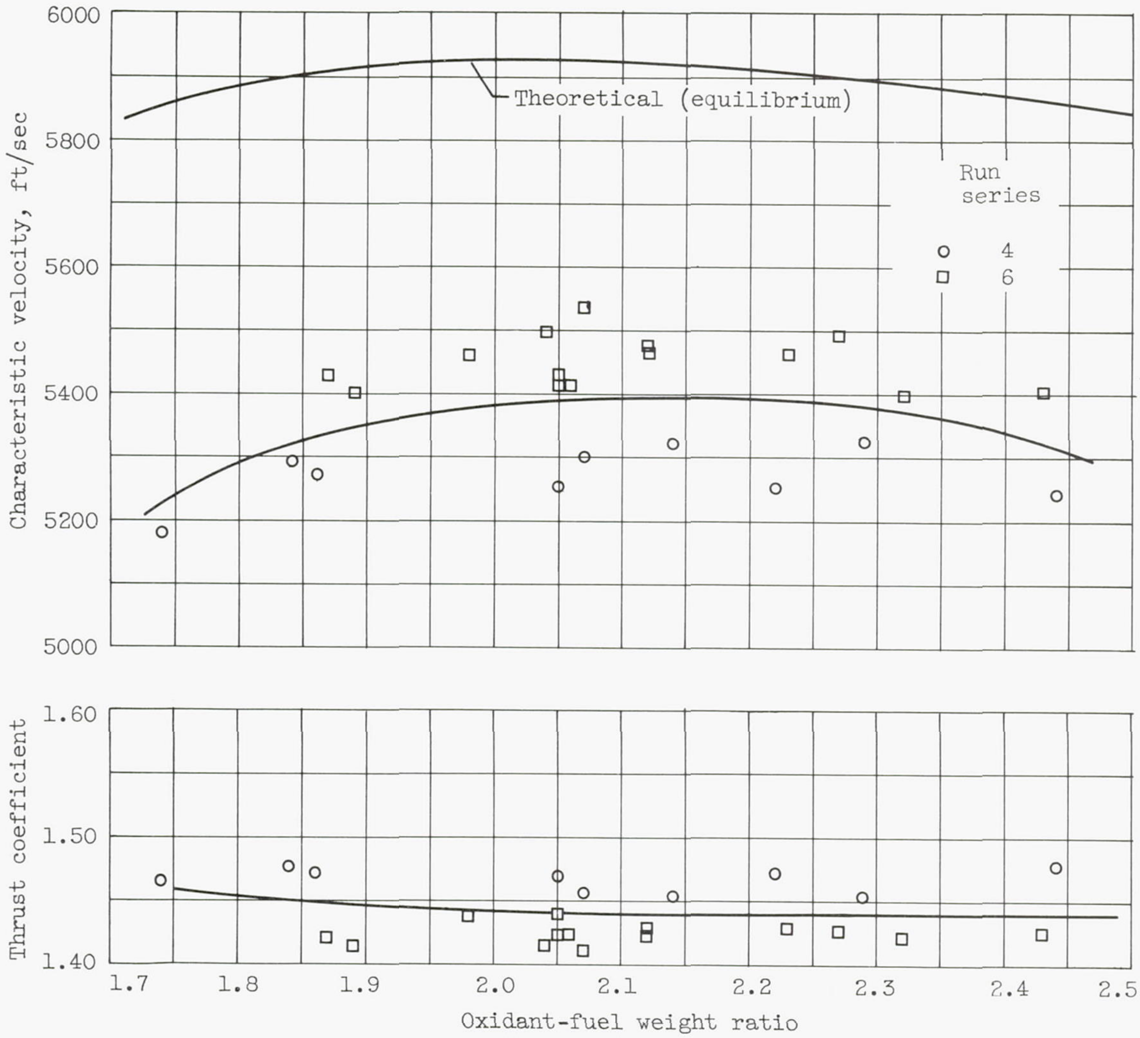
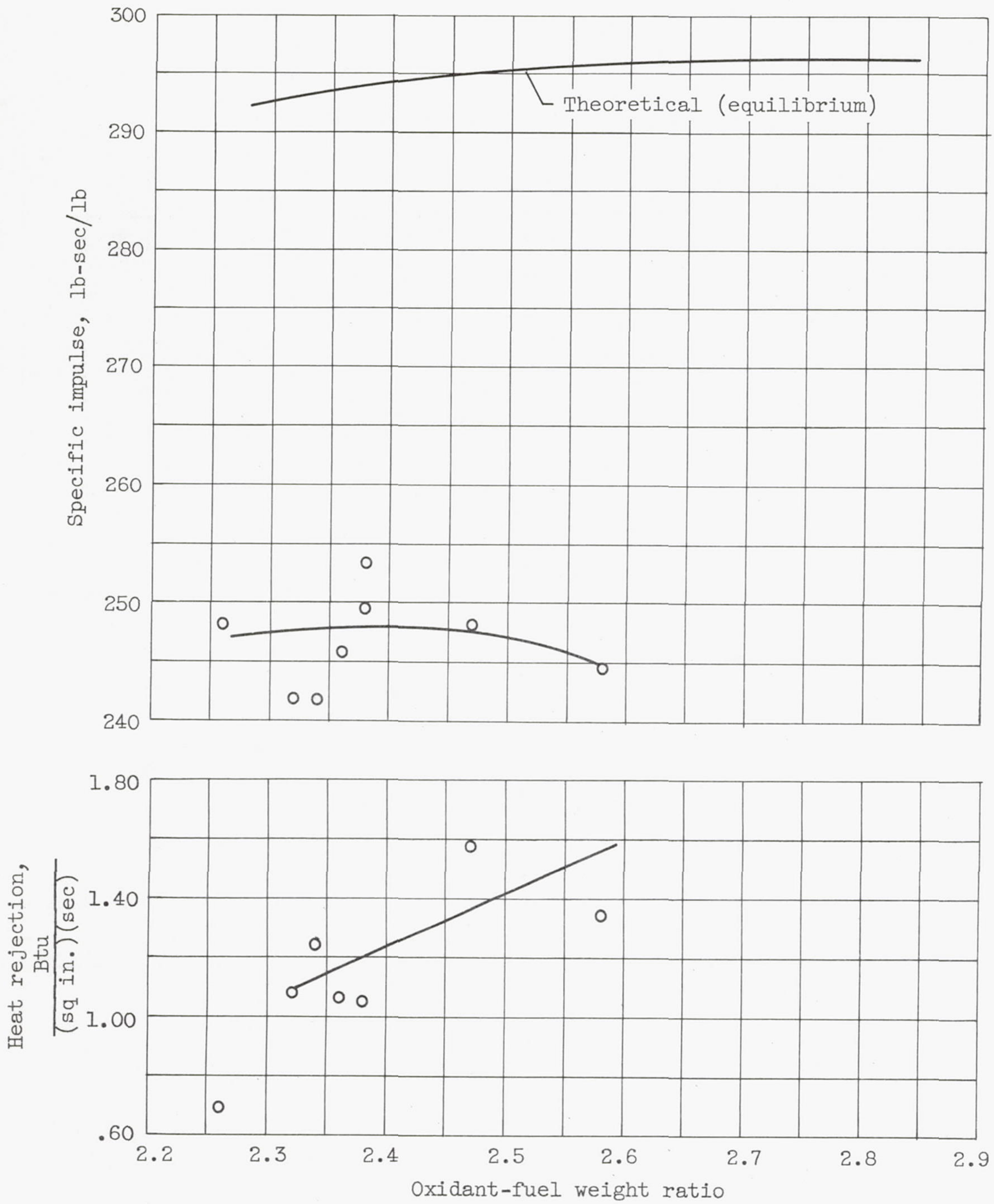


