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RESEARCH MEMORANDUM

PERFORMANCE OF JP-4 FUEL WITH FLUORINE-OXYGEN MIXTURES IN 1000-POUND-THRUST ROCKET ENGINES

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[redacted]

Declassified by authority of NASA
Classification Change Notices No. 67
Dated ** 6/29/66

DECLASSIFIED- AUTHORITY
US: 1286 DROBKA TO LEBOW
MEMO DATED 6/8/66

[redacted]

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
June 11, 1958

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

PERFORMANCE OF JP-4 FUEL WITH FLUORINE-OXYGEN MIXTURES IN 1000-POUND-THRUST ROCKET ENGINES

By Donald L. Nored and Howard W. Douglass

SUMMARY

Seven injectors of four different types were tested for use with JP-4 - oxygen-fluorine propellant combinations. By using the best of these injectors, high characteristic velocities were obtained over the complete range of 0- to 70-percent fluorine in the oxidant. Combustion pressure in the water-cooled thrust chambers was 600 pounds per square inch absolute.

The same basic injection requirements apparently prevail for fluorine-rich oxidants as for pure oxygen where simultaneous atomization and mixing of the propellants gave the most favorable results, and atomization alone yielded better performance than mixing alone.

A triplet injector (atomization with mixing) gave the highest performance and was efficient over wide ranges in oxidant-fuel ratio. However, the design of triplet units seems to be more critical than anticipated. Minor design changes in oxidant orifices resulted in significant shift in performance. Variation in arrangement of triplet units on injector faces greatly influenced the heat-transfer rates through the engine walls. Proper orientation of triplet units with respect to each other reduced the danger of injector-face burning.

A like-on-like injector creating finely divided atomization depended less on engine length for good performance than a triplet injector having coarser sprays.

Equivalent performance efficiencies resulted from two injectors similar in concept, but one had many small injection elements while the other had few large units. The latter injector, however, was more prone to burn at the face.

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INTRODUCTION

This investigation was undertaken as part of a broad study on the advantages of adding fluorine to oxygen for use with JP-4 fuel as rocket-propellant combinations (refs. 1 to 9). Engines for long-range missiles using the oxygen - JP-4 combination have been well developed because of the favorable logistics and performance of this propellant combination. The addition of fluorine to the oxidizer is a feasible means of improving performance with little additional development, and also adds the distinct advantage of self-ignition with jet fuel (ref. 1).

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Theoretical calculations (refs. 2 to 4) and experimental measurements (refs. 5 and 6) indicate a continuous performance increase with the fluorine addition until the oxidant contains 70-percent fluorine. However, oxidant handling becomes more difficult and engine heat rejection increases with the fluorine addition.

The injection techniques successful with oxygen alone may be equally applicable to oxygen-fluorine mixtures, even though fluorine imparts increased reactivity (refs. 7 and 8). Greater care, however, must be exercised in injector design to avoid injector-face burnouts caused by the higher temperatures, heat release, and reactivity associated with fluorine.

The injectors used in the experiments reported herein embodied independent attention to the principles of atomization, mixing, and simultaneous mixing and atomization. The layout of the injector faces was kept geometrically similar in order to analyze the effects of injection techniques upon performance.

Water-cooled rocket engines were designed for 1000 pounds of thrust at a nominal combustion chamber pressure of 600 pounds per square inch absolute. Two engine lengths were used, one giving a characteristic length of 30 inches and the other a characteristic length of 15 inches. JP-4 jet fuel was used with oxidant mixtures containing 0-, 15-, 30-, 45-, 60-, and 70-percent fluorine by weight in the oxygen.

Experimental values of characteristic velocity, specific impulse, nozzle thrust coefficient, and over-all heat rejection were determined as functions of the weight percent of the fuel in the propellant combination. These results were interpretated in relation to work previously reported (ref. 5).

APPARATUS AND PROCEDURE

Experimental facilities, instrumentation, propellant properties, and test procedures were the same as reported in reference 5.

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Chamber pressure was measured with a strain-gage-type transducer. Thrust was measured with a strain gage attached to a flexure-plate thrust stand. Propellant flow rates were determined by differential-pressure transducers across the venturis. These primary measurements were precise within ±2 percent.

Firing operations were controlled remotely; the duration of most runs was 4 seconds. With short fuel leads and overrides, propellants were pressure fed by helium to the engine. An auxiliary ignition system was used when the oxidant contained no fluorine.

Injectors

Seven injectors of four different basic types were used. Three of these injectors employed sets of triplet jets of two oxidant streams on one fuel stream. Two injectors used "V-jet" configurations to provide parallel atomized sheets of fuel and oxidant. One injector was designed to provide mixing of the liquid propellants without atomization. In addition, data were obtained from the injector described in reference 5; it formed a large number of very small atomized fans of the propellants by like-on-like impingement. For most of the injectors, seven unique sets of one fuel and two oxidant orifices were centered on the corners and center of a hexagon. This consistent relation was held to minimize the effects of variables not associated with propellant atomization and mixing, for example, distribution.

The significant characteristics of these injectors are tabulated as follows:

Injector	Process emphasized	Type	Number of elements	Holes/ element	Layout of elements	Unique features
1	Atomization with mixing	Triplet	7	2 Oxidant; 1 fuel	Hexagonal, parallel fans	
1A	Atomization with mixing	Triplet	7	2 Oxidant; 1 fuel	Hexagonal, parallel fans	Square-edged tubes for oxidant jets
2	Atomization alone	V-jet	7	2 Oxidant; 1 fuel	Hexagonal, parallel fans	Protruding inserts
2A	Atomization alone	V-jet	7	2 Oxidant; 1 fuel	Hexagonal, parallel fans	Flush inserts
3	Mixing alone	Concentric jet	7	1 Oxidant; 4 fuel	Hexagonal	
4	Atomization with mixing	Triplet	6	2 Oxidant; 1 fuel	Hexagonal	Skewed fans
5	Atomization alone	Like-on-like	70 Oxidant, 82 fuel	2	Rows	Low thrust/ element

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All of the injectors but one (injector 4) were made of nickel. Injector 1 (fig. 1) was a triplet type designed so that the spray fans formed by each injection element could not interfere with each other. The oxidant holes were drilled at an angle through the flat face, resulting in eliptical ports at the surfaces. Thrust per element was 143 pounds.

Injector 1A was identical to injector 1 in pattern (fig. 1). However, each oxidant hole was formed by a tube inserted in the face to give straight flat entrance and exit edges at the oxidant orifices normal to the direction of fluid flow. It was believed that harder, more compact liquid jets would issue, resulting in better and more precise atomization on impingement.

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Injectors 2 and 2A (fig. 2) utilized drilled and grooved inserts to create V-shaped finely atomized propellant sheets. These inserts were brazed into the injector face with the control grooves parallel. They were protruded beyond the face of injector 2 to minimize a tendency of the oxidant sheets to cause burning of the metal face, and then, were set flush with the face of injector 2A to attempt to prevent burning of the oxidant inserts.

When more than two angled liquid jets impinge symmetrically, negligible atomization occurs and only a larger single straight jet is formed. This phenomenon was employed in the design of injector 3 (fig. 3) where the elements consisted of four fuel holes directed for fuel penetration and mixing in each oxidant stream in the liquid state without atomization.

Unlike the others, injector 4 (fig. 4) was made of solid, uncooled aluminum. The assembly was accomplished by furnace brazing. The six triplet units (similar to those of injector 1) of this injector were arranged in a skewed array so that no interference between spray fans could occur to cause face burning. This particular arrangement is however, not conducive to systematic scaleup to large engine-thrust levels.

Injector 5 (fig. 5) consisted of 82 pairs of fuel holes and 70 pairs of oxidant holes for like-on-like propellant-jet impingement. The hole combinations were oriented to provide many finely atomized parallel fans in alternate rows of fuel and oxidant (ref. 5). The thrust per pair of holes was less than 7 pounds.

Combustion Chambers

The thrust chambers were of either a 30- or 15-inch characteristic length (L^*), had a contraction area ratio of 3.8, and an expansion area ratio of 5.25.

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These chambers were fabricated by two different techniques. Both types were water cooled: one with spiral passages shaped by the hydraulic forming method described in reference 10, and the other with longitudinal passages consisting of wire ribs between the inner and outer walls fabricated by the method discussed in reference 11. Nickel was used for the inner walls and Inconel for the outer walls of all engines. Typical dimensions are given in figure 6, along with a photograph of the two engine types. The cooled surface areas for the 30 L^* and the 15 L^* engines were 79.7 and 50.45 square inches, respectively.

RESULTS AND DISCUSSION

High performance efficiencies, in terms of characteristic velocity, were obtained with all the fluorine-oxygen - JP-4 combinations studied. These combinations covered the entire useful range of 0- to 70-percent fluorine in the oxidant.

The most effective injector used in the present investigation was the triplet-jet type, injector 1. Performance results from this injector, however, were not significantly better than those previously obtained with the like-on-like injector 5 (ref. 5), although engine heat-rejection rates were higher.

Comparisons of the results from the various injectors, when tested with oxygen - JP-4, are made in figures 7 and 8. The experimental values of characteristic velocity plotted in figure 7 demonstrate the relative effectiveness of different injection techniques in promoting efficient combustion. Corresponding data on heat rejection through the engine walls are presented in figure 8.

The effects of fluorine addition to the oxidant may be observed in the detailed curves of figure 9, where characteristic velocity, nozzle thrust coefficient, specific impulse, and heat rejection are presented as obtained from triplet injectors.

The cross plots in figure 10 give summary curves representative of conditions encountered at maximum experimental performance throughout the useful range of fluorine addition. Here the results from a triplet and the like-on-like injector (previously studied) are compared.

A complete compilation of experimental data and performance values is presented in table I. Adjusted values are also listed, which consider variations of experimental combustion pressures from the specified 600 pounds per squre inch absolute and performance losses associated with the heat discharged by the cooling water. Adjustment generally amounted to less than 2 percent of the measured performance.

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Injector Performance

The various injectors were first tested with oxygen - JP-4 in engines of a 30-inch characteristic length as a screening process to determine the respective performance characteristics and tendency toward injector-face burning. Injector performance was evaluated on the basis of characteristic velocity because of somewhat anomolous results relative to nozzle thrust coefficients.

Throughout the investigation, the values for thrust coefficient were lower and less consistent than anticipated. Instrumentation and measurement techniques were thoroughly checked for accuracy to prove that they were correct. Possibly, the difficulty was caused by heterogeneous gas flow or other phenomena occurring in the engine nozzle. No definite explanation for these results was found; but, because of them, the data for characteristic velocity, rather than specific impulse, properly indicate the trends of performance variations among injectors. Characteristic velocity is related more singularly to propellant combustion efficiency than is specific impulse, which also considers other variables such as the process of expansion through the engine nozzle. 4560

The injector performance results of the present investigation agree with those of related work with single-element injectors (refs. 7 and 8). Of the two principles considered most important in propellant preparation by injection element, atomization promotes high efficiency more readily than does mixing. The use of mixing simultaneously with atomization produces still higher efficiency.

Injector 3, which was intended to emphasize propellant mixing while minimizing atomization, gave the lowest performance of all the injectors tested (fig. 7).

Good performance was obtained with injectors that atomized both propellants without providing for enforced mixing (injectors 2, 2A, and 5). Injector 2 yielded a maximum characteristic velocity equivalent to that of injector 5 (fig. 7), even though injector 2 had much coarser and fewer sprays. Injector 2, however, was not immune to face burning; whereas even after very extensive use, injector 5 never showed evidence of deterioration. Injector 2A was identical to injector 2 in pattern, except that the V-jet inserts were set flush with the face to minimize injector damage. The injector was burned nevertheless.

