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REMOVED FROM CATEGORY 7
AUTHORITY- MEMO FROM
DROBKA TO LEBOW DATED 6/9/66

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) #2.00

Microfiche (MF) .50

ff 653 July 65

TECHNICAL MEMORANDUM

X-485

INVESTIGATION OF INJECTORS FOR A LOW-CHAMBER-PRESSURE HYDROGEN-FLUORINE ROCKET ENGINE

By Harold G. Price, Jr., Robert J. Lubick,
and Arthur M. Shinn, Jr.

Lewis Research Center
Cleveland, Ohio

~~CATEGORY~~ [redacted]

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

~~AUTHORITY~~
~~Ltr NASA, Dtd 12 Nov 62, Subj. Aut.~~
~~Time Phased Downgrading & Declass.~~
~~System. Signed A. G. Maines Code BEC~~

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

[redacted]

N66 33333 (ACCESSION NUMBER)

(THRU)

30 (PAGES)

(CODE)

TMX - 455 (NASA CR OR TMX OR AD NUMBER)

28 (CATEGORY)

FACILITY FORM 602

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON [redacted] July 1962

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[redacted]

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INVESTIGATION OF INJECTORS FOR A LOW-CHAMBER-PRESSURE HYDROGEN-FLUORINE ROCKET ENGINE*

By Harold G. Price, Jr., Robert J. Lubick,
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SUMMARY

An investigation of several low-pressure-drop coaxial and showerhead injectors was conducted with gaseous hydrogen and liquid fluorine. Performance data were obtained at chamber pressures from 20 to 60 pounds per square inch absolute (nominally 333 to 1000 pounds thrust). Over a range of propellant mixture ratios, the characteristic velocity efficiency of the best injector, a coaxial type, was from 95 to 99 percent of theoretical values based on equilibrium conditions. High performance efficiency was more difficult to attain at the lower fuel-by-weight percentages and at the lower chamber pressures. Changing the number of injection elements, the chamber length, or the degree of propellant mixing affected performance. The results indicated that at least five coaxial injection elements per square inch of face area were necessary to assure high performance.

Some low-frequency combustion instabilities were observed with both types of injectors, but these were associated with the propellant flow system.

INTRODUCTION

Many of the propulsion requirements for deep-space vehicles can best be met by advanced chemical rockets utilizing high-energy propellants in simple and reliable systems. Hydrogen-fluorine is a promising propellant combination for this application. In addition to very high performance capability, the hydrogen-fluorine combination is hypergolic, assuring reliable restarts for the more complex space maneuvers. Considering these factors and others, hydrogen-fluorine seems well suited to a highly reliable, pressure-fed system, avoiding the complexity of pumps.

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*Title, Unclassified.

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Previous investigations have attested to the high performance efficiencies of hydrogen-fluorine (refs. 1 to 4) even with short thrust chambers and simple injectors. The present study represents an extension of these investigations to the very low combustion pressures of interest for pressure-fed systems. Further, it was intended to define limits to which hydrogen-fluorine injectors could be simplified without performance penalty.

The injectors included various coaxial and showerhead types, designed for low propellant pressure drops. The coaxial or concentric orifice type was of greater interest because it inherently promotes uniformity of the oxidant-fuel mixture, while permitting design freedom in the placement of the coaxial elements. The number of elements (or pattern fineness) was varied, and details within the coaxial element geometry were altered to determine their effects on performance.

The data presented herein were obtained with gaseous hydrogen and liquid fluorine in heavy-wall, uncooled engines that exhausted to atmospheric pressure. Combustion pressures from 20 to 60 pounds per square inch absolute and propellant proportions from 6 to 12 percent-by-weight hydrogen were investigated.

APPARATUS AND PROCEDURE

Test Facility

The major components of the test facility are shown in figure 1. This is the same facility described in reference 2 with the exception that in the present investigation a gaseous, rather than liquid, hydrogen system and simple, heat-sink-type thrust chambers, instead of regeneratively cooled ones, were used.

Propellants were supplied to the thrust chamber by the system shown in figure 2. The fluorine system has been described in reference 2. The gaseous hydrogen was supplied from a high-pressure trailer, and its pressure was reduced to between 400 and 1500 pounds per square inch absolute, depending upon the running conditions required. The flow line from the trailer to the engine contained a surge tank, shutoff valve, an orifice meter, and a fuel control valve.