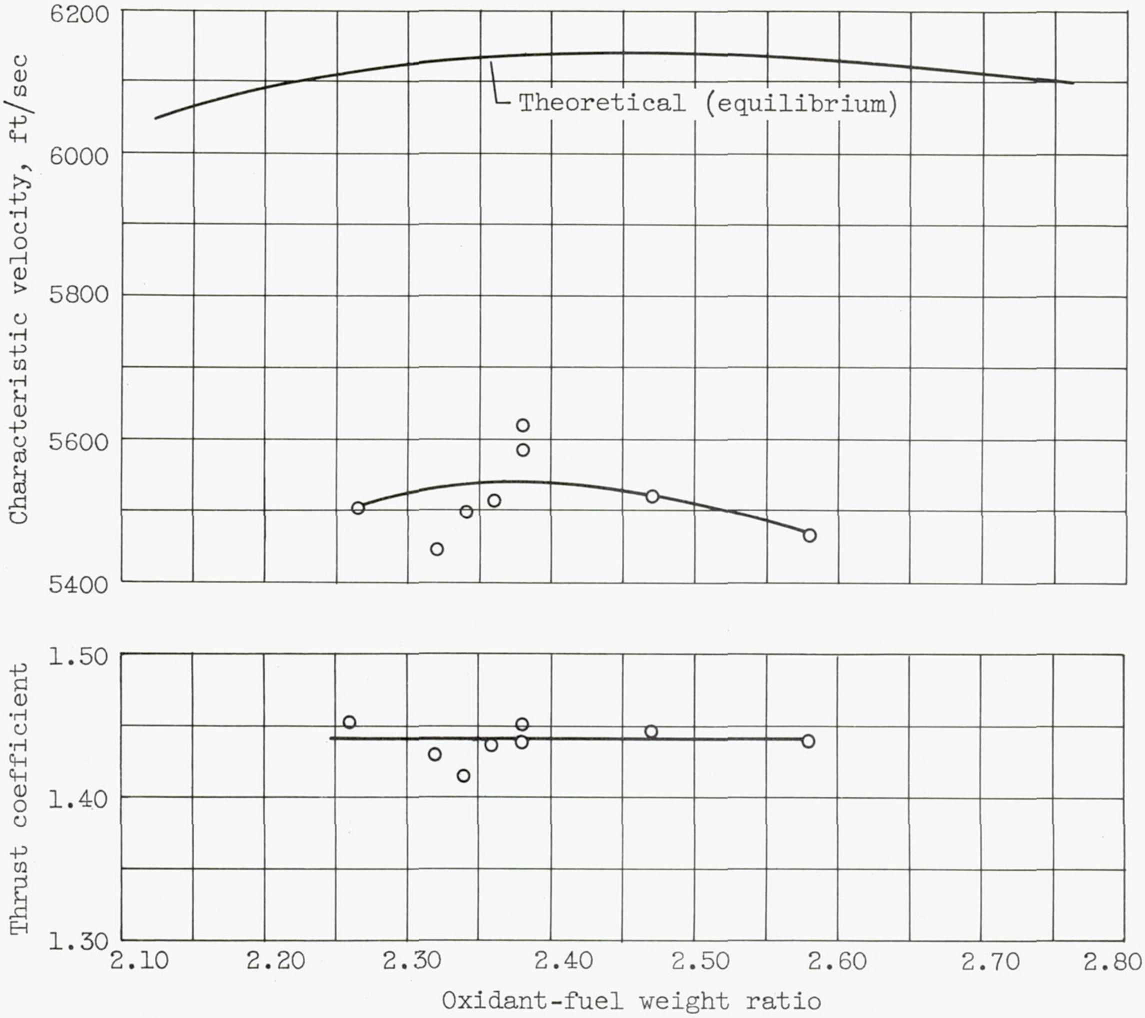
(b) Characteristic velocity and thrust coefficient.