Of the injectors studied with oxygen - JP-4, a triplet-jet type (injector 1) gave the highest characteristic velocity. The triplet configuration was chosen because it provided for both atomizing and mixing of the propellants simultaneously.

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Triplet injector 1A was patterned after injector 1; but it was expected to produce finer atomization while retaining the same realistic level of thrust per unit. When injector 1A was tested, it gave a considerably different performance than injector 1; but its performance was lower, evidently because of some change in oxidant-jet characteristics resulting from minor design changes. The difference in performance between the two injectors indicates that triplet units, combining the principles of mixing and atomization, are more critical in design than previously suspected. Variations in oxidant-fuel ratio do not alter the efficiency of a triplet injector to any appreciably extent, but designs for proper atomization and mixing must be understood before high performance levels can be obtained consistently.

Reduction in engine length produced an interesting comparison between the only two injectors (1 and 5) that had given high performance without failure through burnouts. It would be expected that triplet injectors, by virtue of their simultaneous atomizing and mixing characteristics, would foster a concentrated and intense combustion zone close to the injector face; whereas injectors, which only atomize the propellants, would produce a more diffuse combustion region extending farther down the thrust chamber. (This was true in the work reported in refs. 7 and 8.) Nevertheless, data obtained in engines with only a 15-inch characteristic length (15 L^*) clearly show a greater decrease in performance for the triplet than for the like-on-like injector. As shown in figure 7, performance of injector 1 fell 7 percent below the comparable data from 30 L^* engines; that of injector 5 dropped only 4 percent. This behavior is more obvious when the effect of engine characteristic length on over-all heat rejection measured for the two injectors is observed (fig. 8).

Apparently, the triplet injector depended more on engine length for high efficiency than the like-on-like injector, although at all times the triplet gave the higher absolute characteristic velocity. However, the two injectors (1 and 5) represent widely different levels of thrust-per-injection element. Accordingly, it may be concluded that fineness of injector detail (if this entails fineness of propellant atomization) will cause the combustion flame to seat near the injector face, while propellant preparation by both atomization and mixing will give highest efficiency.

Heat Rejection

Variation in injection method had an even greater effect on the engine heat-rejection rate than on performance efficiency. Although the duration of most of the runs (4 sec) was rather short for complete stabilization of heat transfer with these engines, the results given in figure 8 probably represent the injection influence adequately.

All of the injectors (except injector 3, which gave poor performance) produced greater heat rejection than the reference injector 5. The coarser spray pattern (higher thrust-per-injector element) of these injectors apparently resulted in greater scrubbing of local areas of the engine walls by burning gases.

Almost all of the injectors tested (with the notable exception of injector 5) exhibited burning or melting of the injector face to some extent. Usually, the low thermal conductivity of braze joints was clearly responsible rather than the arrangement of the injection elements. The triplet elements of injector 1, for example, were arranged in such a way that the spray fans, which result from jet impingement, could not interfere with each other. Previous experience with fluorine had revealed that such interference, as well as the presence of protruding and recessed surfaces on the injector face, could cause severe burning of the injector face (ref. 11). The face of injector 1 was not burned in this manner; thus, avoidance of interference between triplet sprays can minimize injector burnouts.

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These results again emphasize the care that must be exercised in injector design. Proper attention to braze and weld joints, cooling of the face, and, most important, the arrangement of injection units on the face will alleviate face burning.

Injector with Triplet-Jet Elements in Skewed Array

Injector 4 had triplet elements similar to those of injector 1. These elements were arranged differently, however, (fig. 4) to obtain additional confirmation that triplet injectors are not susceptible to face burning if the sprays do not interfere. Injector 4 was made of solid aluminum and was essentially uncooled. It was run repeatedly with an oxidant containing 15-percent fluorine covering a wide range of oxidant-fuel ratio. Little burning of the face was evidenced. The characteristic velocities obtained were equivalent to those of injector 1; whereas, heat-transfer requirements to cool the engine walls were considerably lower (fig. 9(b)).

Injector 4 was run with an engine which had only been used before with injector 5 for the work reported in reference 5. Both of the injectors tested with this chamber yielded the only high values of thrust coefficient (and, consequently, specific impulse) recorded in the course of the program. For this reason, injector 4 and its engine were next reassembled for running with JP-4 - oxygen mixture (without fluorine addition). A detonation on starting destroyed both engine and injector.

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Fluorine Addition

The two injectors selected for the continuation of the study with fluorine addition to the oxidant were the triplet injectors 1 and 1A. While similar in design, they differed greatly in performance. They were chosen to determine whether the addition of fluorine to the oxidant would alter the relation in performance between two geometrically similar injectors embodying the same injection principles. In short, would injection techniques successful with oxygen be equally applicable to fluorine-oxygen mixtures.

These two injectors (1 and 1A) were used with oxidant mixtures containing 0-, 15-, and 30-percent fluorine (figs. 9(a), (b), and (c)). In general, the percentage difference in performance between the two injectors, 1 and 1A, held uniform over the range of fluorine concentrations tested, indicating that for injectors using the same type of propellant preparation, the addition of fluorine does not alter injection demands.

Only the injector that gave the highest performance (injector 1) was used for the examination of fluorine-oxygen - JP-4 combinations rich in fluorine. Results of the work with the various oxidant compositions are presented in figure 9. Values from the faired curves of figure 9, taken at the oxidant-fuel ratio of maximum performance for injector 1, were plotted in figure 10 as functions of oxidant composition. Similar data from injector 5 (ref. 5) were included for comparison.

The region of lowest efficiency for injector 1 occurred at the intermediate fluorine concentrations. This apparently indicates lack of design optimization rather than a phenomenon characteristic of the propellants, since injector 5 was particularly efficient in this region. At no point, however, did the performance curves of either injector fall more than 2.5 percent away from a mean of the two curves when considering either characteristic velocity or specific impulse (fig. 10(a)). This is within the probable limits of accuracy of the data.

Heat rejection when using injector 1 was about double that obtained with injector 5 (fig. 10(b)).

Concluding Remarks

The results obtained, in general, indicated that high performance can be obtained from injectors of very few injection units per 1000 pounds of engine thrust as well as from those having a large number of units. Proper care as to optimization is necessary for obtaining the highest performance levels. The same considerations and principles of injection should be applied for JP-4 with fluorine-oxygen mixtures as for the JP-4 and oxygen combination, but design details should be evaluated with the oxidant mixture in question for final optimization.

SUMMARY OF RESULTS

Injectors for use with JP-4 - oxygen-fluorine rocket-propellant combinations were evaluated experimentally with 1000-pound-thrust engines at a combustion pressure of 600 pounds per square inch absolute over a range of fluorine addition to the oxygen. The results are summarized as follows:

1. High characteristic velocity efficiencies were obtained over the complete range of useful fluorine addition (0 to 70 percent), although injector design was not optimized.

2. Values at highest performance from the faired curves are as follows:

Fluorine in oxidant, weight percent	0	15	30	45	60	70
Fuel, weight percent	30	31	27	27	27	23
Oxidant-fuel weight ratio	2.33	2.23	2.70	2.70	2.70	3.35
Characteristic velocity, ft/sec	5740	5760	5780	6000	6280	6520
Percent of theoretical maximum,						
Equilibrium	97	95	93	93	94	96
Frozen	99	97	95	96	97	99
Nozzle thrust coefficient	1.45	1.41	1.48	1.45	1.41	1.40
Percent of theoretical maximum,						
Equilibrium	93	90	96	----	93	91
Frozen	96	93	99	----	96	93
Specific impulse, (lb)(sec)/lb	260	254	265	268	276	282
Percent of theoretical maximum,						
Equilibrium	91	87	88	87	87	87
Frozen	96	92	93	93	93	94
Heat rejection, average over-all, Btu/(sec)(sq in.)	4.6	4.6	4.3	4.0	4.2	5.1

3. The triplet injector, which gave the above results, indicated that high performance is obtainable with high thrust per triplet unit (143 lb-thrust/unit).

4. The fact that the lowest efficiencies occurred at intermediate fluorine concentrations seems to depend on injector design rather than on any basic combustion characteristics of the propellant.

5. Arrangement of triplet units on the injector faces considerably influenced over-all engine heat rejection.

6. Burning of injector faces was alleviated by careful orientation of triplet units to minimize interaction of sprays.

7. Although triplet injectors are relatively insensitive to variation of oxidant-fuel ratio, the design of triplet units for high efficiency and reliability is more critical than previously expected.

8. The same basic injection requirements prevail for jet fuel with oxygen-fluorine mixtures as for the JP-4 - oxygen combination. Final optimization of injectors, however, should be done by testing with the oxidant mixture in question.

9. Injectors, which only atomized the propellants, gave better performance than the injector that emphasized propellant mixing alone. Atomizing and mixing the propellants simultaneously, as by triplet injection units, improved performance further.

10. Injection by finely divided atomization apparently caused the flame to seat nearer the injector face and was less dependent on engine length for high efficiency than injection by coarser sprays.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 20, 1958

