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RESEARCH MEMORANDUM

EXPERIMENTAL PERFORMANCE OF FLUORINE-OXYGEN WITH JP4 FUEL IN A ROCKET ENGINE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The performance increase resulting from the addition of fluorine to the oxygen-JP4 rocket propellant combination was evaluated experimentally in a 1000-pound-thrust engine with 0, 30, and 70 percent of fluorine by weight in the oxidant. Maximum specific impulse values obtained were 259, 278, and 287 pound-seconds per pound, respectively, at a combustion pressure of 600 pounds per square inch absolute. These values are 95 to 99 percent of the corresponding theoretical maximum values calculated for frozen expansion and range from 88 to 93 percent of theoretical equilibrium values. The data indicate that the performance increase with the addition of fluorine to the oxidizer is greater between 0 and 30 percent fluorine than between 30 and 70 percent fluorine. A net increase of 11 percent in specific impulse was obtained with the 70-percent-fluorine oxidizer.

For 0, 30, and 70 percent fluorine, characteristic velocities were 5500, 6000, and 6340 feet per second; these values are 95 to 97 percent of theoretical frozen data and 93 percent of theoretical equilibrium data. Nozzle thrust coefficients at maximum performance fell within 97 to 98 percent of theoretical equilibrium coefficients. Average over-all heat rejections to engine walls for the oxidant-fuel ratios giving highest performance were 1.85, 2.40, and 2.65 Btu per second per square inch.

INTRODUCTION

The object of this investigation was to learn the extent to which the performance of the oxygen-JP4 rocket propellant combination can be increased by the addition of fluorine to the oxygen.

Oxygen-JP4 is a promising propellant combination for present long-range rockets with respect to logistics and engine development considerations. The JP4 fuel can be the same as that used for aircraft, and liquid oxygen can be made in the field. Rocket engine development for this combination is progressing rapidly. To boost performance by the addition of fluorine to the oxidizer would seem to be a logical extension of the work requiring a minimum of additional engine development. The advantage of spontaneous ignition, characteristic of fluorine, would also be realized (ref. 1).

Theoretical maximum specific impulse values for JP4 fuel with different oxidant mixtures at a combustion pressure of 600 pounds per square inch absolute are listed in the following table:

Composition of mixture, percent		Theoretical maximum specific impulse, lb-sec/lb
Oxygen	Fluorine	
100		284
63	37	303
30	70	326
	100	305

These values are from an extension of the work of reference 2.

The theoretical work, which covered the complete range in oxidant mixture, showed that the mixture containing 70 percent fluorine offers the highest performance potential. The performance with 100 percent fluorine is not as high as that attainable with mixed oxidizer combinations, because: (1) there is difference in molecular weights and thermodynamic properties between carbon fluorides and carbon oxides formed as products of combustion, and (2) in the burning of hydrocarbons with pure fluorine, a considerable amount of unburned graphite is exhausted from the engine.

The experimental work reported here was conducted with water-cooled rocket engines designed for 1000-pound thrust at a nominal chamber pressure of 600 pounds per square inch absolute. The propellant injectors utilized like-on-like impinging-jet doublets. These engine assemblies were run with JP4 fuel and oxidant mixtures containing 0, 30, and 70 percent fluorine, covering in each case a range of oxidant-fuel ratio.

Specific impulse, characteristic velocity, nozzle thrust coefficient, and over-all heat rejection to engine walls were measured.

EQUIPMENT AND PROCEDURE

Materials, apparatus, and procedures employed in this investigation were the same, where applicable, as those used for the work reported in

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reference 3. A description of these and the necessary modifications is given in the following paragraphs.

Equipment

Propellants. - The liquid oxygen contained no more than 0.5 percent impurities. The physical properties of fluorine are tabulated in reference 4. The cylinder manifold for transferring fluorine is described in reference 5. Oxidant mixtures were prepared by condensing gaseous fluorine directly into liquid oxygen in the oxidant tank, which was surrounded by a liquid nitrogen bath. Helium was then bubbled through the oxidant to ensure mixing. The specific gravity of each fluorine-oxygen mixture was taken as the reciprocal of the sum of the products of specific volume and weight fraction in the mixture.

Properties of the JP4 fuel used are presented in table I.

Injectors. - The two nickel injectors embodied the design concept of large numbers of like-on-like impingement units to provide fine atomization, uniform propellant distribution, and thorough coverage across a flat injector face. The injectors differed from each other in the total number of injection units and the arrangement of these units on the injector face.

Figure 1 shows the like-on-like row injector, which contained 82 units of like-on-like impinging doublets for fuel and 70 for oxidant. These units were arranged in alternate rows for fuel and oxidant and provided parallel finely atomized sheets of fuel and oxidant as indicated in the figure. Of the two holes in each fuel unit, one was 0.020 inch in diameter and the other was 0.025 inch. Because of the way the fuel flowed through the internal manifold, these two diameters were used in order to obtain equal discharge. The diameter of all oxidant holes was 0.025 inch.

The units of the like-on-like ring injector (fig. 2) were arranged in concentric rings, alternately for fuel and oxidant, with the outermost ring containing fuel units. Fuel and oxidant holes were of 0.021- and 0.026-inch diameter, respectively. There were 65 oxidant and 70 fuel units.

Engine chambers. - The combustion chambers were of 30-inch characteristic length and had a chamber-to-throat area ratio of 3.8. The engines were water-cooled by spiral passages as shown in figure 3. Fabrication of the engine chamber was by the hydraulic-forming method described in reference 6. Nickel was used for the inner walls and Inconel for the outer walls.

Instrumentation. - Propellant flow rates were determined by Venturi meters and differential-pressure transducers. Thrust was measured with

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a strain gage and chamber pressure with a strain-gage-type transducer. Coolant water temperatures were measured by iron-constantan thermocouples, and flow rates were determined with a variable-area orifice. Thrust measurements are accurate within ±1 percent, other measurements within ±2 percent.

Test facilities. - The engine was mounted on a flexure-plate thrust stand. Propellant flow rates through the injector were controlled by the extent of pressurization of the tanks with helium. Helium purges were used in both propellant flow lines, and the helium valves were electrically interlocked with the propellant valves for control purposes. All firing operations were remotely controlled. 3643

Electrical controls provided for immediate shutdown of engine operation in the event of a burn-out. A wire, wrapped liberally around the engine, conducted low-voltage electricity to a relay coil. If a burn-out were to occur, the wire would be cut by flame and electrical continuity would be broken. Immediately the relay would become de-energized, thereby closing the main propellant valves and activating a carbon dioxide fire-protection system.

An auxiliary ignition system was necessary for use with the oxygen-JP4 combination. This involved connection of a propane supply line to the main fuel-flow line and a gaseous-oxygen supply line to the main oxidant-flow line. A spark plug was mounted outside the engine nozzle about 3 inches away from it.