Figure 5. - Concluded. Theoretical and experimental performance of RP-1 and liquid oxygen in Vanguard 5000-pound-thrust engine (water-cooled) at nominal chamber pressure of 650 pounds per square inch absolute.



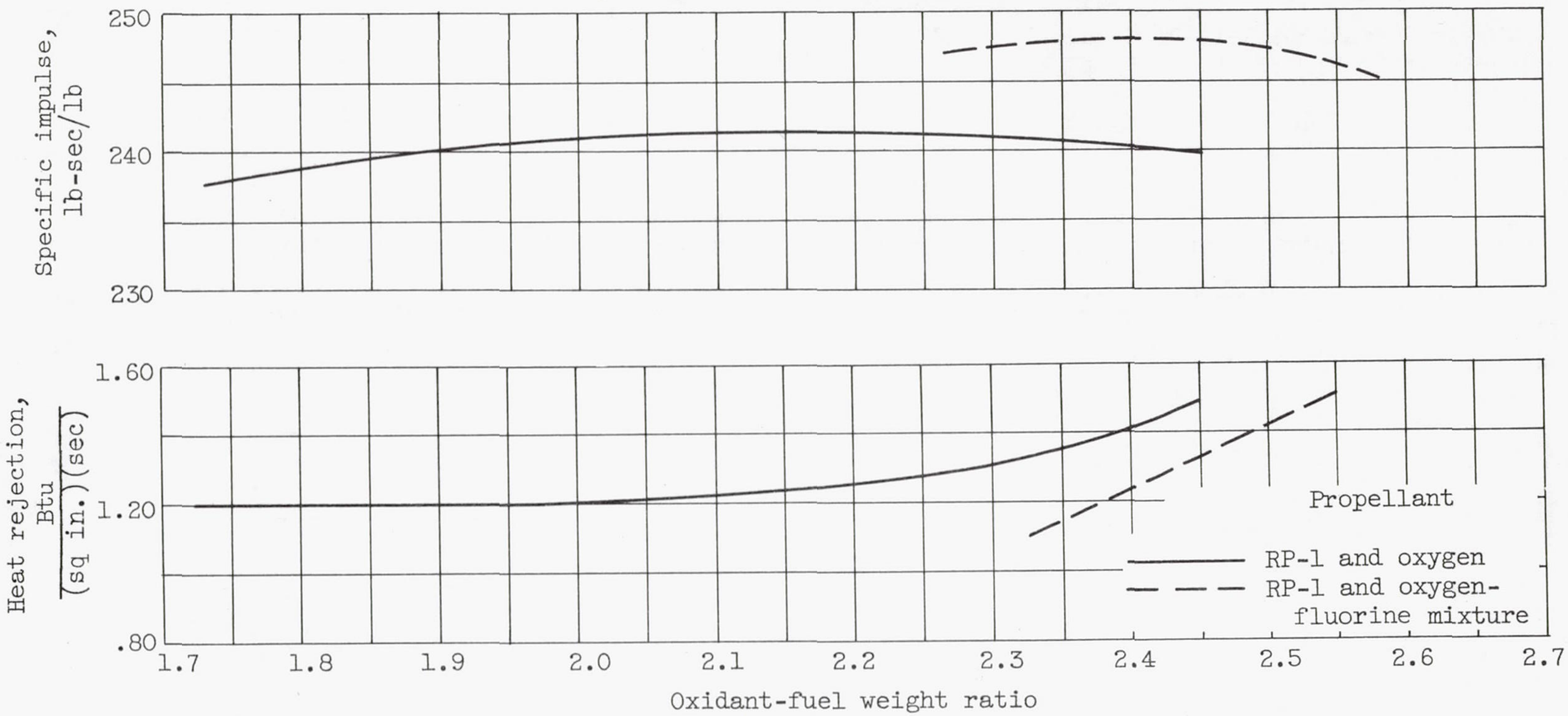
(a) Specific impulse and heat rejection.