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TABLE I. - EXPERIMENTAL PERFORMANCE OF FLUORINE-OXYGEN JP-4

Fluorine in oxidant, weight percent	Injector	Engine characteristic length, L*, in.	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
0	1	30	24.4	3.10	4.44	1116	661	251	5560	1.46	6.21	251.1
			26.9	2.72	4.33	1098	657	254	5670	1.44	5.18	254.1
			27.4	2.65	4.25	1068	643	251	5660	1.43	5.04	251.8
			27.9	2.59	4.24	1095	655	258	5700	1.46	5.38	258.4
			29.2	2.43	4.24	1100	657	260	5720	1.46	5.16	260.5
			29.7	2.36	4.21	1090	652	259	5720	1.46	4.88	259.8
			30.8	2.25	4.24	1086	659	256	5730	1.44	3.82	256.1
			30.9	2.24	4.23	1064	645	251	5690	1.42	3.87	251.8
			31.1	2.22	4.34	1081	657	249	5670	1.42	4.05	249.5
			31.2	2.21	4.08	1088	640	266	5830	1.47	4.77	267.6
			31.6	2.16	4.23	1084	653	256	5690	1.45	4.59	257.1
			33.0	2.03	4.28	1052	644	246	5620	1.41	3.62	247.1
			33.1	2.02	4.28	1086	662	254	5700	1.43	3.56	254.2
			33.9	1.95	4.41	1116	659	253	5560	1.46	5.14	254.6
	1A	30	24.9	3.01	4.27	1033	599	242	5230	1.49	4.72	244.3
			27.1	2.69	4.28	1049	612	245	5340	1.48	4.33	246.7
			27.4	2.65	4.44	1102	638	248	5350	1.49	4.29	248.5
			29.6	2.38	4.11	1013	597	246	5410	1.46	3.72	248.6
			30.9	2.23	4.18	985	599	235	5330	1.42	3.42	237.7
	2	30	31.2	2.20	4.05	1004	603	248	5540	1.44	5.43	252.0
			31.5	2.17	3.99	982	591	246	5530	1.43	5.23	250.6
			32.0	2.13	4.02	978	586	243	5440	1.44	4.96	247.7
			32.3	2.10	3.95	962	575	244	5430	1.44	4.74	249.2
			32.7	2.06	3.96	969	587	245	5530	1.42	4.95	249.9
			35.6	1.81	4.03	975	581	242	5370	1.45	4.72	247.4
	2A	30	27.1	2.69	4.20	1015	606	242	5380	1.45	5.64	244.7
			28.4	2.52	4.11	1008	594	245	5390	1.46	5.56	248.6
			28.9	2.46	4.05	985	586	243	5390	1.45	5.42	247.1
	3	30	32.2	2.10	4.48	988	576	220	4800	1.48	1.14	221.9
			33.2	2.01	4.50	1004	575	223	4780	1.50	1.24	225.1
			34.5	1.90	4.55	1016	565	223	4640	1.55	1.38	225.7
	1	15	29.6	2.38	4.11	1004	592	244	5350	1.47	3.05	245.7
			29.9	2.34	4.19	1024	605	244	5360	1.47	3.12	245.2
			31.1	2.22	4.03	976	576	242	5300	1.47	3.05	244.6
			31.8	2.15	4.23	1024	607	242	5320	1.46	3.22	243.3
			32.6	2.06	4.27	1025	606	240	5270	1.47	3.28	241.5
			33.2	2.01	4.47	1090	640	244	5320	1.48	3.35	244.1
			33.2	2.01	4.34	1041	617	240	5280	1.46	3.41	241.1
			35.3	1.83	4.35	1020	601	234	5140	1.47	3.40	236.0
	5	15	25.7	2.89	4.62	1060	657	230	5240	1.41	2.03	228.4
			26.6	2.76	4.64	1062	658	229	5230	1.41	1.78	227.3
			29.3	2.42	4.59	1060	655	231	5250	1.42	1.51	229.5
			30.2	2.31	4.42	1012	630	229	5240	1.40	1.44	228.5
			31.8	2.15	4.63	1056	653	228	5200	1.41	1.54	226.7
			32.1	2.12	4.65	1051	651	226	5160	1.41	1.46	224.8
			33.3	2.00	4.27	959	596	225	5140	1.41	1.37	226.0
			35.8	1.79	4.37	974	602	223	5080	1.42	----	-----
15	1	30	26.8	2.73	4.43	1008	630	227	5300	1.38	4.01	228.4
			26.8	2.73	4.20	1008	625	240	5550	1.39	4.72	241.9
			26.9	2.72	4.13	993	617	240	5560	1.39	4.66	242.2
			29.2	2.43	4.12	979	615	238	5560	1.38	4.03	240.5
			29.3	2.41	4.08	995	614	244	5610	1.40	4.26	246.7
			29.9	2.34	4.04	964	607	239	5600	1.37	3.80	241.8
			30.2	2.31	3.87	975	605	252	5740	1.42	5.23	256.1
			30.5	2.27	3.95	1016	620	257	5770	1.43	4.83	260.1
			30.7	2.26	3.74	932	582	249	5710	1.40	4.70	253.9
			30.9	2.24	4.08	1052	645	258	5810	1.43	4.88	260.0
			31.2	2.20	3.96	1022	624	258	5800	1.43	4.72	261.0
			31.3	2.19	4.01	1035	637	258	5840	1.42	4.78	260.5
			31.3	2.19	3.90	1006	619	258	5840	1.42	4.59	261.1
			31.5	2.18	3.93	977	608	248	5680	1.41	4.78	251.9
			32.3	2.09	3.85	949	592	246	5640	1.40	4.54	250.6
			32.6	2.07	4.04	1052	636	260	5780	1.45	5.05	262.9
			33.3	2.01	4.08	958	606	235	5530	1.37	3.60	238.3
			33.9	1.95	3.93	966	(a)	246	(a)	(a)	4.46	-----
			34.9	1.86	3.87	938	(a)	242	(a)	(a)	4.26	-----

[a]Chamber pressure tap plugged.

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TABLE I. - Concluded. EXPERIMENTAL PERFORMANCE OF FLUORINE-OXYGEN JP-4

Fluorine in oxidant, weight percent	Injector	Engine characteristic length, L*, in.	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
15	1A	30	24.4	3.10	4.40	1086	630	247	5360	1.49	4.55	248.0
			27.2	2.67	4.28	1045	618	244	5400	1.46	3.85	245.6
			27.9	2.59	4.37	1064	624	244	5350	1.47	3.92	245.5
			28.4	2.52	4.28	1040	617	243	5380	1.45	3.55	244.7
			29.6	2.39	4.26	1007	614	236	5380	1.41	(a)	-----
			30.9	2.23	4.16	994	596	239	5360	1.44	3.13	241.8
	4	30	28.0	2.58	4.12	1092	621	265	5520	1.54	3.14	266.0
			29.4	2.41	4.11	1087	631	264	5620	1.51	2.68	264.6
			30.1	2.32	4.15	1107	640	267	5650	1.52	2.40	267.1
			30.3	2.30	4.19	1107	651	264	5720	1.49	2.11	263.5
			30.7	2.26	4.17	1109	647	266	5680	1.51	2.27	265.8
			31.2	2.21	4.21	1106	652	262	5690	1.48	1.91	261.4
			31.3	2.20	4.24	1116	658	264	5710	1.48	1.56	262.9
			31.7	2.16	4.17	1093	650	262	5730	1.47	1.83	261.5
			31.8	2.14	4.24	1100	651	256	5650	1.48	1.76	255.4
			32.0	2.12	4.12	1098	636	266	5650	1.52	1.97	266.1
			32.4	2.09	4.18	1109	642	265	5630	1.52	1.78	264.8
			34.2	1.92	4.35	1115	668	256	5650	1.46	1.65	254.8
			34.6	1.89	4.22	1089	651	258	5680	1.46	1.46	257.3
			35.5	1.82	4.22	1079	646	256	5640	1.46	1.44	255.3
30	1	30	27.0	2.71	4.25	1128	648	265	5800	1.47	4.25	265.8
			29.0	2.44	4.23	1106	642	261	5770	1.46	3.72	262.1
			29.1	2.43	4.16	1076	626	259	5720	1.46	3.58	260.7
			30.1	2.32	4.11	1064	619	259	5720	1.46	3.45	261.1
			31.5	2.17	4.12	1048	611	255	5640	1.45	3.08	257.3
			32.7	2.06	4.08	1032	606	253	5650	1.44	3.30	255.9
	1A	30	23.0	3.35	4.56	1159	658	254	5490	1.49	(a)	-----
			26.8	2.72	4.40	1118	641	254	5550	1.48	(a)	-----
			27.2	2.67	4.44	1133	651	255	5580	1.48	(a)	-----
			28.8	2.48	4.28	1092	627	255	5570	1.48	(a)	-----
45	1	30	24.7	3.06	3.94	1052	619	267	5810	1.48	4.45	269.2
			25.4	2.93	3.94	1055	631	268	5940	1.45	4.27	269.7
			26.4	2.78	3.92	1044	632	266	5970	1.44	4.00	267.7
			29.7	2.37	3.91	1024	614	262	5810	1.45	3.30	264.5
			31.0	2.23	3.97	1034	617	261	5800	1.45	3.37	263.5
			32.2	2.11	3.90	1000	600	256	5690	1.45	2.85	257.7
60	1	30	23.9	3.18	3.46	951	591	275	6260	1.41	5.13	279.6
			24.4	3.10	3.47	944	587	272	6210	1.41	4.91	276.6
			25.6	2.91	3.46	956	588	276	6240	1.42	4.70	280.4
			26.0	2.85	3.43	948	587	276	6290	1.42	4.43	280.2
			27.0	2.70	3.39	929	580	274	6290	1.40	4.21	278.4
			28.0	2.57	3.44	944	589	274	6290	1.40	3.88	277.7
			30.6	2.26	3.46	947	588	274	6240	1.41	2.57	276.7
70	1	30	15.4	5.48	3.64	980	611	269	6160	1.41	7.03	273.9
			17.6	4.67	3.63	958	615	264	6220	1.37	7.14	269.1
			19.2	4.21	3.54	958	617	271	6400	1.36	6.55	275.6
			19.7	4.08	3.55	981	616	276	6370	1.40	6.36	280.4
			21.7	3.61	3.52	1008	638	286	6660	1.38	5.04	287.9
			22.2	3.50	3.69	1034	644	280	6410	1.41	4.50	281.3
			24.2	3.14	3.69	1031	643	279	6390	1.41	4.82	280.6
			24.3	3.12	3.64	1001	631	275	6370	1.39	4.35	276.9
			25.4	2.94	3.70	1020	643	275	6370	1.39	4.47	276.4
			26.1	2.83	3.50	988	625	282	6550	1.39	4.31	284.2

[a]Temperature records not obtained.

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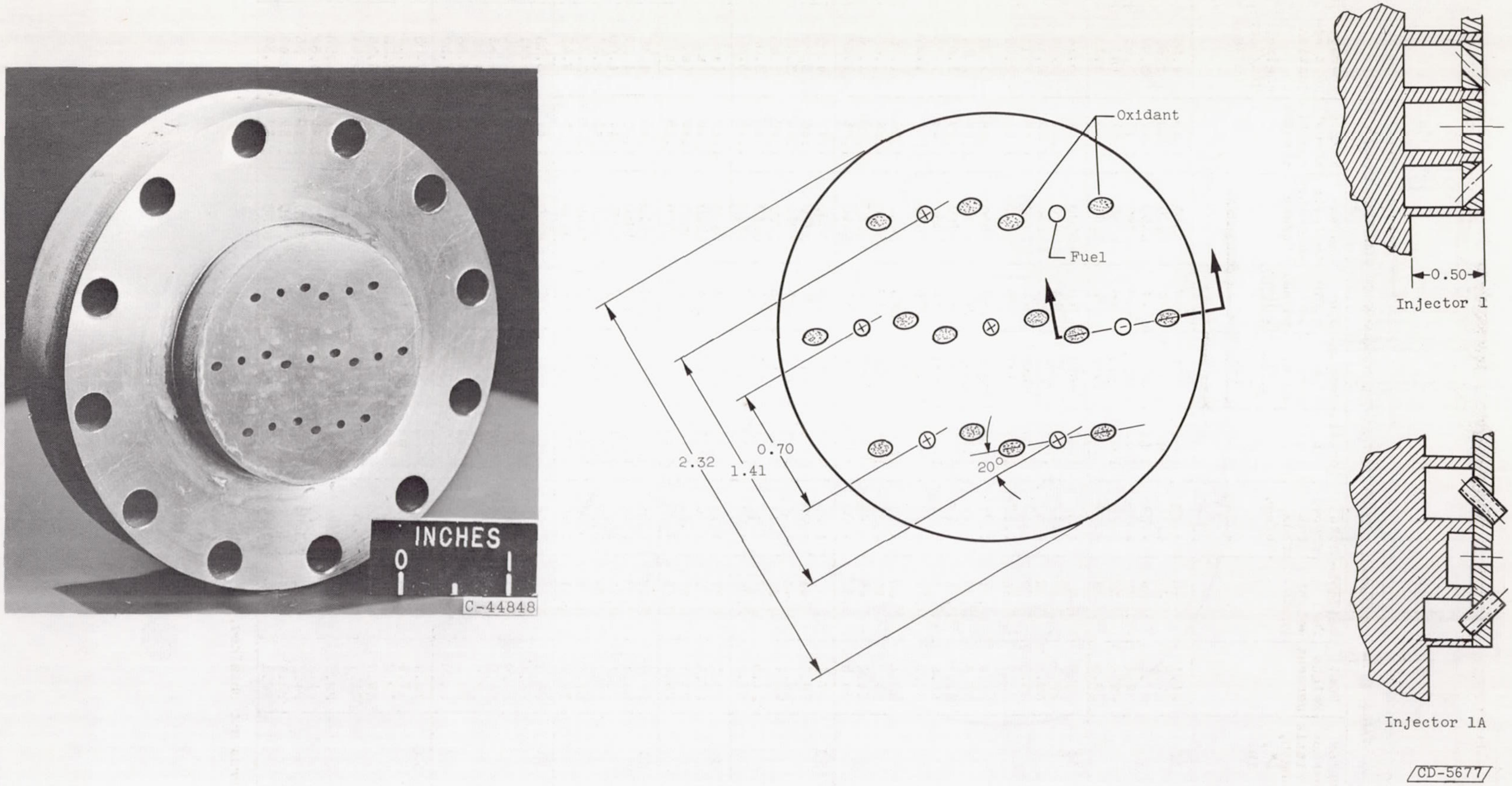

Figure 1. - Triplet-jet-type injectors; elements arranged to produce parallel spray fans; elements provide simulteous atomization and mixing of propellants. (All dimensions in inches.)