Procedure

In operation involving the oxygen-JP4 combination, the ignition propellants (gaseous propane and oxygen) were passed through the propellant injector first and ignited by the external spark plug. The flame immediately flashed back into the engine. When fluorine mixtures were used, no external ignition source was needed. The main propellant flows were started with a slight fuel lead, using quick-opening valves. Most runs were of 5- or 6-second duration.

RESULTS

Experimental data are completely listed in table II. Performance values at highest specific impulse from faired curves for the like-on-like row injector are listed in the following table:

Fluorine in oxidant, weight percent	0	30	70
Oxidant-fuel weight ratio	2.45	3.16	3.00
Fuel, weight percent	29	24	25
Specific impulse, lb-sec/lb	259	278	287
Percent of theoretical maximum,			
equilibrium -	91	93	88
frozen -	95	99	95
Characteristic velocity, ft/sec	5500	6000	6340
Percent of theoretical maximum,			
equilibrium -	93	--	93
frozen -	95	--	97
Nozzle thrust coefficient	1.52	1.50	1.46
Percent of theoretical, equilibrium	98	--	97
Heat rejection, average over-all, Btu/(sec)(sq in.)	1.85	2.40	2.65

Performance curves for oxygen-JP4 are shown in figure 4(a). Characteristic velocity, nozzle thrust coefficient, and specific impulse are plotted against weight percent fuel in the propellant mixture. Oxidant-fuel weight ratios are indicated. Theoretical curves based on equilibrium expansion and on frozen expansion are also presented.

Experimental curves have been drawn for both injectors. Although characteristic velocity curves for the two injectors are the same, data for thrust coefficient (and consequently specific impulse) are about 10 percent lower for the like-on-like ring injector than for the like-on-like row injector. No explanation for this discrepancy was found, but in view of the data, the like-on-like row injector was selected for further investigation with fluorine-oxygen mixtures.

Performance data are plotted in figure 4(b) for the oxidant mixture containing 30 percent fluorine by weight. Theoretical data are not complete for this particular mixture, but the points of theoretical maximum specific impulse are indicated for both equilibrium and frozen conditions.

Figure 4(c) presents the data for the oxidant mixture containing 70 percent fluorine. Although the experimental data do not definitely establish the point of maximum performance, it is probably represented closely by the values at 25 percent fuel.

Experimental average over-all heat rejection values for the three oxidant mixtures are plotted in figure 5 as a function of weight percent fuel. Theoretical curves for chamber temperature are included for reference. Arrows, designating the points of maximum specific impulse, indicate that, when fluorine content was increased from 0 to 70 percent, heat rejection increased 43 percent.

Correction of experimental specific impulse for loss of performance through heat rejection to engine walls amounted, in general, to less than 1 percent of the measured specific impulse. Table II lists adjusted specific impulse values corrected for heat rejection and for variation of experimental combustion pressures from the specified 600 pounds per square inch absolute. 3643

DISCUSSION

The object of this investigation was to determine to what extent the performance of the oxygen-JP4 propellant combination can be improved by the addition of fluorine to the oxidant. In figure 6 are plotted specific impulse values for fluorine-oxygen-JP4 combinations as a function of the fluorine content of the oxidant. Theoretical curves are presented for both equilibrium and frozen expansion. The experimental curve represents maximum specific impulse for 0- to 70-percent-fluorine mixtures. The figure shows that experimental performance most nearly approached theoretical performance in the region of 30 percent fluorine. It would seem that the like-on-like injector used was optimized for the particular conditions prevailing in this region; however, this is doubtful. Because of the rectilinear arrangement of the basic injection units across the injector face, distribution of oxidant-fuel weight ratio and mass flow should be uniform across the face. Hence, any variations in over-all oxidant-fuel ratio and mass flow would not affect the efficiency of the injector to any appreciable extent. Furthermore, data from North American Aviation, Inc. (ref. 7) for work of this same type, but conducted at a chamber pressure of 300 pounds per square inch absolute and a thrust level of 3000 pounds, indicated the same general trend; that is, experimental performance most nearly approached theoretical values in the region of 30 percent fluorine. The investigations were made with injectors employing quite different principles from the like-on-like type presently reported, and the injectors were optimized in design for the particular conditions under which they were to be operated.

The performance increase with the addition of fluorine is higher between 0 and 30 percent fluorine than between 30 and 70 percent fluorine (fig. 6). Increasing fluorine content from 0 to 30 percent increased specific impulse 7.3 percent; addition of 40 percent more fluorine brought a further gain of 3.5 percent in impulse, giving a net increase near 11 percent. The exact oxidant composition needed for maximum performance was not determined by this investigation.

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The addition of fluorine also increases the bulk density of the propellant combination, as may be noted from the example in the following table:

	Oxygen[a]	70-Percent-fluorine - 30-percent-oxygen mixture[b]	Increase, percent
Specific impulse	259	287	10.8
Specific gravity	1.036	1.177	13.6

[a]Oxidant-fuel weight ratio, 2.45.

[b]Oxidant-fuel weight ratio, 3.00.

The relative importance of propellant density on missile performance is debatable, but it may readily be seen that consideration of density-impulse makes the addition of fluorine even more favorable than does consideration of specific impulse alone.

Estimates were made of the temperature rise of JP4 fuel if used as a regenerative coolant for a 70-percent-fluorine oxidant mixture with 20 to 25 percent fuel in the propellant combination. Experimental data from the curves of figures 4(c) and 5 were used in determining rates of fuel flow and total heat rejection (cooled surface area, 79.7 sq in.). The specific heat of JP4 fuel was assumed to be 0.5 Btu per $^{\circ}$F.

Results of these calculations are seen in figure 7, where fuel temperature rise is plotted against weight percent fuel in the propellant. At conditions of maximum experimental performance (25 percent fuel), the final fuel temperature apparently would approach the critical temperature, which is about 625° F; and for combinations requiring less fuel, this temperature would be exceeded.

The critical pressure of JP4 fuel is close to 500 pounds per square inch. Regenerative coolant pressures would be considerably higher than this for engines operating at a combustion pressure of 600 pounds per square inch absolute. Reference 8 indicates that cooling under these conditions must be considered purely convective in nature, since nucleate boiling, as an aid to cooling, cannot occur above the critical pressure.

CONCLUDING REMARKS

The addition of fluorine to oxygen-JP4 improves performance, increases propellant bulk density, and obviates ignition systems, but increases the engine cooling problem.

More work is needed on regenerative cooling with JP4 fuel. Analysis indicated that, in designing regenerative-cooled engines for the 70-percent-fluorine oxidant at 600 pounds per square inch absolute combustion pressure, the coolant (JP4) should be assumed to function above the critical point.