Figure 6. - Theoretical and experimental performance of RP-1 and 20-percent-fluorine - 80-percent-oxygen mixture in Vanguard 5000-pound-thrust engine (water-cooled) at nominal chamber pressure of 650 pounds per square inch absolute.



(b) Characteristic velocity and thrust coefficient.

Figure 6. - Concluded. Theoretical and experimental performance of RP-1 and 20-percent-fluorine - 80-percent-oxygen mixture in Vanguard 5000-pound-thrust engine (water-cooled) at nominal chamber pressure of 650 pounds per square inch absolute.



(a) Specific impulse and heat rejection.

Figure 7. - Comparison of performance of RP-1 and oxygen with RP-1 and 20-percent-fluorine - 80-percent-oxygen mixture in Vanguard 5000-pound-thrust engine (water-cooled) at nominal chamber pressure of 650 pounds per square inch absolute.

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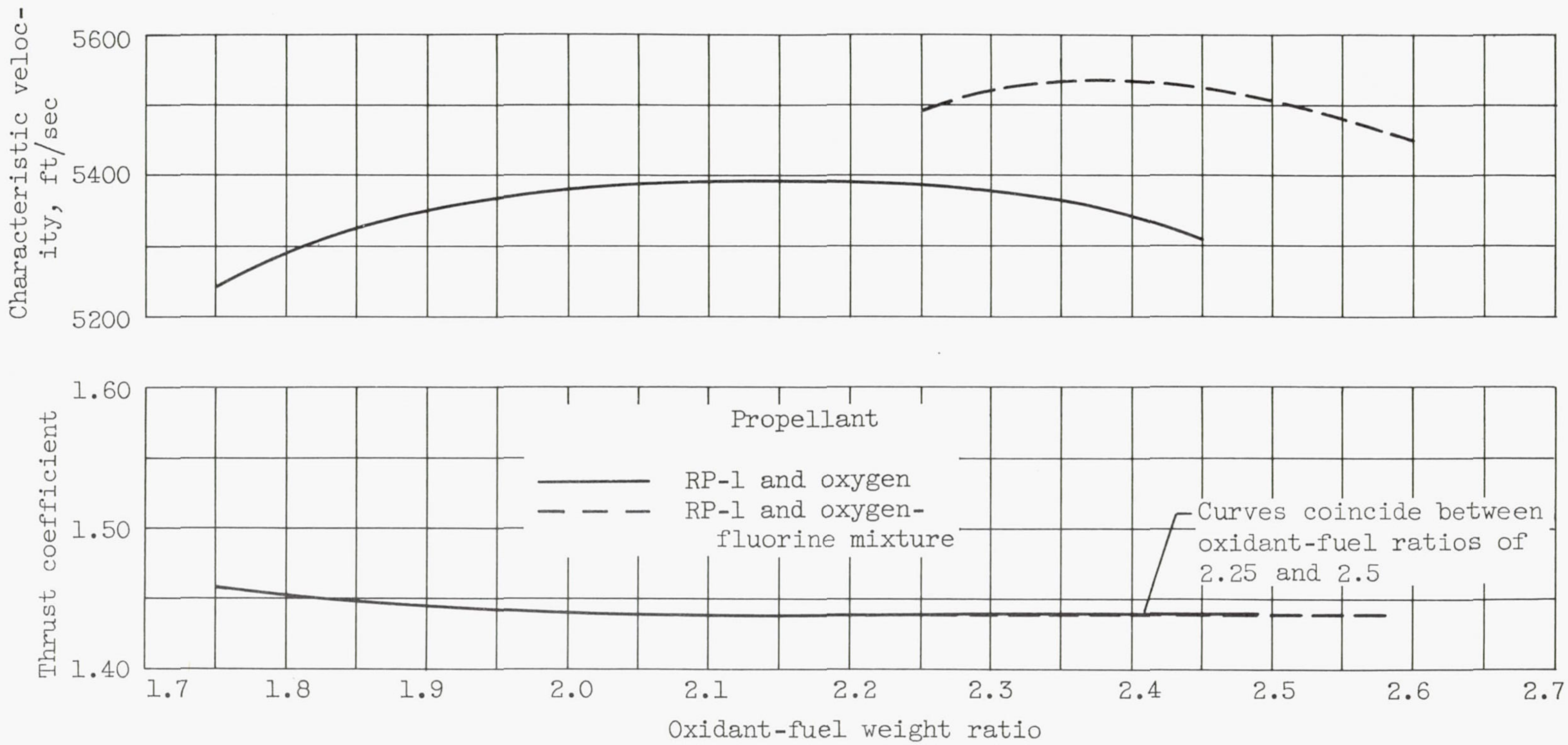

(b) Characteristic velocity and thrust coefficient.