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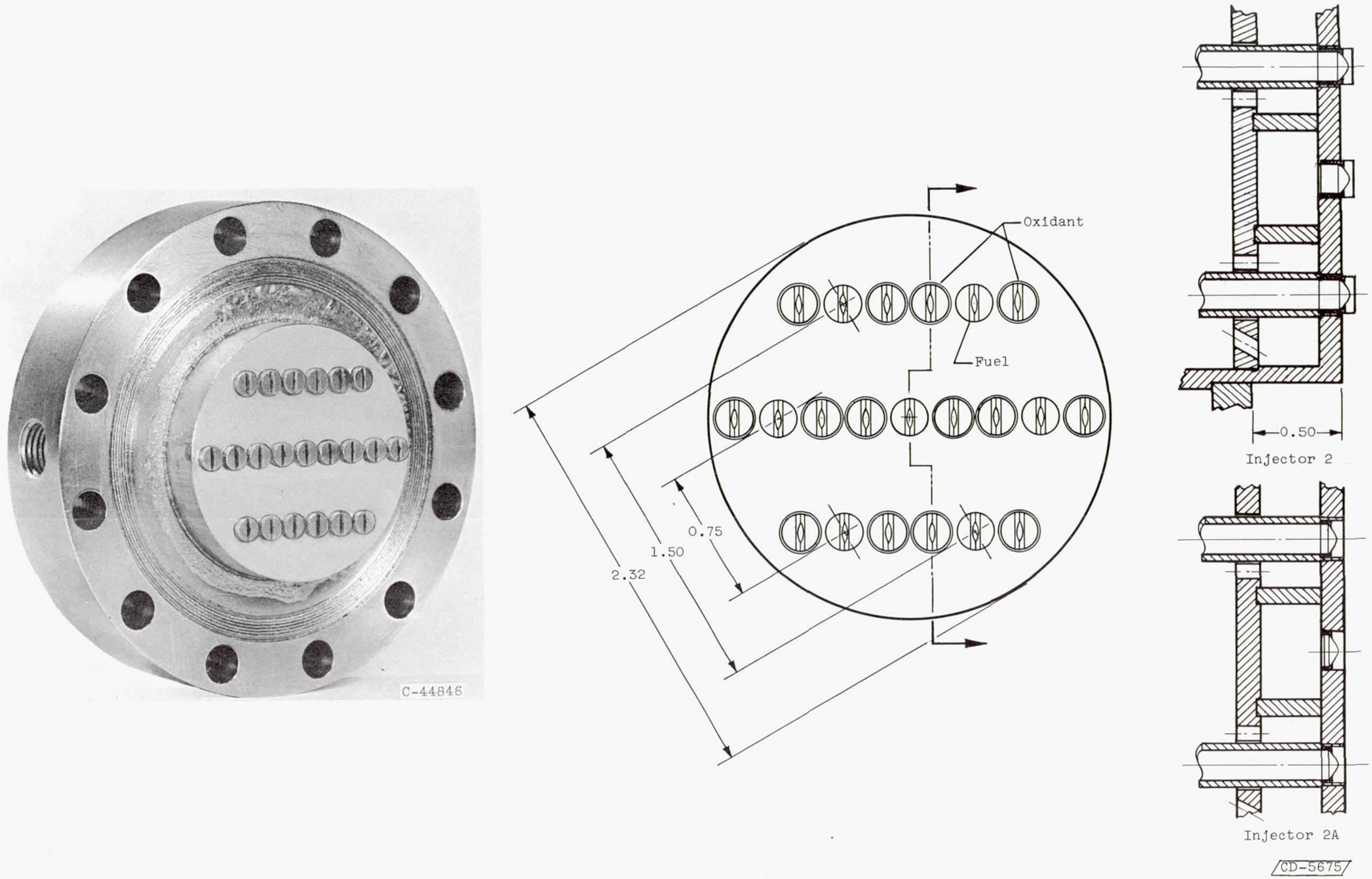

Figure 2. - V-jet-type injectors; elements arranged to produce parallel spray fans; elements emphasize atomization of propellants. (All dimensions in inches.)

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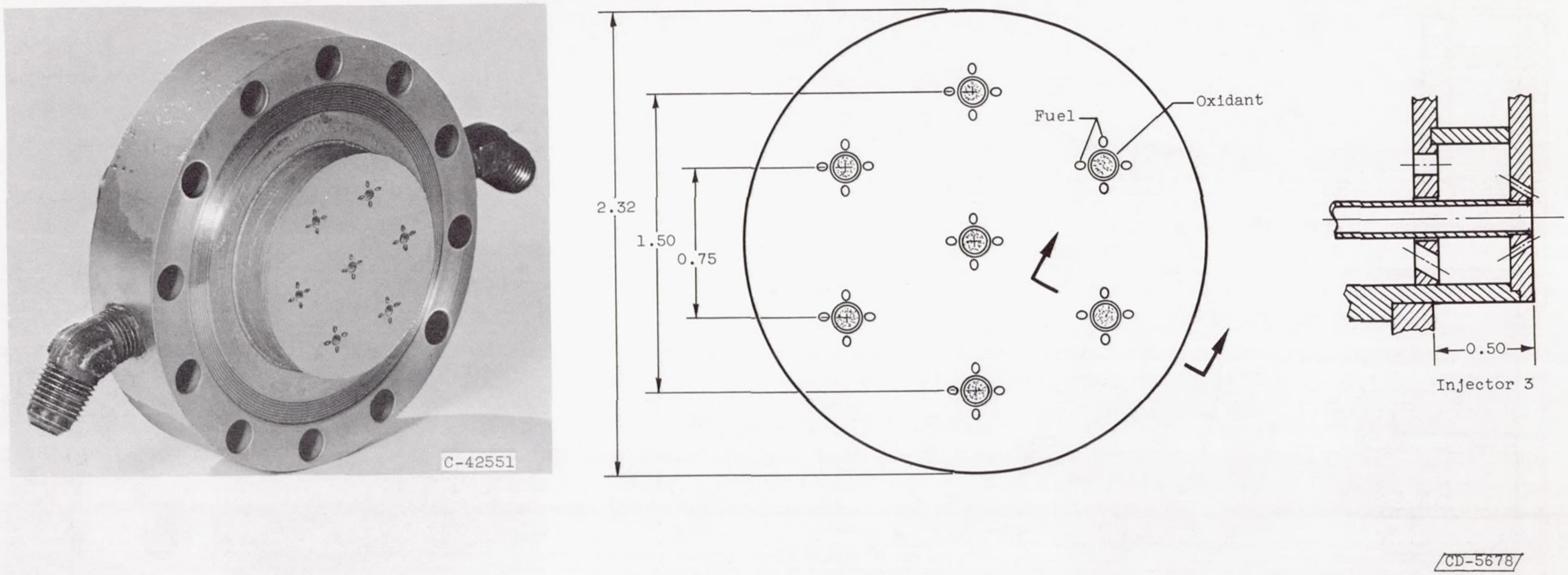

Figure 3. - Concentric-jet-type injector; elements emphasize mixing of propellants. (All dimensions in inches.)

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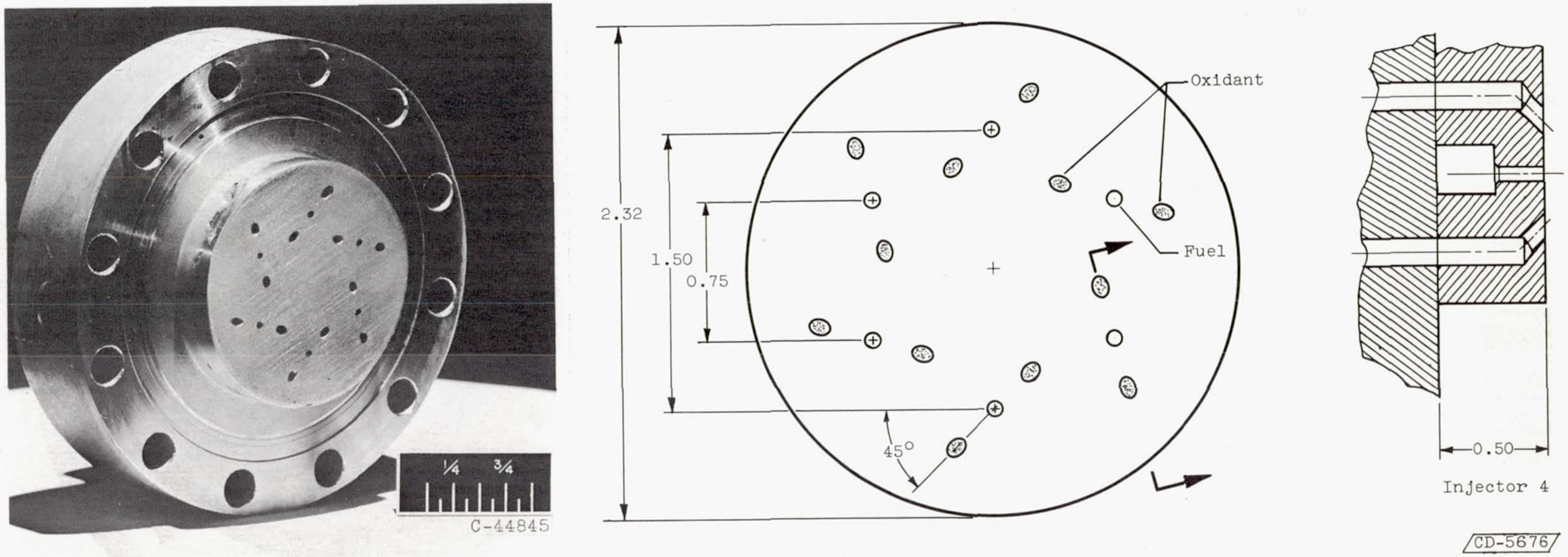

Figure 4. - Triplet-jet-type injector; elements arranged to produce spray fans in skewed array; elements provide simultaneous atomization and mixing of propellants. (All dimensions in inches.)