SUMMARY OF RESULTS

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The performance increase resulting from the addition of fluorine to the oxygen-JP4 rocket propellant combination was evaluated experimentally at a combustion pressure of 600 pounds per square inch absolute using a 1000-pound-thrust engine and a like-on-like row injector.

1. Specific impulse was increased 11 percent, from 259 to 287 pound-seconds per pound, by using a 70-percent-fluorine oxidizer.

2. The following table lists values obtained from faired curves at highest impulse:

Fluorine in oxidant, weight percent	0	30	70
Oxidant-fuel weight ratio	2.45	3.16	3.00
Fuel, weight percent	29	24	25
Specific impulse, lb-sec/lb	259	278	287
Percent of theoretical maximum,			
equilibrium -	91	93	88
frozen -	95	99	95
Characteristic velocity, ft/sec	5500	6000	6340
Percent of theoretical maximum,			
equilibrium -	93	--	93
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Nozzle thrust coefficient	1.52	1.50	1.46
Percent of theoretical, equilibrium	98	--	97
Heat rejection, average over-all, Btu/(sec)(sq in.)	1.85	2.40	2.65

3. The performance increase with addition of fluorine is greater between 0 and 30 percent fluorine content than between 30 and 70 percent fluorine.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 4, 1955

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TABLE I. - PROPERTIES OF JP4 FUEL

A.S.T.M. distillation D86-52, °F	
Percentage evaporated:	
Initial point	138
5	207
10	249
20	295
30	317
40	331
50	345
60	357
70	371
80	391
90	422
95	448
End point	480
Residue, percent	1.0
Loss, percent	1.0
Reid vapor pressure, lb/sq in.	2.3
Hydrogen-carbon ratio	0.168
Heat of combustion, Btu/lb	18,675
Specific gravity, 60/60 °F	0.779
Gravity, °API	50.2
Aniline point, °F	139.3

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TABLE II. - EXPERIMENTAL PERFORMANCE OF FLUORINE-OXYGEN-JP4 PROPELLANT COMBINATIONS

Flourine in oxidant, weight percent	Injector	Fuel, weight percent	Oxidant-fuel weight ratio	Total propellant flow, lb/sec	Thrust, lb	Combustion pressure, lb/sq in. abs	Specific impulse, lb-sec/lb	Characteristic velocity, ft/sec	Nozzle thrust coefficient	Average heat rejection to engine, Btu/(sec)(sq in.)	Specific impulse adjusted for heat rejection and pressure deviations, lb-sec/lb	Run time, sec
0	Like-on-like ring	26.3	2.80	4.16	965	606	232	5360	1.40	1.85	233	10
		27.3	2.66	4.35	1022	645	235	5450	1.39	1.73	235	7
		28.0	2.58	4.23	978	627	231	5460	1.36	2.08	232	12
		28.5	2.51	4.20	977	625	233	5490	1.37	1.97	233	9
		28.6	2.49	4.07	956	585	235	5280	1.43	1.68	236	19
		28.7	2.48	4.21	968	622	230	5450	1.36	1.85	231	8
		28.8	2.47	4.22	980	622	232	5430	1.38	1.80	233	10
		29.8	2.36	4.28	998	630	233	5410	1.39	1.52	233	9
		30.6	2.27	4.26	1001	634	235	5470	1.38	1.42	236	12
		31.3	2.19	4.20	970	624	231	5480	1.36	2.04	232	12
		31.4	2.19	4.26	986	624	231	5390	1.38	1.48	232	9
		31.5	2.18	4.25	990	631	233	5460	1.37	1.83	234	9
		32.0	2.12	4.27	993	623	233	5370	1.40	1.64	234	8
		32.9	2.04	4.39	1013	640	231	5360	1.39	1.55	231	6
		34.3	1.92	4.38	996	636	227	5340	1.37	1.46	228	11
		34.5	1.90	4.33	1009	632	233	5370	1.40	1.48	234	12
		36.0	1.78	4.42	1013	640	229	5330	1.39	1.52	230	5
0	Like-on-like row	26.1	2.83	4.33	1098	615	254	5210	1.57	2.49	255	3
		27.9	2.58	4.10	1068	619	260	5530	1.52	2.03	261	6
		29.2	2.42	4.09	1038	604	254	5410	1.51	2.08	255	6
		29.5	2.39	4.19	1068	611	255	5340	1.54	2.15	256	6
		29.8	2.36	4.12	1053	612	256	5440	1.51	1.73	256	6
		30.0	2.33	4.16	1078	625	260	5520	1.52	1.96	261	6
		30.5	2.28	4.14	1059	619	256	5470	1.50	1.65	256	6
		32.3	2.10	4.11	1046	612	254	5450	1.50	1.67	255	6
30	Like-on-like row	21.0	3.75	3.79	1053	613	278	5930	1.51	2.79	---	6
		22.4	3.46	3.73	1030	599	276	5890	1.51	2.66	---	6
		23.4	3.28	3.76	1046	607	278	5930	1.51	2.32	---	6
		23.5	3.26	3.77	1040	610	276	5950	1.50	2.70	---	4
		24.5	3.09	3.80	1060	620	279	5990	1.50	2.32	---	6
		25.3	2.95	3.74	1038	615	277	6030	1.48	2.11	---	6
		30.9	2.24	3.68	975	572	265	5710	1.50	1.76	---	6
70	Like-on-like row	16.0	5.23	3.80	1002	594	264	5740	1.48	4.16	267	5
		17.0	4.88	3.78	1016	598	269	5820	1.49	4.03	272	5
		18.5	4.40	3.63	1017	605	281	6130	1.48	3.95	283	5
		19.3	4.17	3.62	1012	611	280	6190	1.45	3.74	282	5
		20.2	3.94	3.59	1020	608	284	6220	1.47	3.60	288	5
		21.4	3.68	3.63	1033	623	285	6300	1.45	3.40	288	5
		24.7	3.06	3.51	1007	605	287	6330	1.46	2.70	289	5