Figure 7. - Concluded. Comparison of performance of RP-1 and oxygen with RP-1 and 20-percent-fluorine - 80-percent-oxygen mixture in Vanguard 5000-pound-thrust engine (water-cooled) at nominal chamber pressure of 650 pounds per square inch absolute.

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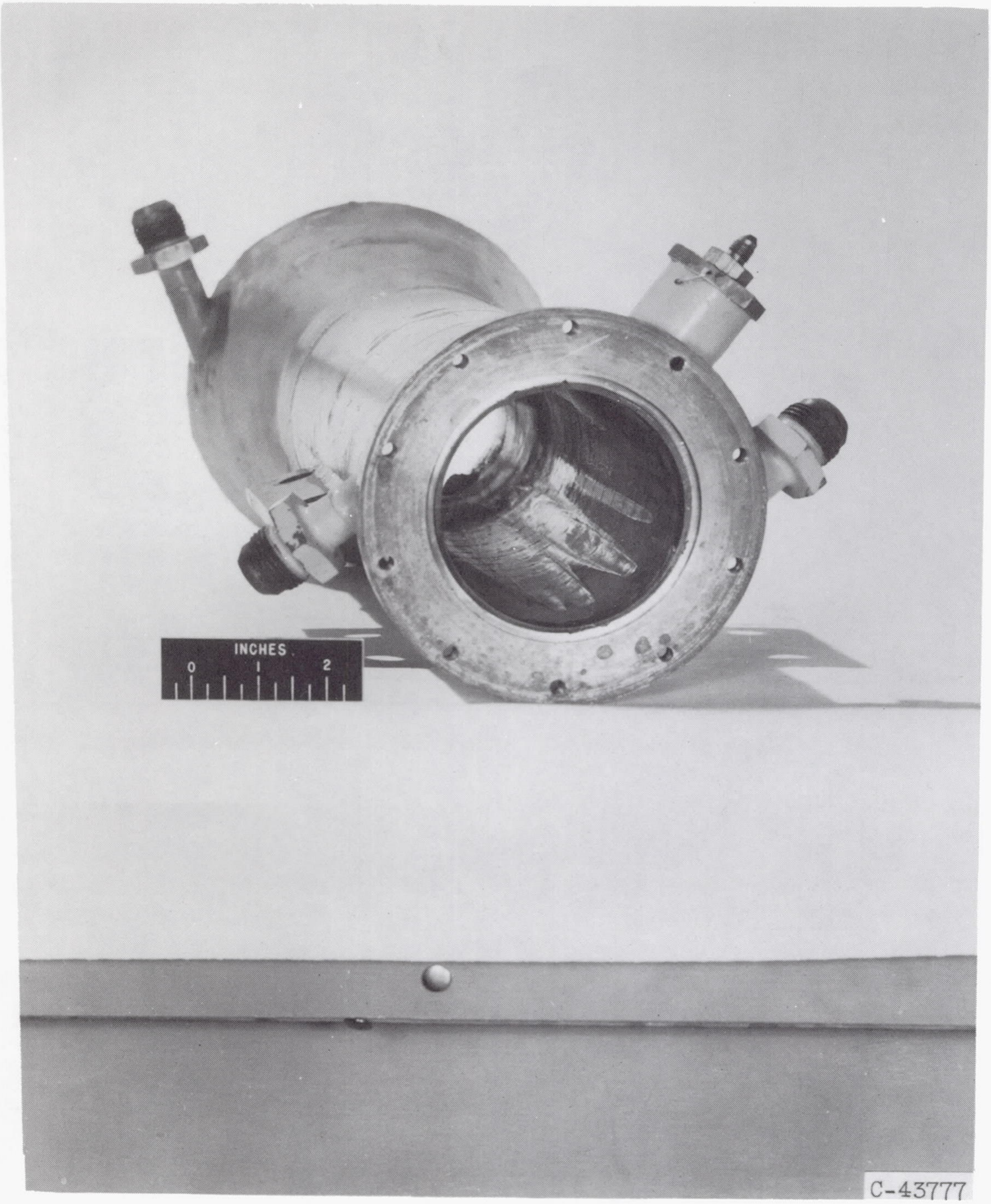

Figure 8. - Engine damage following series 3.