Instrumentation and Controls

The relative positions of all instrumentation are shown in figure 2. The static-pressure transducers were accurate to 0.25 percent at full scale; the differential pressure transducers were accurate to 1.00 percent at full scale. Temperatures were measured with copper-constantan thermocouples. This is essentially the same type of instrumentation described in reference 2 [redacted]

Figure 3 is a schematic diagram of the control system used to set the propellant flow rates. A precalculated hydrogen flow rate was set into the controller to provide the proper chamber pressure. The flow measured by the hydrogen orifice was compared with the set value, and the difference, or error, was used to adjust the hydrogen throttle valve. The desired percent fuel was also set into the controller, which measured the flow rate of the fluorine and hydrogen and adjusted the fluroine control valve to provide the proper propellant proportions.

Data were obtained at two values of percent fuel during each firing of the engine by switching the controller at timed intervals. Reference 5 gives a more detailed description of the controller.

Thrust Chamber and Injectors

A detailed drawing and a photograph of the heat-sink thrust chamber and nozzle are shown in figure 4 with a table of chamber lengths and characteristic lengths. The chamber was designed for a nominal thrust of 1000 pounds at a chamber pressure of 60 pounds per square inch absolute.

Combustion data obtained in a sea-level facility are normally limited to a minimum chamber pressure of about 30 pounds per square inch absolute. To further extend the chamber pressure operating range of this investigation, a shallow-angle (5°) nozzle diffuser was attached to the thrust chamber, which permitted choked operation of the engine down to a chamber pressure of approximately 20 pounds per square inch absolute.

Three injectors were used to investigate the effect of "fineness" of the injector pattern on performance. These injectors incorporated different numbers (121, 61, or 31) of basic coaxial injection elements (figs. 5(a), (b), and (c)). The coaxial injectors were so constructed that the fluorine flowed through tubes; the exit of each tube was surrounded by an annular hydrogen port. The fluorine tubes were very carefully positioned at the centers of the hydrogen annuli. Each hydrogen annulus was tapered 10° so that it converged upon the fluorine jet. The pattern of the elements was chosen to provide, insofar as possible, a constant flow per unit area across the injector face.

The injection elements shown in figures 5(d) and (e) represent modifications to the basic pattern. The design of figure 5(d) was intended to provide parallel jets rather than converging the hydrogen onto the fluorine. Figure 5(e) is an element used with a thin, dished face intended to be more nearly representative of lightweight injector design. The impingement point was 20 inches away from the injector face. These two designs (figs. 5(d) and (e)) were incorporated into 121-element injectors.

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Swirlers, 1/4 inch in length, were installed in the oxidant tubes of a 31-element injector, as shown in figure 5(f). The objectives of the swirlers were to promote oxidant dispersion, to improve hydrogen and fluorine mixing, and to reduce fluorine droplet size. Photographs showing the improvement of dispersion with water are shown in figure 6. The spray angle was estimated to be 44°.

The showerhead injector design investigated is shown in figure 7. This design utilized 277 fluorine and 664 hydrogen orifices as compared with a maximum of 121 fluorine holes and 121 hydrogen annuli in the coaxial types. The face of the showerhead design was dished so that the jets would impinge 20 inches from the face of the injector. Two showerhead injectors were tested; they differed only in the size of the fluorine orifices, as indicated in figure 7.

Procedure

The preparation, firing sequence, and shutdown procedures have been described in reference 2. Total firing time for each run was limited to 13 seconds to prevent the destruction of the heat-sink engine.

The range of test conditions investigated with each injector and thrust chamber combination is summarized as follows:

Injector and thrust-chamber combination		Injector pressure drop		Chamber pressure, lb/sq in. abs	Hydrogen, percent by weight
Injector type	Thrust-chamber length, in. (injector to throat)	Hydrogen, lb/sq in.	Fluorine, lb/sq in.		
121 Converging element coaxial	6	3 to 20	5 to 20	20 to 60	6 to 12
121 Thin face coaxial		3 to 13	2 to 15		
121 Parallel element coaxial		2 to 12	7 to 19		
61 Converging element coaxial		7 to 40	5 to 18		
31 Converging element coaxial		6 to 35	13 to 44		
31 Converging element coaxial (with swirlers)		5 to 32	14 to 41		
31 Converging element coaxial	12	6 to 15	9 to 17	25	
Showerhead	6	2 to 17	7 to 25	20 to 60	
Showerhead	12	7 to 18	13 to 17	60	

[redacted]

Since chamber pressure was measured at the injector face, a momentum pressure loss was calculated to obtain the total pressure at the nozzle entrance. This value was then used in the calculation of experimental characteristic velocity. The method used to calculate the momentum loss may be found in appendix B of reference 1.