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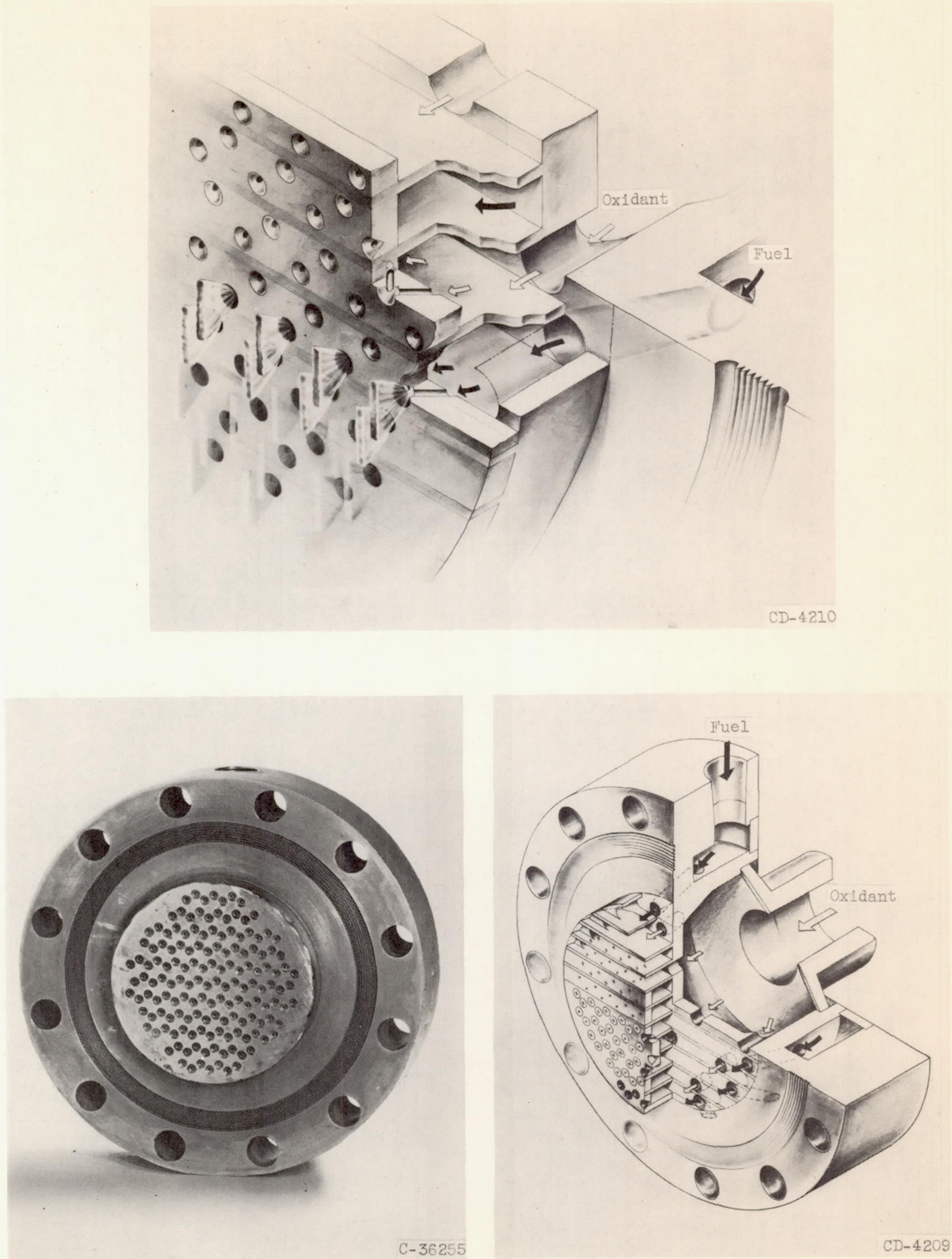

Figure 1. - Like-on-like propellant injector with holes arranged in rows on flat face. (82 pairs of fuel jets, 70 pairs of oxidant jets.)

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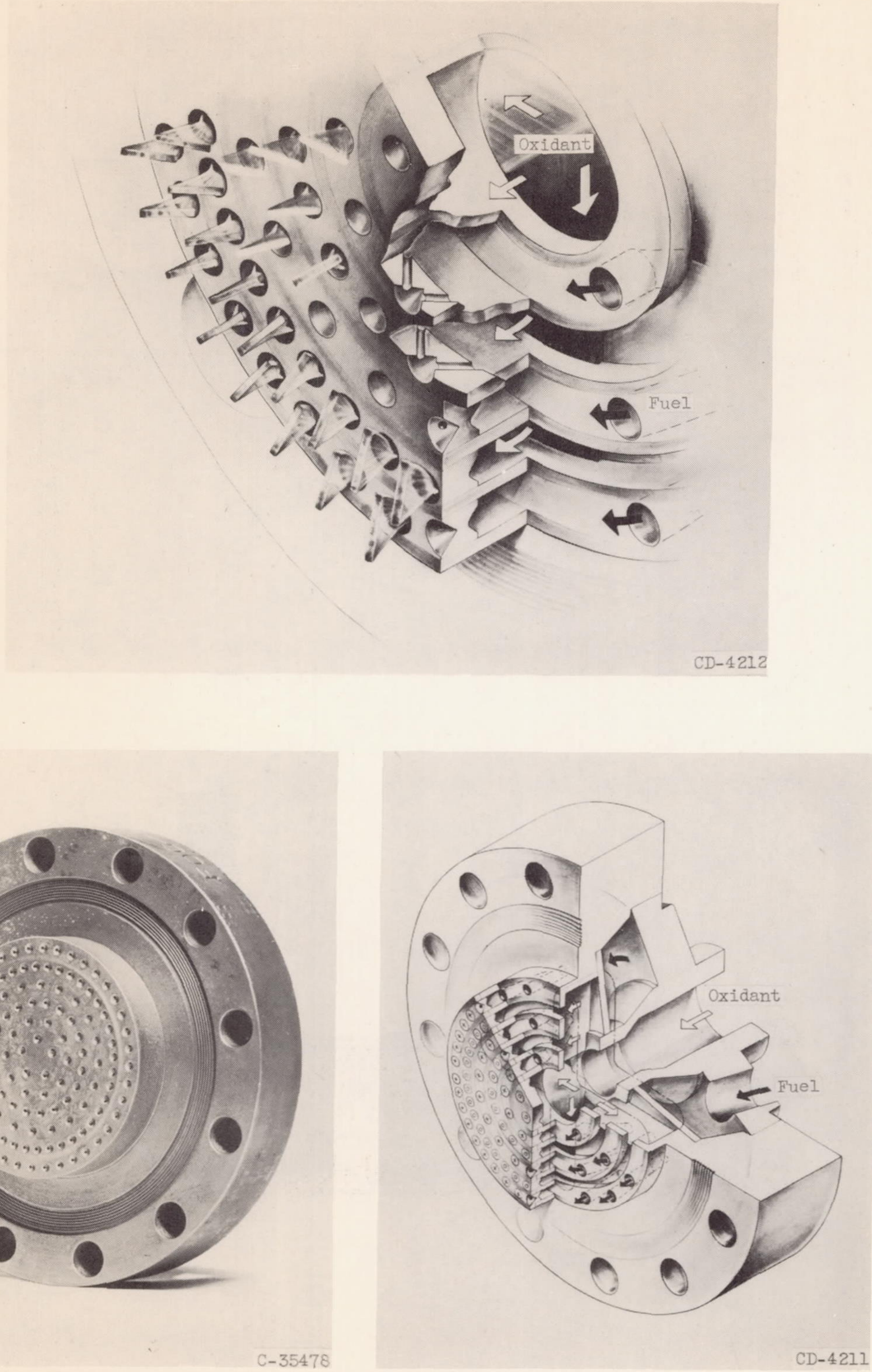

Figure 2. - Like-on-like propellant injector with holes arranged in rings on flat face. (70 pairs of fuel jets, 65 pairs of oxidant jets.)