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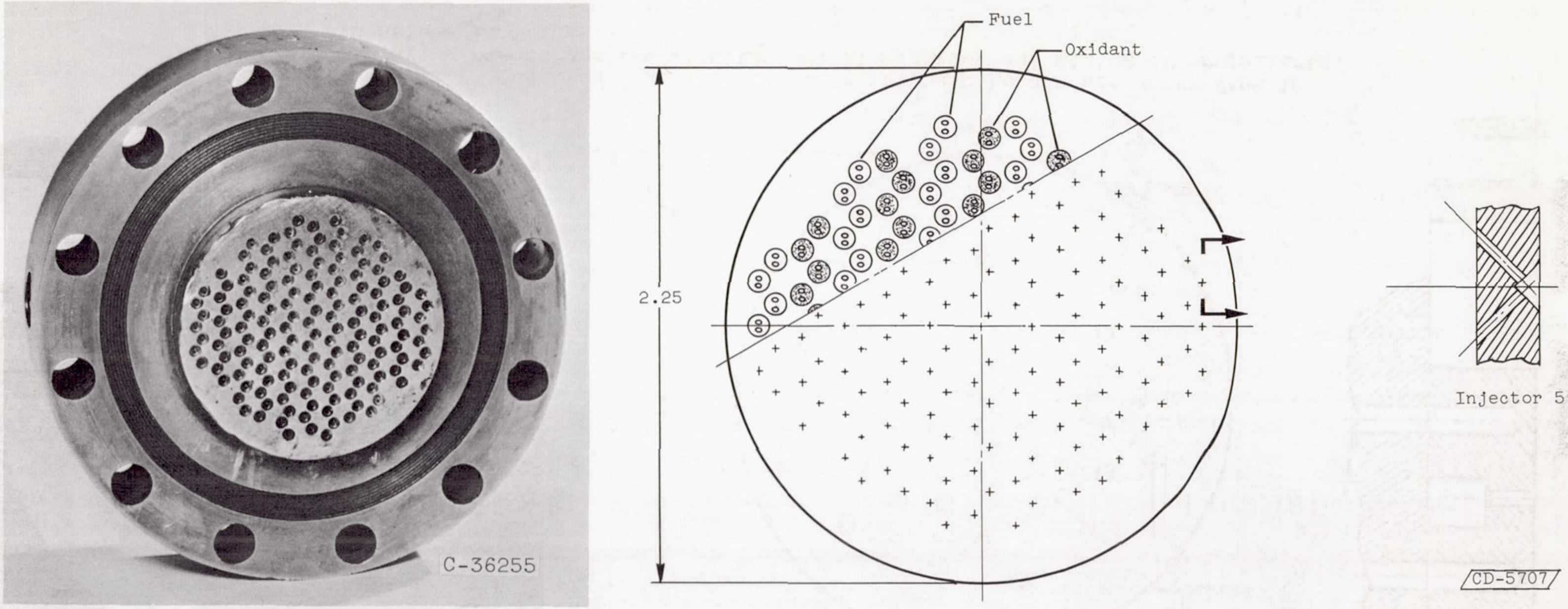

Figure 5. - Like-on-like-type injector; elements emphasize atomization of propellants. (All dimensions in inches.)

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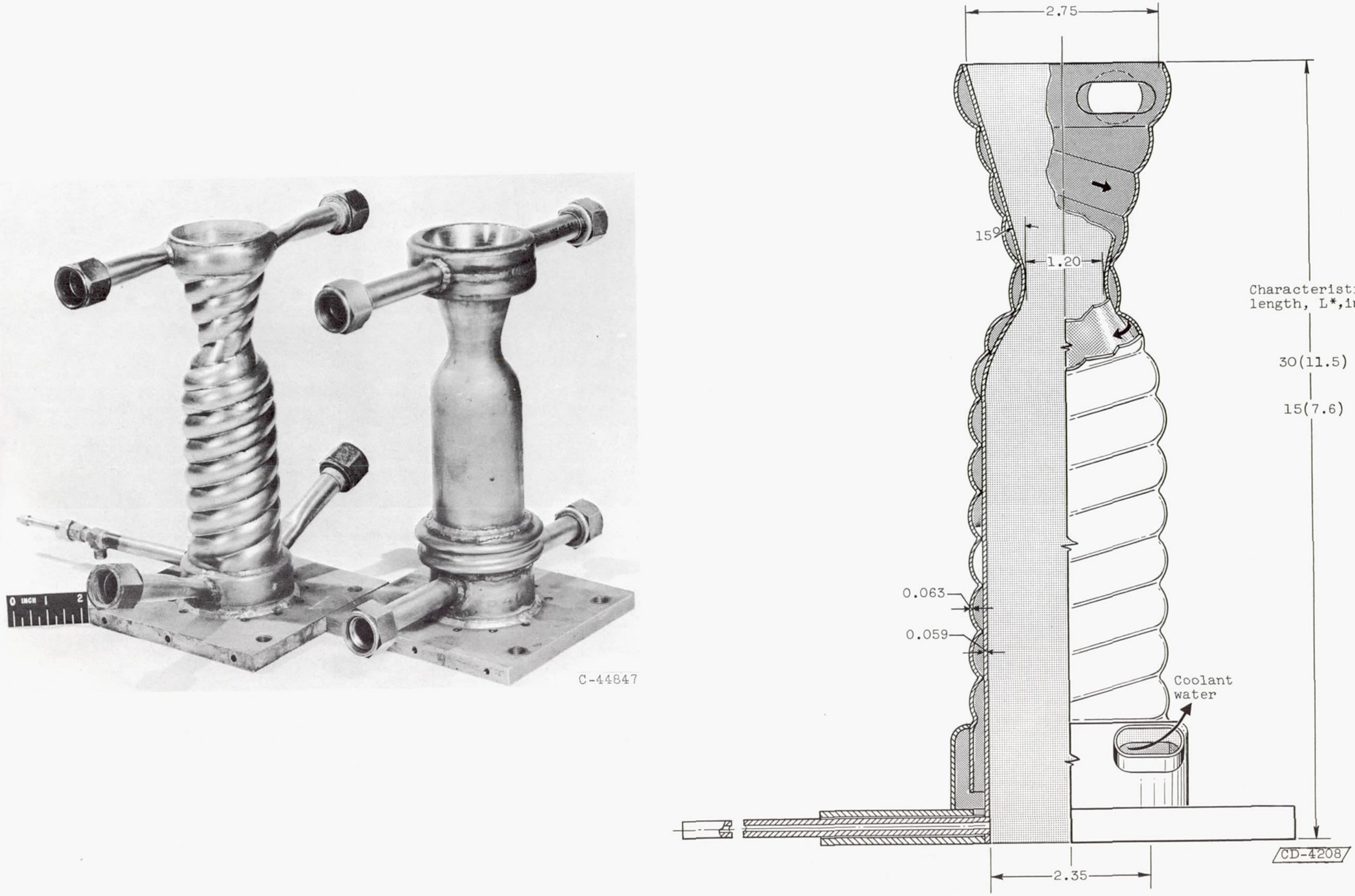

Figure 6. - Rocket thrust chambers for 1000 pounds of thrust at 600 pounds per square inch absolute combustion pressure. (All dimensions in inches.)

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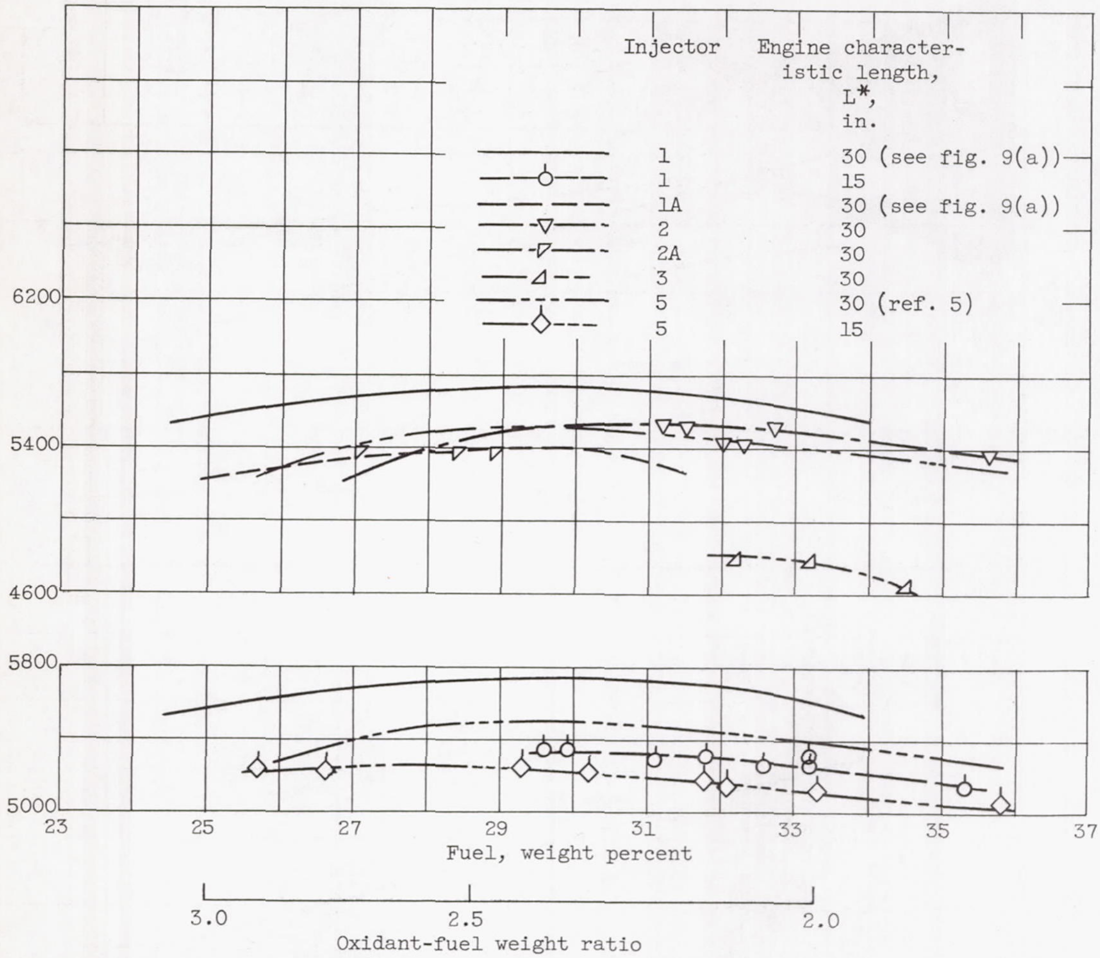

Figure 7. - Experimental and theoretical characteristic velocities; fuel, JP-4; oxidant, oxygen; combustion pressure, 600 pounds per square inch absolute; rocket engine thrust, 1000 pounds.