RESULTS AND DISCUSSION

Experimental results are listed in table I. Injectors of both the coaxial and showerhead types gave very high performance efficiency at the low combustion pressures studied. Characteristic velocity values obtained fell between 95 and 99 percent of the corresponding theoretical data.

In figure 8, data obtained with the coaxial and showerhead injectors at 25 and 60 pounds per square inch absolute are compared with previous showerhead data (ref. 1) at combustion pressures above 200 pounds per square inch absolute. The showerhead injector used in the present investigation had a much finer pattern (over twice as many propellant orifices) than the showerhead previously used at higher combustion pressure. The coaxial injector had the same fineness of pattern as the earlier showerhead, if the number of fluorine orifices (121) is taken as the criterion.

Inasmuch as these three injectors, as well as a triplet type reported in references 1 and 2, gave essentially equivalent performance, always very near that theoretically possible, it would appear that further search for performance improvement by injector modification would yield meager returns. On the other hand, if injectors could be simplified without performance deterioration, some gain might be realized through weight savings and fabrication ease. Consequently, much of the work presently reported herein is aimed toward such simplification. Coaxial injectors were favored in these studies because they offer greater freedom in placement of injection elements without disrupting the local established oxidant-fuel ratio.

In many of the tests with both injector types, chamber pressure oscillations were observed. The frequencies of these oscillations were between 100 and 400 cycles per second. Since instability in this frequency range is commonly associated with the "chugging" phenomenon, it was presumed that the oscillations involved coupling between the fluids in the combustion chamber and in the propellant systems. Subsequent modification of the fluorine flow system, to reduce its volume by about two-thirds, alleviated the oscillations. The instability, when it occurred, apparently did not degrade the performance of the coaxial injectors, although anomalous behavior was experienced with showerhead injectors.

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Coaxial Injectors

Effect of number of injection elements. - As one step toward injector simplification, the number of coaxial injection elements was reduced from 121 to 61 and then 31. Characteristic velocity data are shown in figure 9(a) for a combustion pressure of 60 pounds per square inch absolute and in figure 9(b) for 25 pounds per square inch absolute, as functions of weight-percent-fuel. In figure 9(c) the data are presented as a function of combustion pressure at a fixed 8-percent fuel, chosen as a rather arbitrary compromise among considerations of performance with nozzles of high area ratio, propellant bulk density, thrust-chamber cooling, and propulsion system weights for spacecraft. The injectors used are described by figures 5(a), (b), and (c).

The 121-element coaxial injector consistently gave the highest performance. Decreasing the number of elements decreased performance, particularly at the lower combustion pressures and lower percentage fuel. The data indicate that a pattern density of at least five elements per square inch (corresponding to the 121-element injector) is required to maintain high performance.

Effect of increased mixing of propellants. - In an attempt to maintain high performance efficiency with reduced injection element density, swirler inserts were added to the fluorine delivery tubes in the 31-element coaxial injector (fig. 5(f)). The swirlers caused the fluorine streams to diverge into the annular hydrogen streams to provide better mixing. The effect is indicated by the water-spray photographs of figure 6. As shown in figure 10, the swirlers improved the performance of the 31-element injector to nearly the same level as the 61-element, but the 31-element remained inferior to that of the 121-element coaxial injector.

To ascertain the effect of converging the annular fuel streams into the straight fluorine jets, injection elements were modified as shown in figure 5(d) (as compared with fig. 5(a)). Injectors with these designs then allowed comparative tests with converging and with axial fuel flow. The convergence of hydrogen into the fluorine accounted for about a 5-percent performance increase at 25 pounds per square inch absolute, as shown in figure 11. At a combustion pressure of 60 pounds per square inch absolute, however, there was no significant difference between the two injectors. A third injector (fig. 5(e)), having a thin face representative of lightweight designs, provided a performance level between that of the other two injectors at the lower combustion pressures. This injector probably did not provide as good directivity to the hydrogen flow because of the shorter path of straight flow. Therefore, propellant mixing was less complete than with the converging element injector of figure 5(d). At a 60-pound-square-inch-absolute chamber pressure, however, where injector design seems to be less critical, the thin-face injector appeared to exceed the other two.