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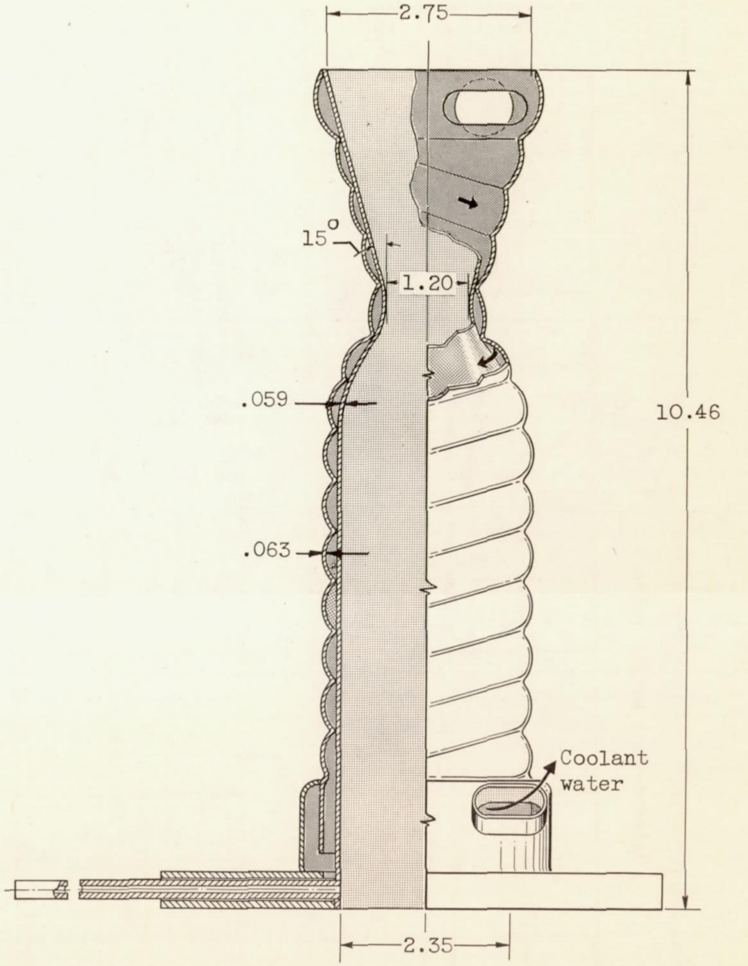

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Figure 3. - Cutaway section and diagram of chamber and nozzle of 1000-pound-thrust rocket engine. (Dimensions in inches.)

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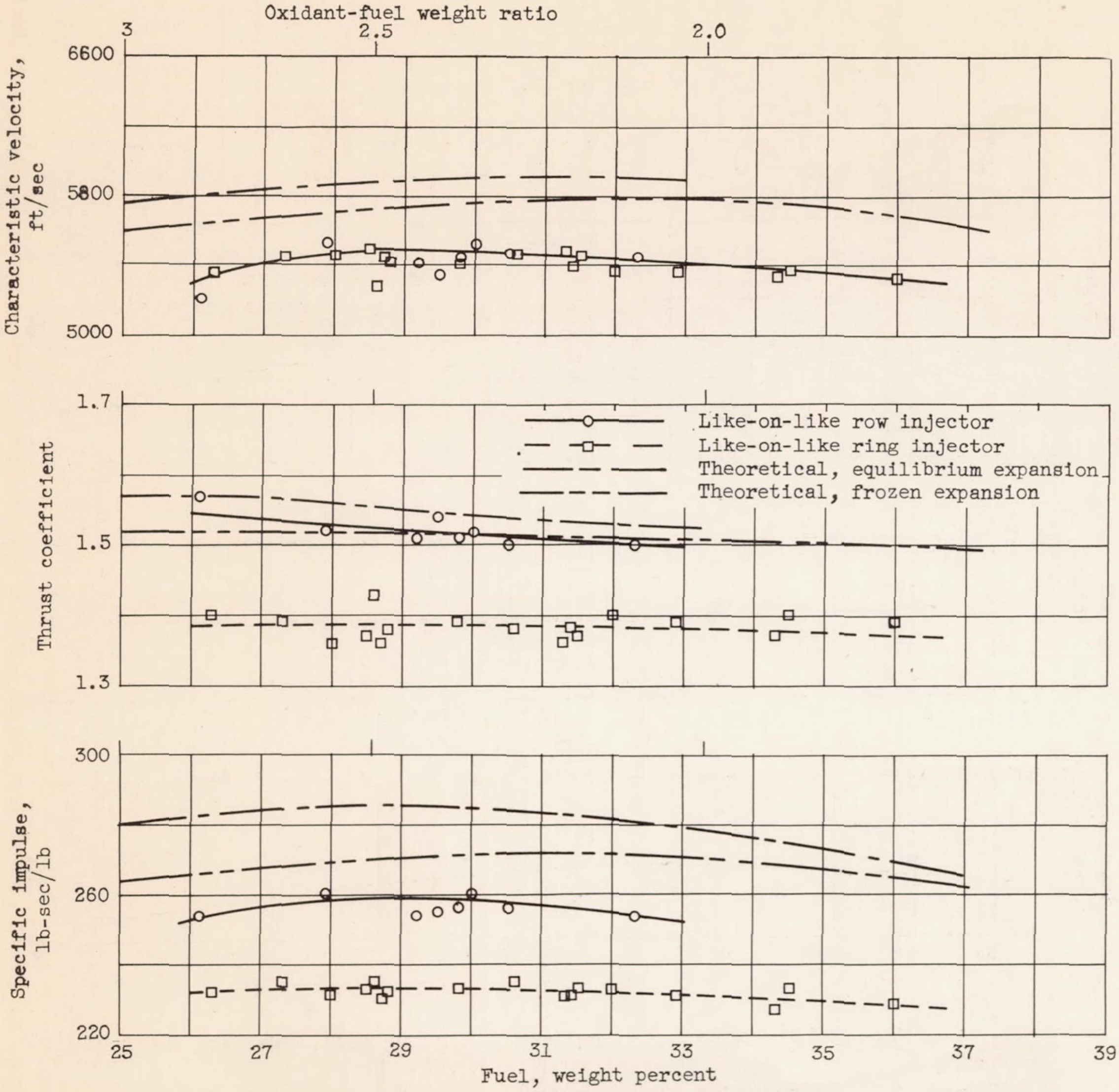

(a) Fuel, JP4; oxidant, oxygen.