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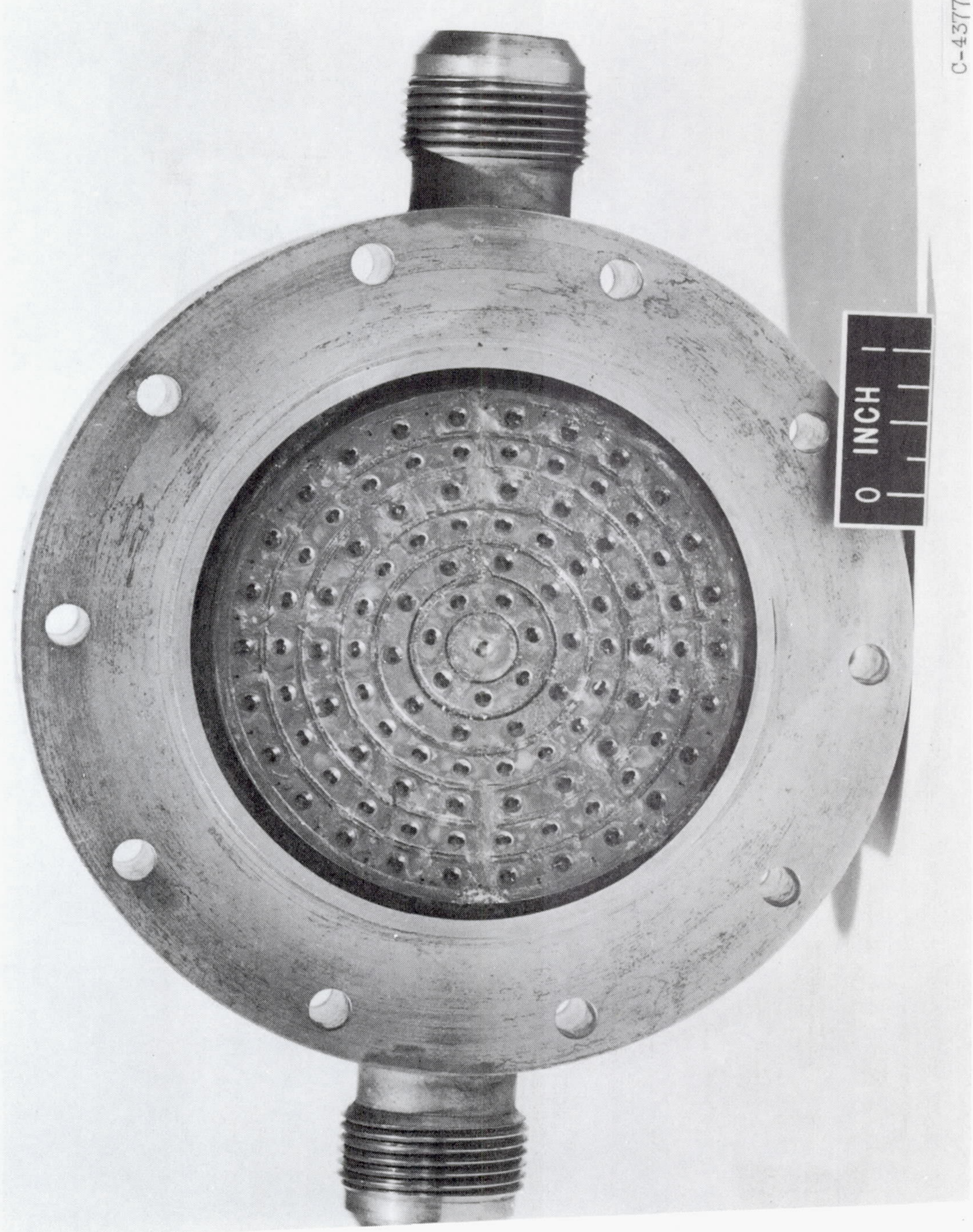

Figure 9. - Injector scoring following series 5.