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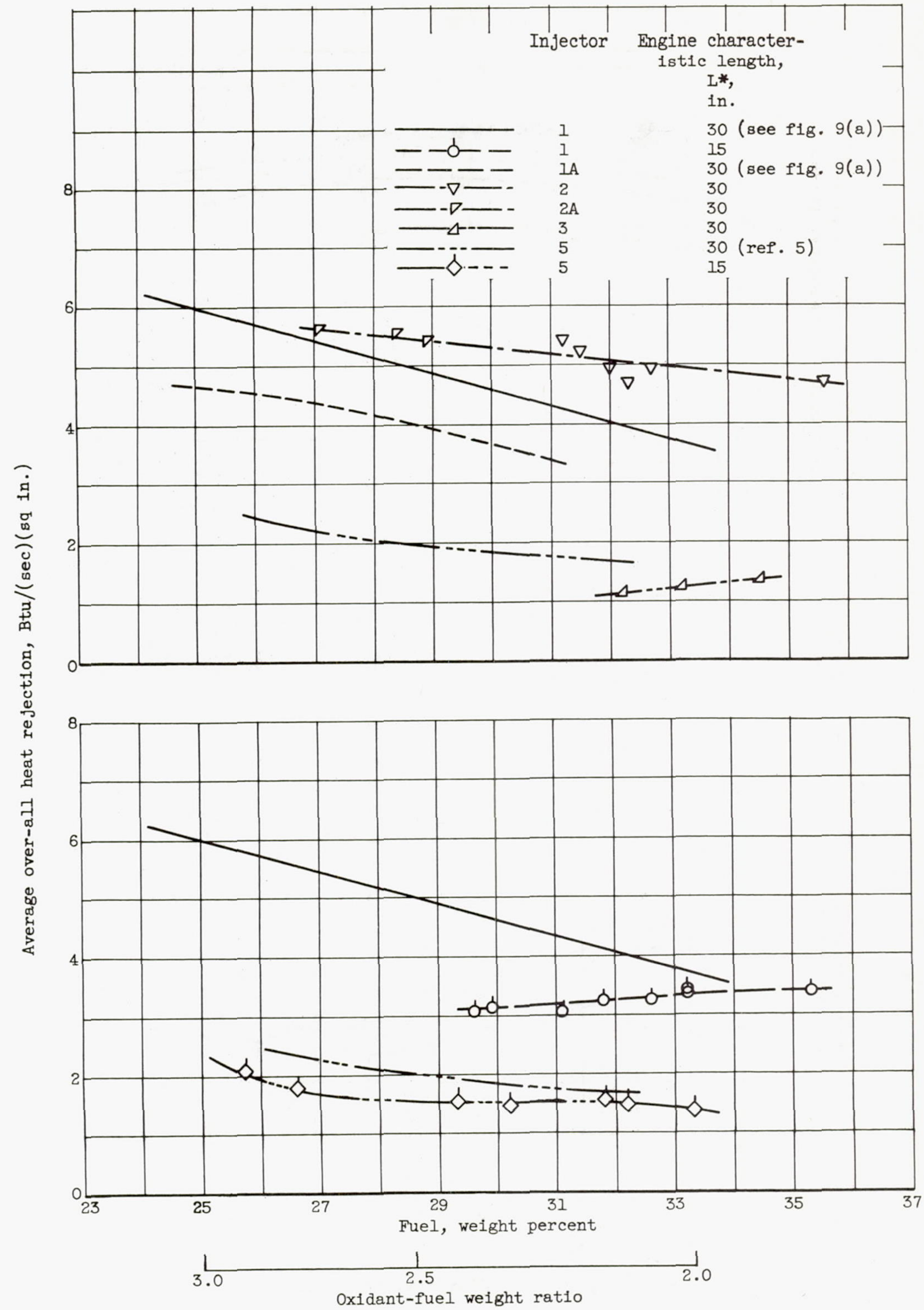

Figure 8. - Experimental heat rejection. Fuel, JP-4; oxidant, oxygen; combustion pressure, 600 pounds per square inch absolute; rocket engine thrust, 1000 pounds.

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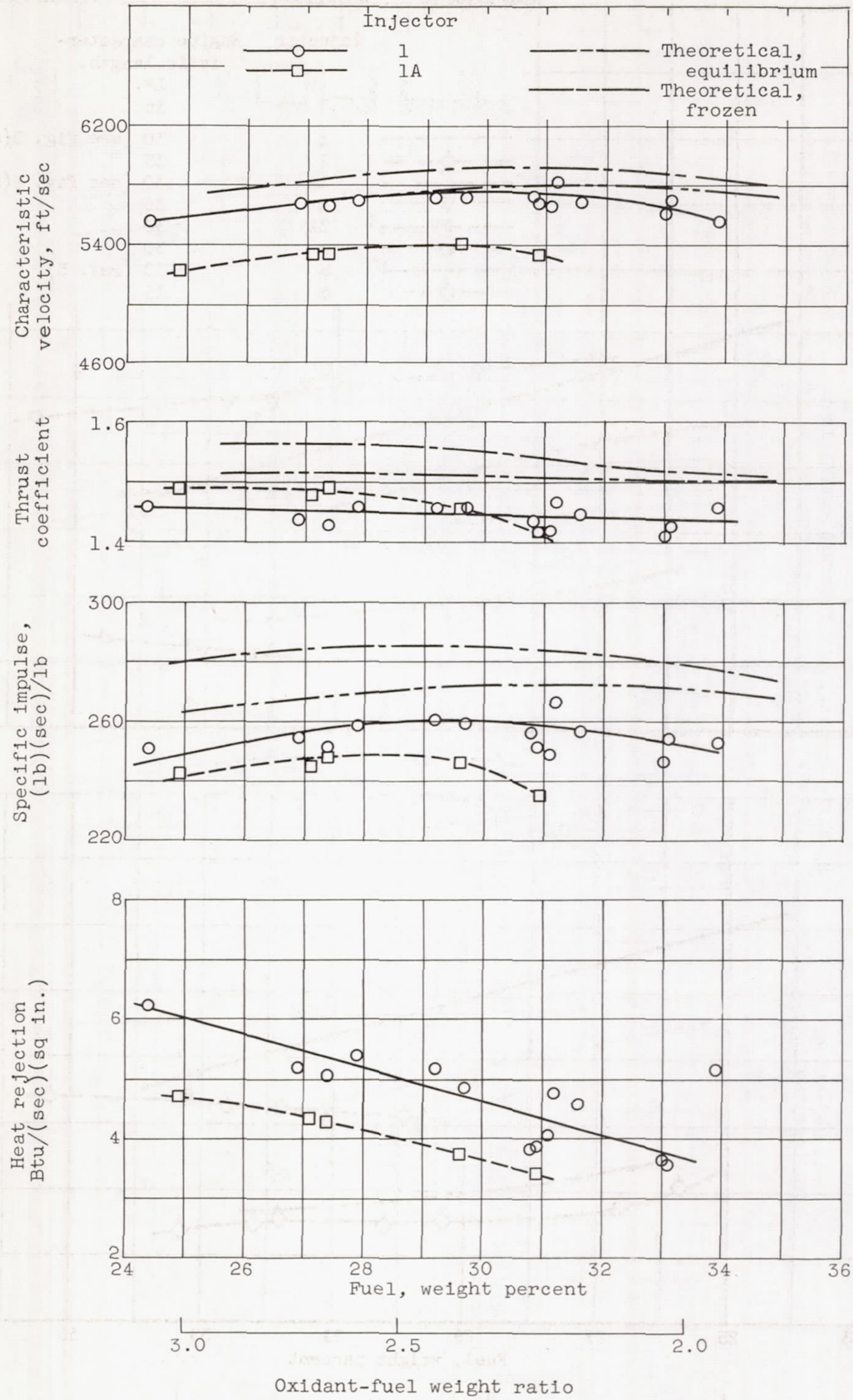

(a) Fuel, JP-4; oxidant, oxygen.

Figure 9. - Experimental and theoretical characteristic velocity, thrust coefficient, specific impulse, and heat rejection. Combustion pressure, 600 pounds per square inch absolute; rocket engine thrust, 1000 pounds.

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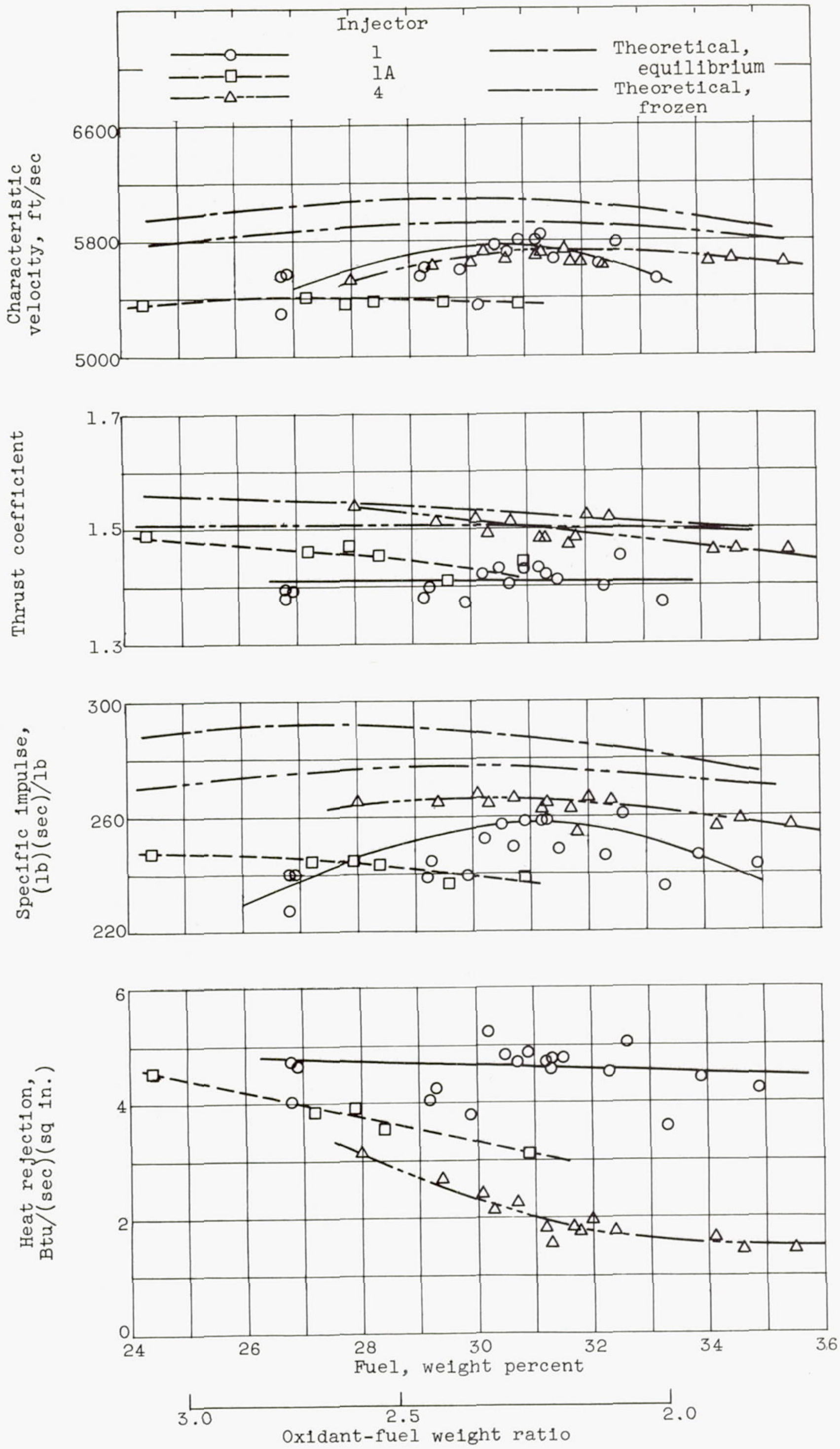

(b) Fuel, JP-4; oxidant, 15-percent fluorine and 85-percent oxygen.

Figure 9. - Continued. Experimental and theoretical characteristic velocity, thrust coefficient, specific impulse, and heat rejection. Combustion pressure, 600 pounds per square inch absolute; rocket engine thrust, 1000 pounds.