Figure 4. - Experimental and theoretical characteristic velocity, thrust coefficient, and specific impulse. Combustion pressure, 600 pounds per square inch absolute; rocket engine thrust, 1000 pounds.

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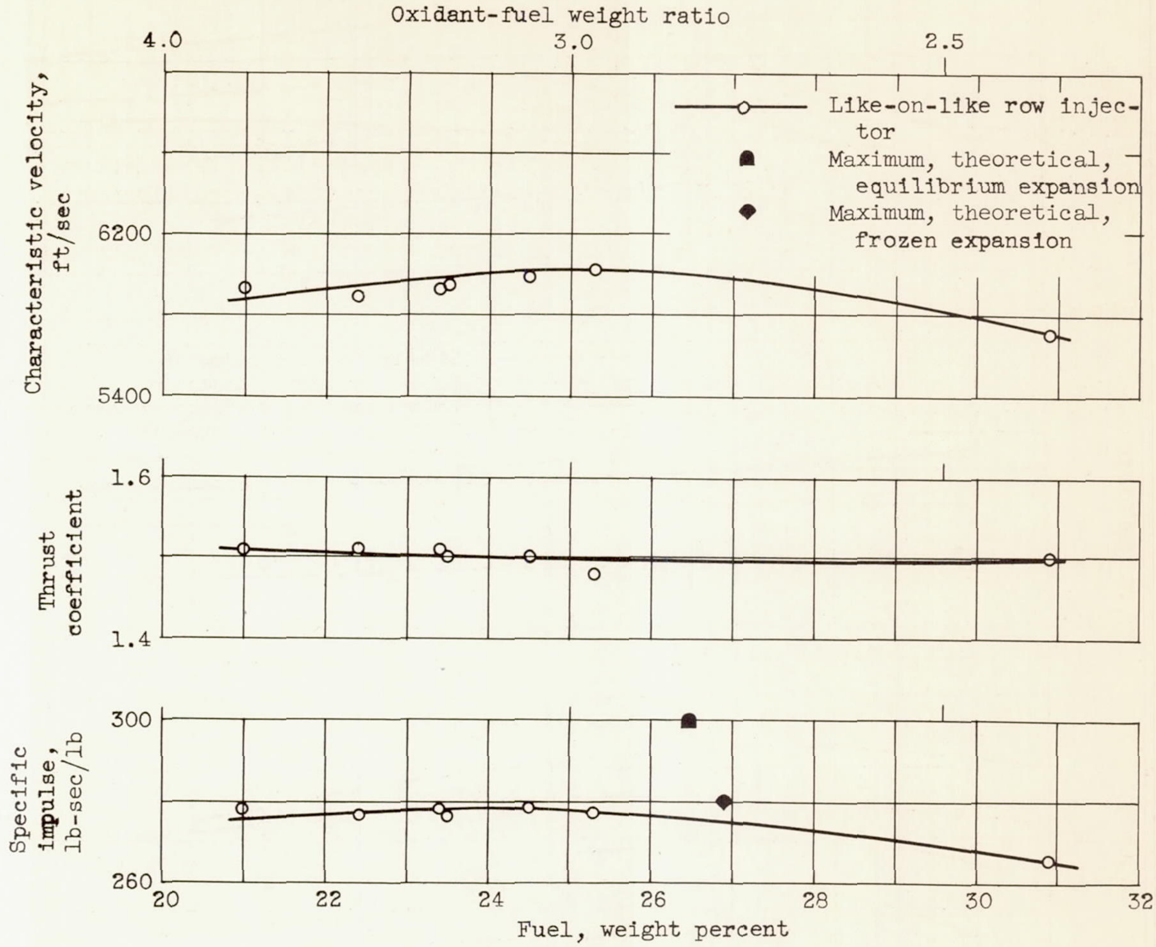

(b) Fuel, JP4; oxidant, 30 percent fluorine and 70 percent oxygen.

Figure 4. - Continued. Experimental and theoretical characteristic velocity, thrust coefficient, and specific impulse. Combustion pressure, 600 pounds per square inch absolute; rocket engine thrust, 1000 pounds.

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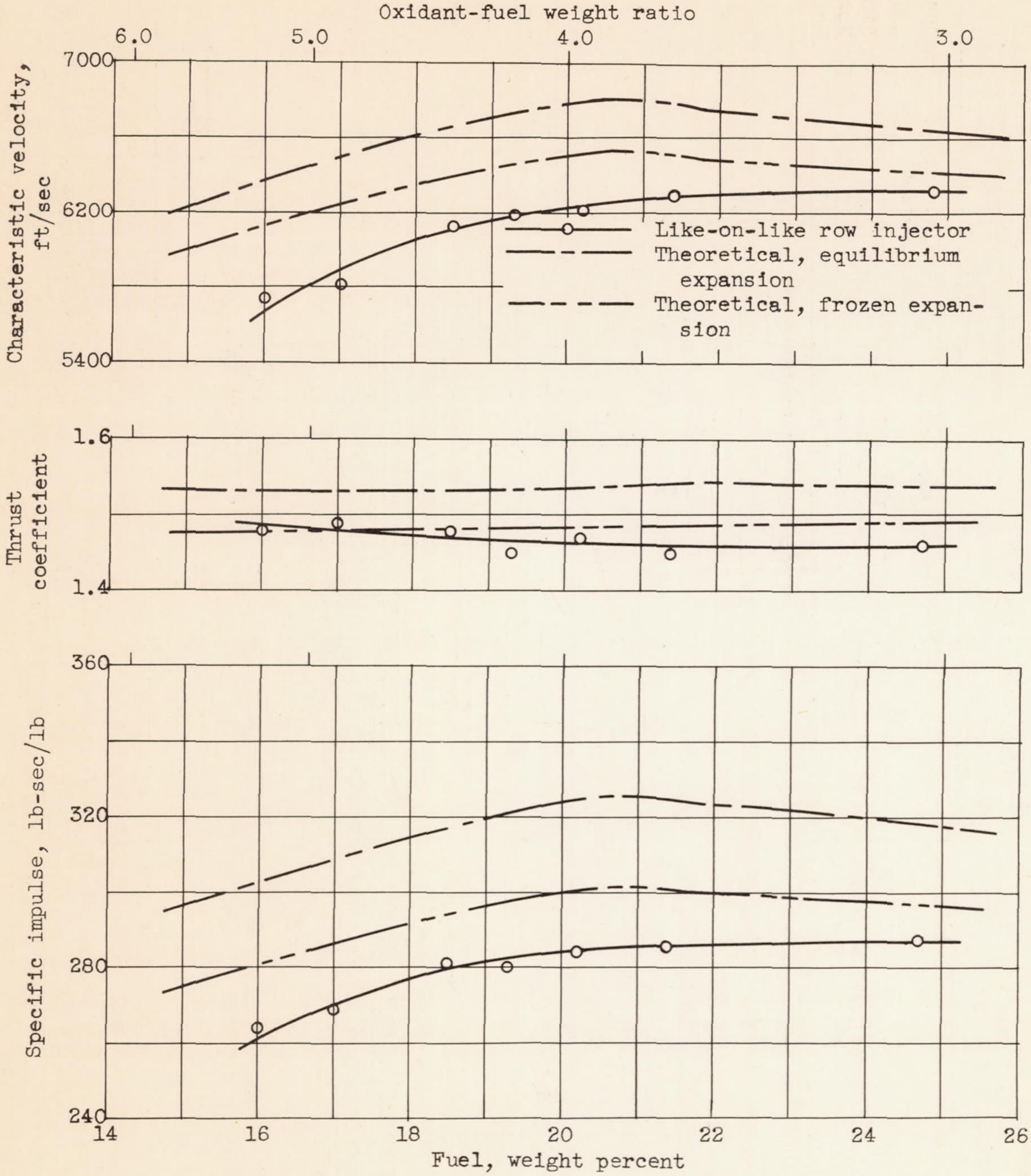