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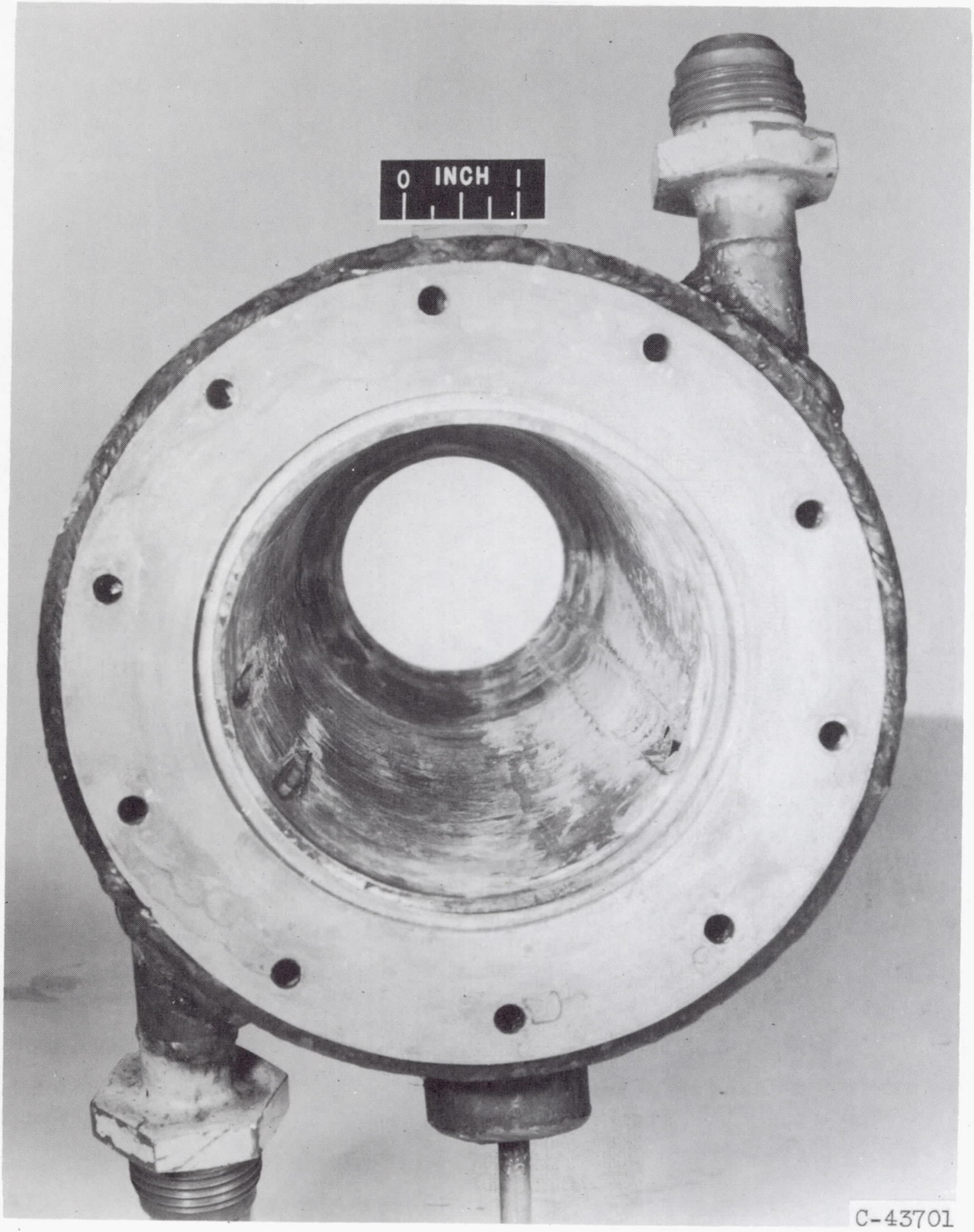

Figure 10. - Engine damage following series 8.

[redacted]