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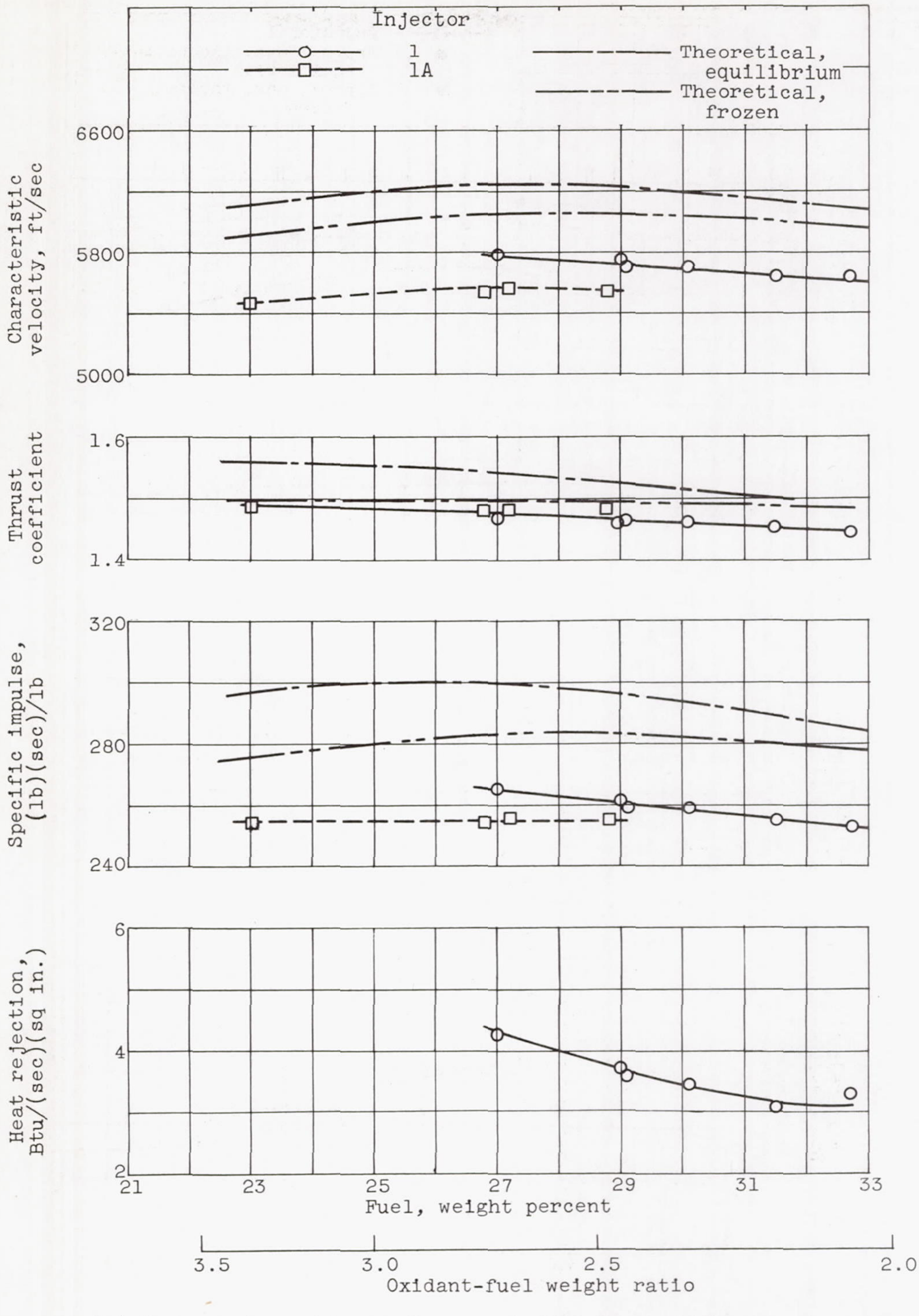
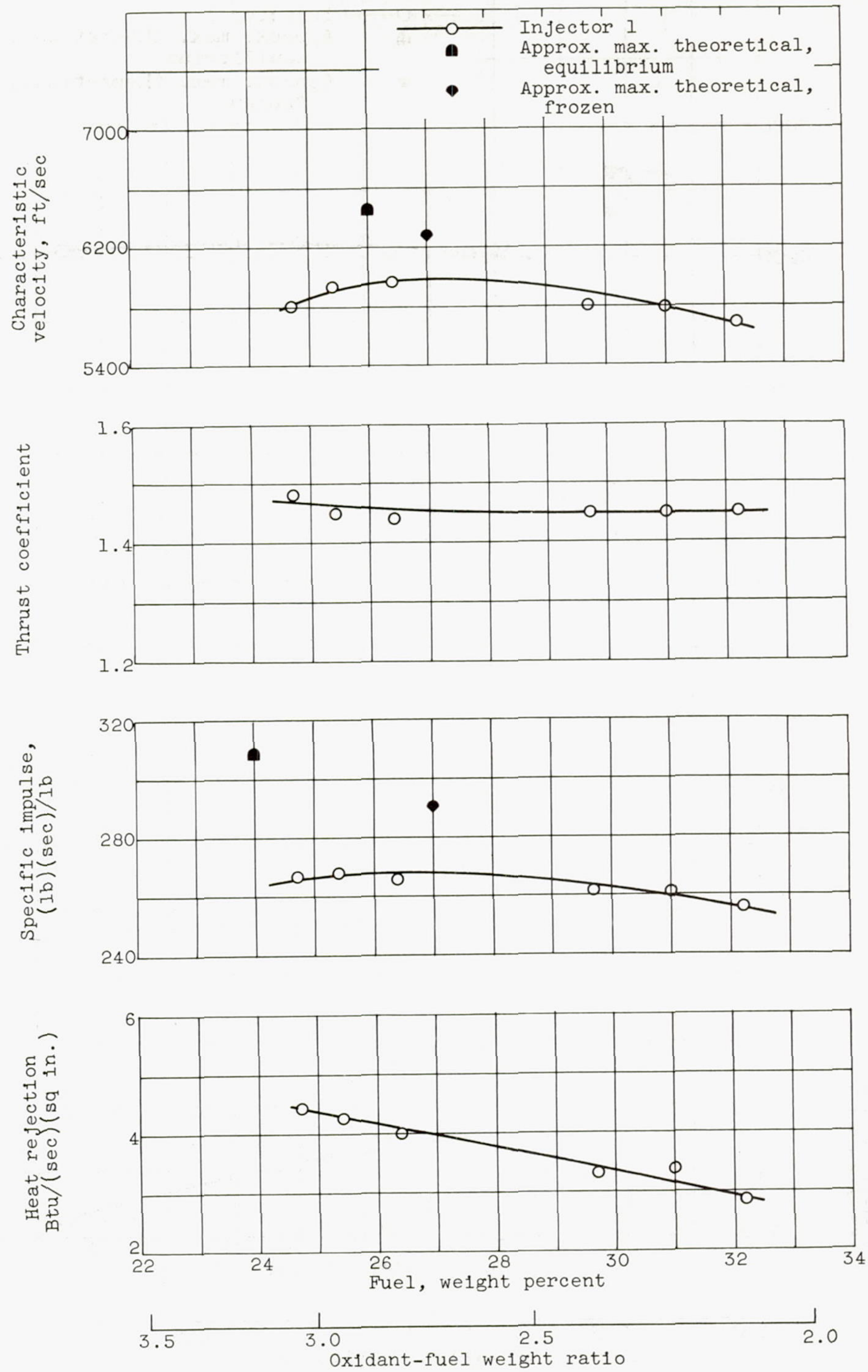


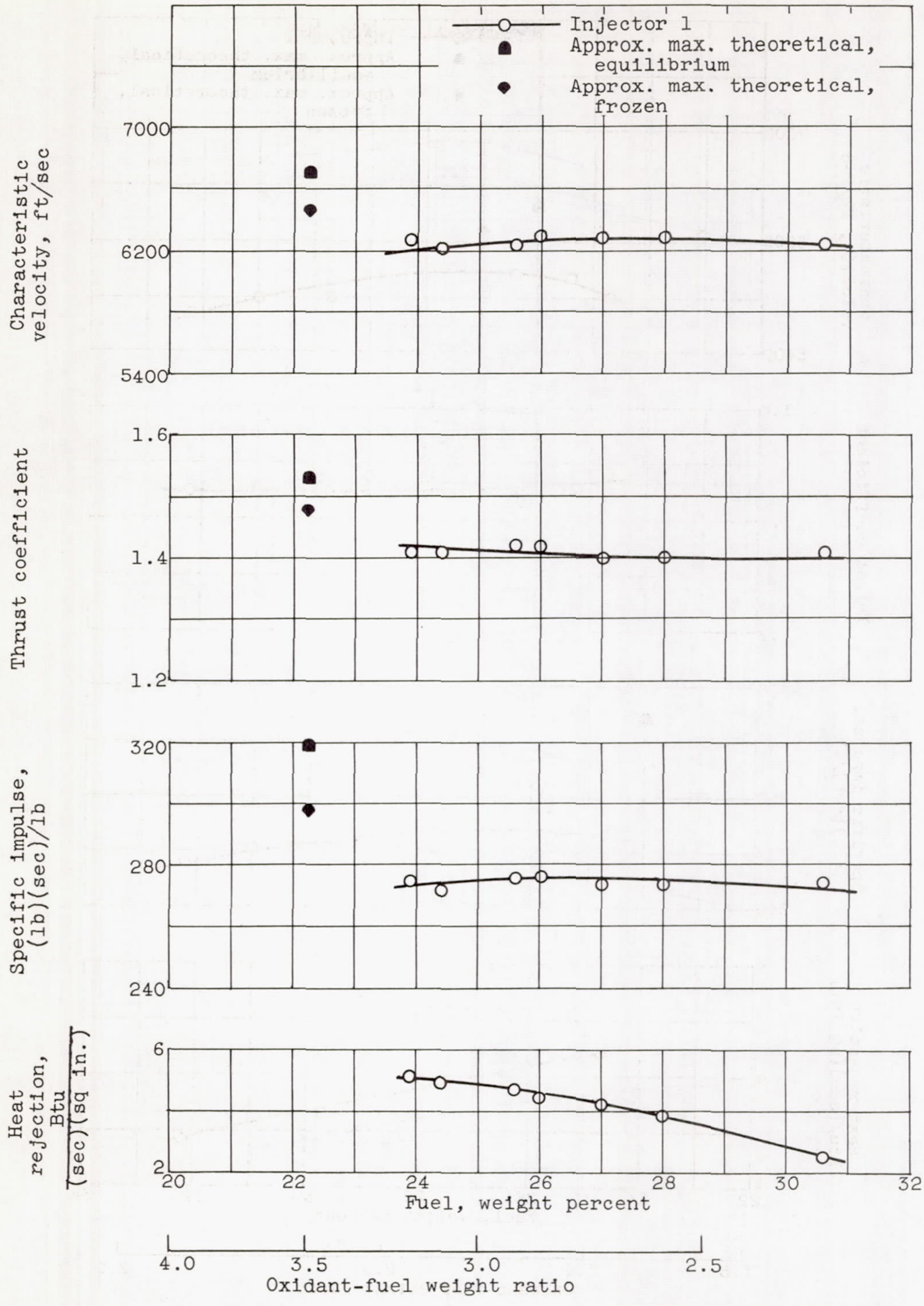
(c) Fuel, JP-4; oxidant, 30-percent fluorine and 70-percent oxygen.

Figure 9. - Continued. Experimental and theoretical characteristic velocity, thrust coefficient, specific impulse, and heat rejection. Combustion pressure, 600 pounds per square inch absolute; rocket engine thrust, 1000 pounds.



(d) Fuel, JP-4; oxidant, 45-percent fluorine and 55-percent oxygen.

Figure 9. - Continued. Experimental and theoretical characteristic velocity, thrust coefficient, specific impulse, and heat rejection. Combustion pressure, 600 pounds per square inch absolute; rocket engine thrust, 1000 pounds.



(e) Fuel, JP-4; oxidant, 60-percent fluorine and 40-percent oxygen.

Figure 9. - Continued. Experimental and theoretical characteristic velocity, thrust coefficient, specific impulse, and heat rejection. Combustion pressure, 600 pounds per square inch absolute; rocket engine thrust, 1000 pounds.