(c) Fuel, JP4; oxidant, 70 percent fluorine and 30 percent oxygen.

Figure 4. - Concluded. Experimental and theoretical characteristic velocity, thrust coefficient, and specific impulse. Combustion pressure, 600 pounds per square inch absolute; rocket engine thrust, 1000 pounds.

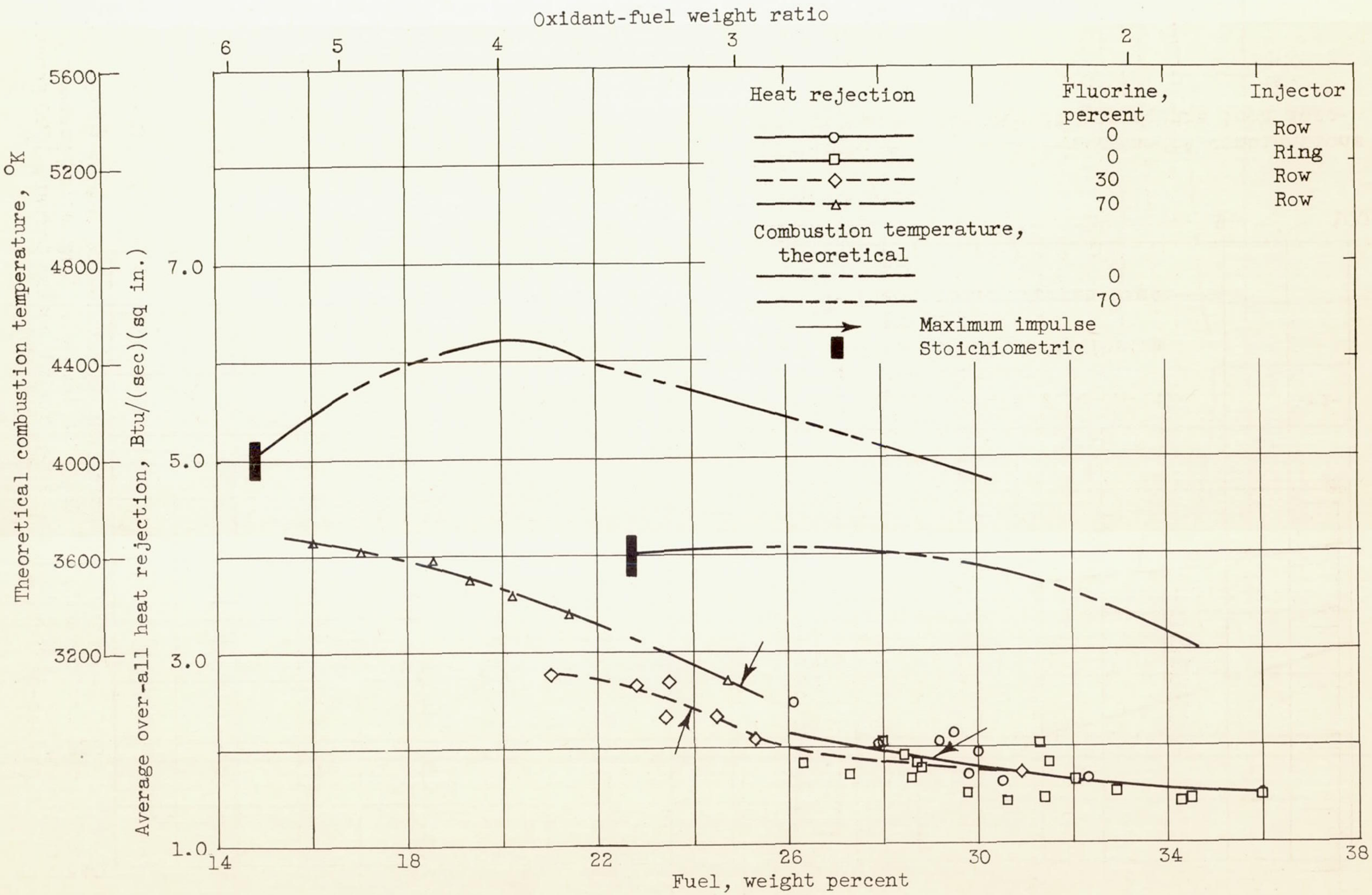

Figure 5. - Experimental heat rejection and theoretical combustion temperature of combinations of fluorine-oxygen with JP4 fuel. Combustion pressure, 600 pounds per square inch absolute; rocket engine thrust, 1000 pounds.