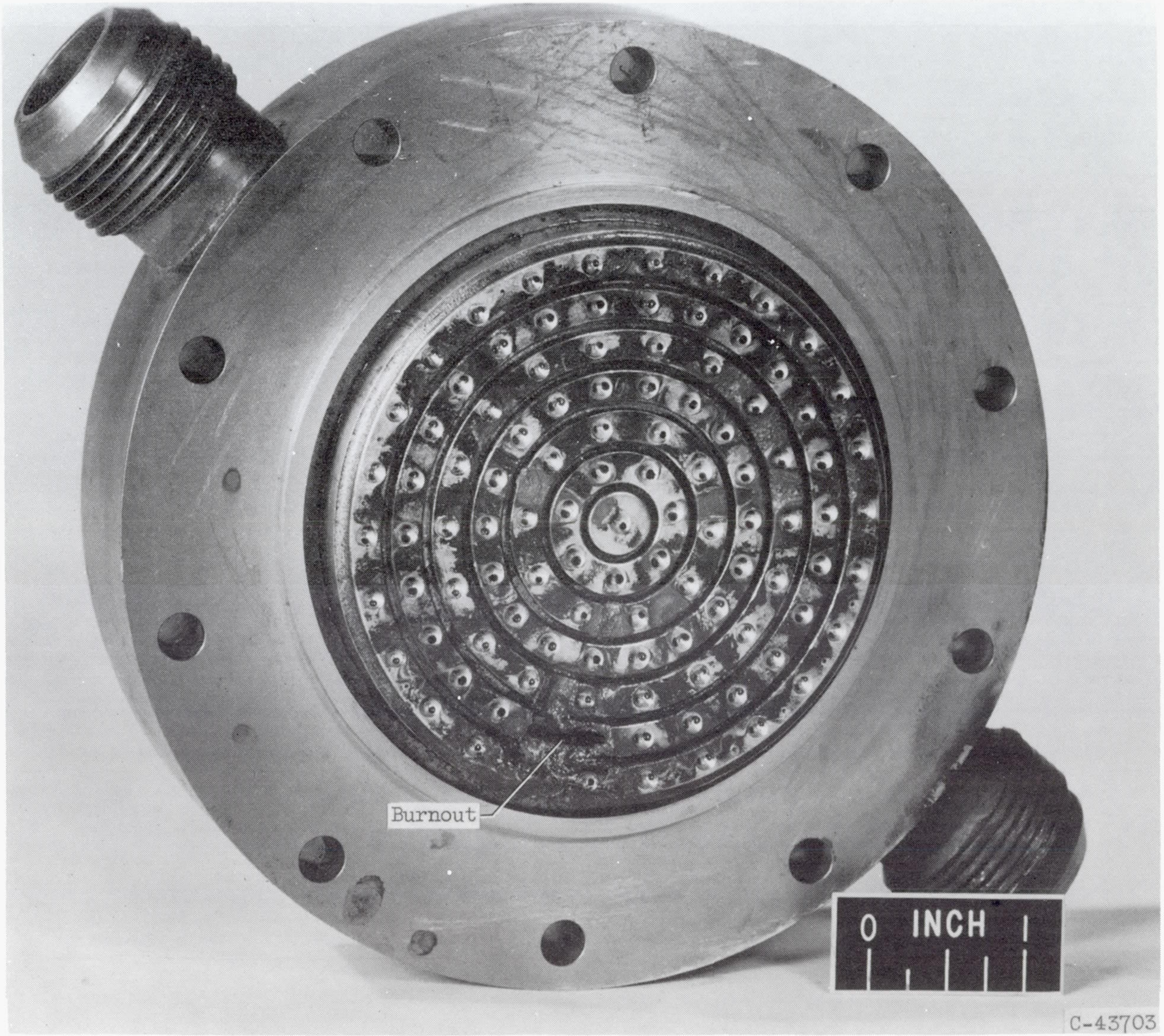

Figure 11. - Injector following series 9 showing burned-out ring.

[redacted]

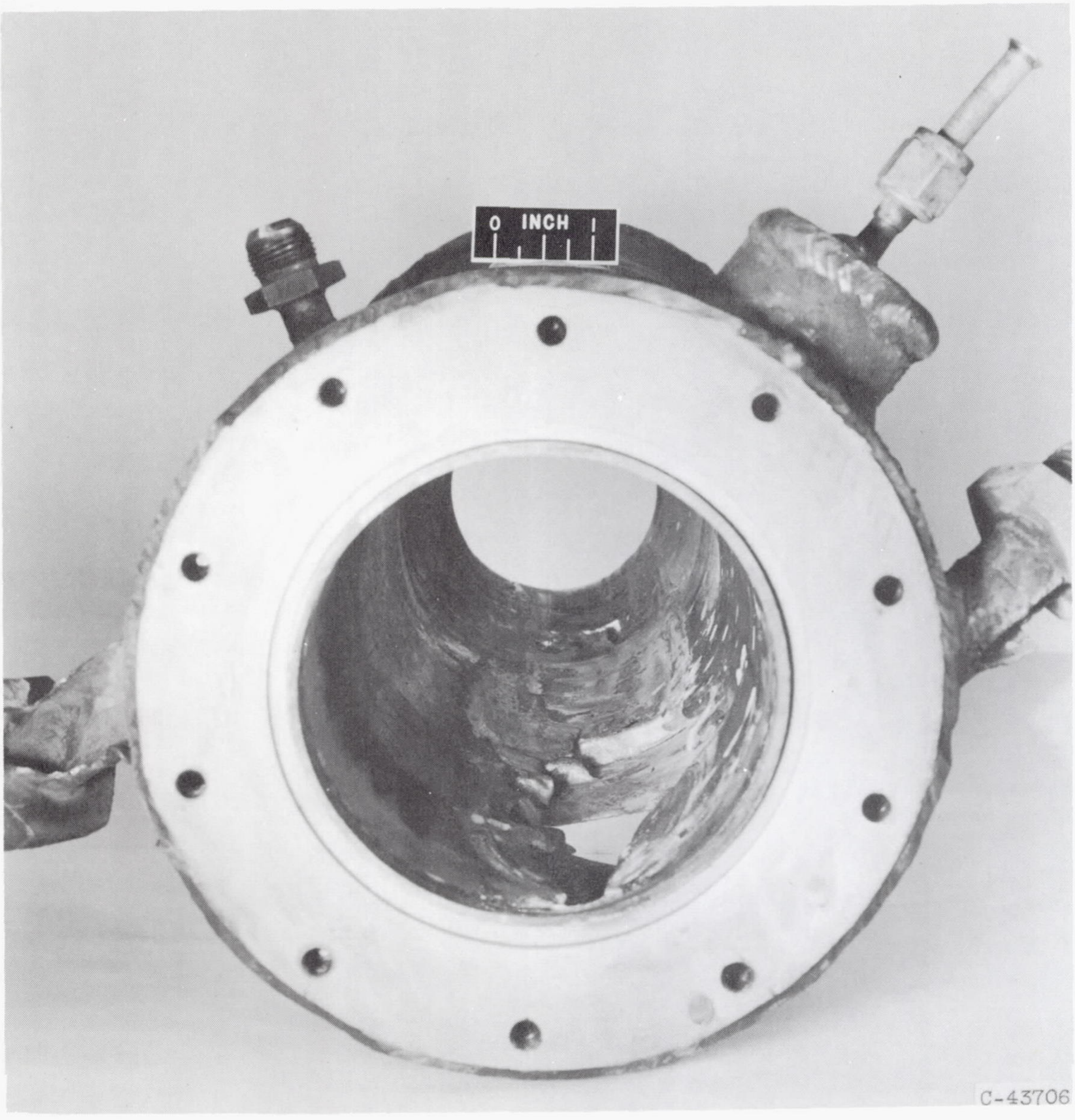

Figure 12. - Engine damage following series 9.

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