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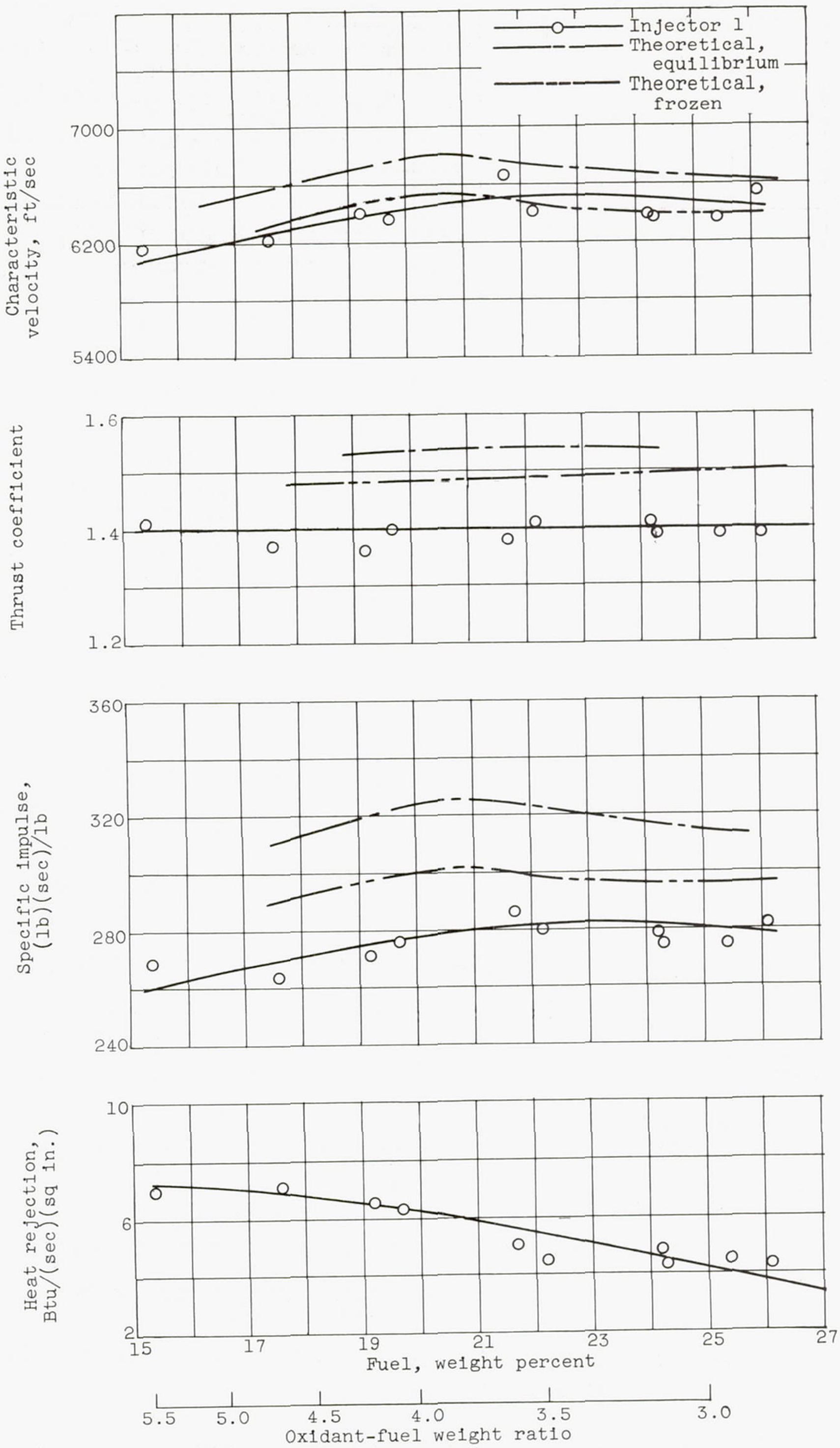

(f) Fuel, JP-4; oxidant, 70-percent fluorine and 30-percent oxygen.

Figure 9. - Concluded. Experimental and theoretical characteristic velocity, thrust coefficient, specific impulse, and heat rejection. Combustion pressure, 600 pounds per square inch absolute; rocket engine thrust, 1000 pounds.

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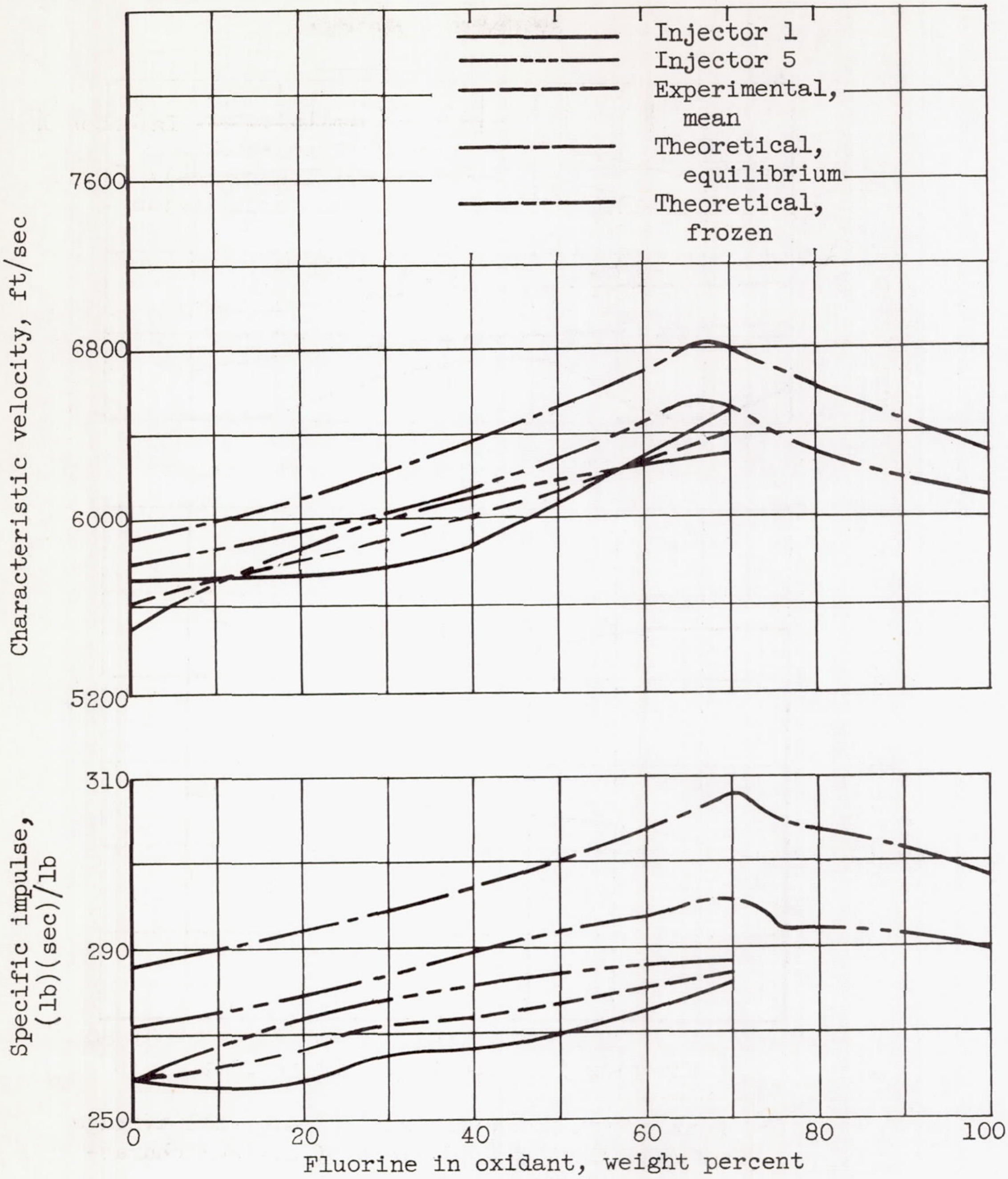

(a) Maximum experimental and theoretical characteristic velocity and specific impulse.

Figure 10. - Performance of fluorine-oxygen - JP-4 combinations as functions of fluorine content in oxidant. Combustion pressure, 600 pounds per square inch absolute; rocket engine thrust, 1000 pounds.

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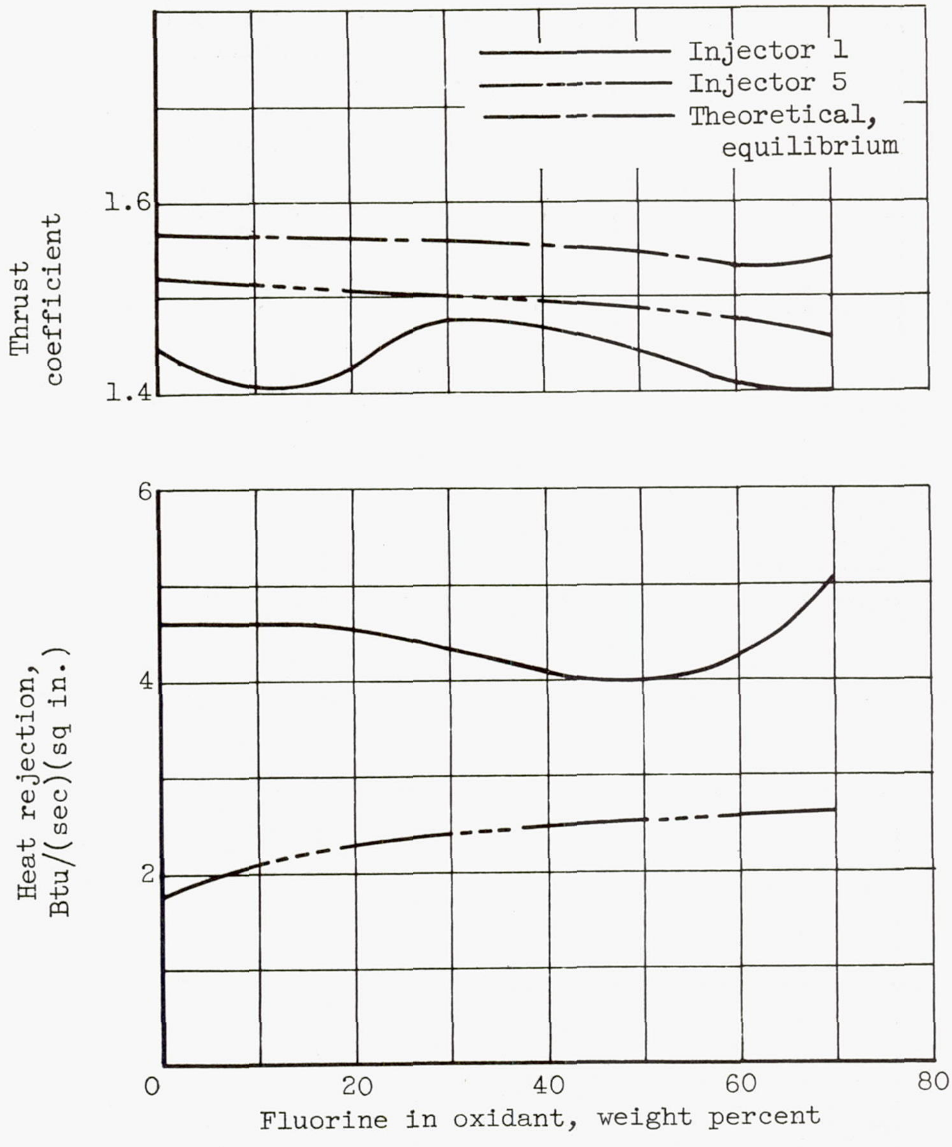

(b) Nozzle thrust coefficient and over-all average heat rejection at conditions of maximum characteristic velocity.

Figure 10. - Concluded. Performance of fluorine-oxygen - JP-4 combinations as functions of fluorine content in oxidant. Combustion pressure, 600 pounds per square inch absolute; rocket engine thrust, 1000 pounds.

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