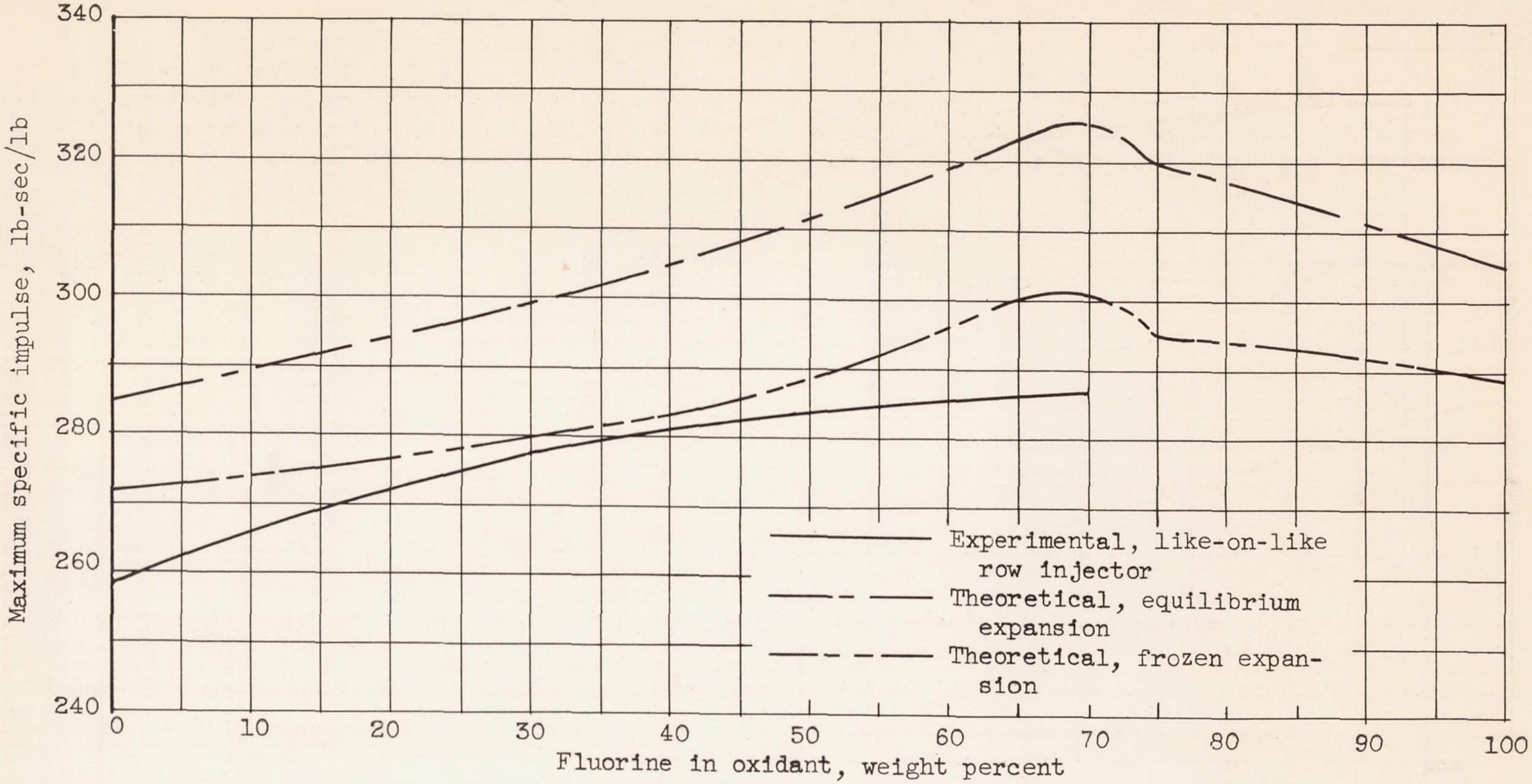

Figure 6. - Maximum experimental and theoretical specific impulse of fluorine-oxygen-JP4 combinations as function of fluorine content in oxidant. Combustion pressure, 600 pounds per square inch absolute; rocket engine thrust, 1000 pounds.

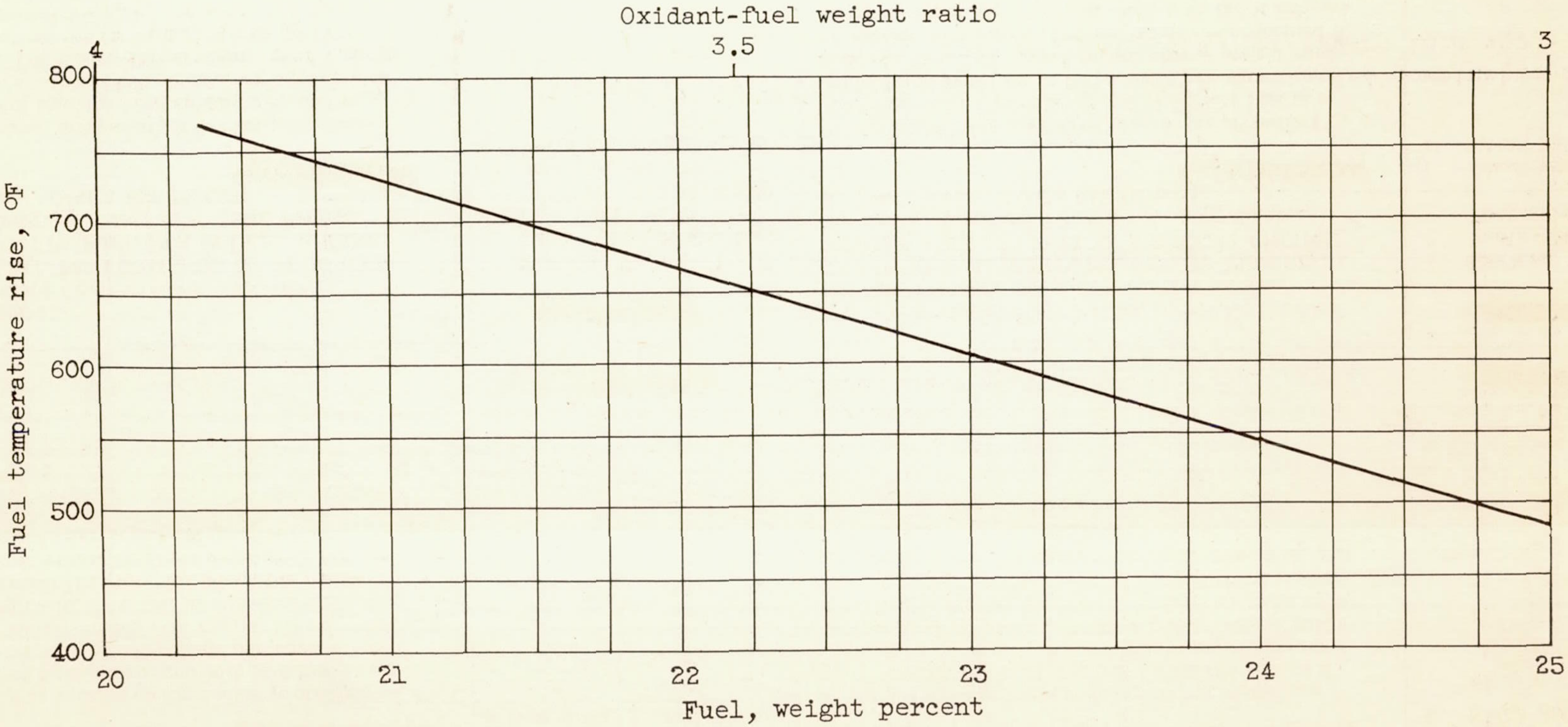

Figure 7. - Estimated temperature rise of JP4 fuel as regenerative coolant, converted from experimental temperature rise of water as coolant. Combustion pressure, 600 pounds per square inch absolute; rocket engine thrust, 1000 pounds; fuel, JP4; oxidant, 70 percent fluorine and 30 percent oxygen.

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