Effect of chamber length. - The performance of relatively poor injectors generally increases with an increase in combustion-chamber length, which provides additional time for propellant mixing and combustion. The thrust chambers used for most of the present work were deliberately made very short (6 in. in length from injector to throat) to aid in separating good injectors from poor ones. The effect of increasing chamber length on the performance of the lowest performance injector (31 element) is shown in figure 12. Doubling the chamber length (from 6 to 12 in.) increased performance by 10 percent at the lower percent fuels and low combustion pressure. It may be noted that a chamber length of 12 inches is not unreasonable for engines of a practical thrust level.

The results of these studies indicate that, to maintain high performance, a coaxial injector with a density of about five elements per square inch should be used. If, however, because of fabrication difficulties or some other reason the use of fewer elements is desirable, performance loss can be lessened by adding swirler inserts in the fluorine elements, by directing hydrogen into the fluorine through converging annuli, and by increasing combustion-chamber length.

Showerhead Injectors

Two showerhead injectors having different sized fluorine orifices, and hence different fluorine injection velocities, were tested. The injector with the smaller fluorine holes (thus higher pressure drop and higher injection velocity) gave the lower performance, as shown by figure 13. Even when used with a longer, 12-inch thrust chamber, the efficiency with this injector was less than that with the one providing lower injection velocities. It would seem then that minimum oxidant injector pressure drops consistent with combustion stability would be desirable for maximum performance efficiency.

With each of the three thrust-chamber and injection combinations tested, chamber pressure oscillations were noted over the entire range of percent fuel. The peak-to-peak amplitudes of these oscillations were about ±5 percent of the average chamber pressure. As indicated by figure 13(a), a discontinuous behavior was observed, consisting of two distinct regions having different oscillation frequencies with correspondingly different performance levels. In the range where chamber pressure oscillations of 250 and 350 cycles per second were observed, decreasing the percent fuel from 12 percent resulted in a rather marked continuous decrease in combustion efficiency for all three configurations (open symbols, fig. 13(a)). At some value of percent fuel, dependent on the configuration, a further reduction in percent fuel resulted in an abrupt increase in combustion efficiency (solid symbols) accompanied by chamber pressure oscillations having frequencies approximately one-half those observed at the higher percent fuels.

In the presence of low pressure drops, such as those in these experiments, variations in orifice flow and spray characteristics have been observed. It was thought that a variation in flow characteristics might account for the discontinuities observed for the showerhead data; however, no discontinuities were apparent in either the hydrogen or fluorine orifice discharge coefficients for the range covered. However, pressure oscillations were observed in the fluorine system between the injector and the control valve. Analysis of the data available did not reveal the nature or cause of the performance discontinuity encountered.

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Subsequent reduction of the fluorine system volume led to operation at the two levels of chamber pressure with no combustion oscillations over the entire range of percent fuel. It may be noted in figure 13(b) that for both chamber pressures, the performance did not deteriorate as rapidly with decreasing percent fuel, nor were there discontinuities when the chamber pressure oscillations were absent.

SUMMARY OF RESULTS

The following results were obtained from an investigation of several low-pressure-drop injectors for gaseous-hydrogen - liquid-fluorine rocket chambers operating at a chamber pressure of 20 to 60 pounds per square inch absolute and 6 to 12 percent hydrogen:

1. Of several coaxial injectors tested, one having five injection elements per square inch of face area gave the highest performance. Characteristic velocity varied from 95 to 99 percent of the theoretical, with the lower performance being obtained at the lower percent fuels and chamber pressures. Reducing the number of elements in the coaxial injectors reduced performance. Low-frequency combustion oscillations were noted.

2. Increased mixing of the propellants, either by diverging the central fluorine streams or by converging the annular hydrogen streams, improved the performance of coaxial element injectors.

3. A showerhead injector gave just as high performance as the 121-element coaxial injector, but was erratic. Low-frequency combustion oscillations were associated with discontinuities in performance. These oscillations are believed to be associated with system flow characteristics.

4. Doubling the length of the thrust chamber improved the performance of the poorer coaxial and showerhead injectors.

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TABLE I. - INJECTOR CHARACTERISTICS AND PERFORMANCE WITH GASEOUS HYDROGEN AND LIQUID FLUORINE

Injector type	Thrust-chamber length, in.	Injector pressure drop		Chamber pressure at injector face, lb/sq in. abs	Chamber pressure corrected to nozzle entrance, lb/sq in. abs	Propellant proportions		Total flow rate, lb/sec	Nozzle throat area, sq in.	Characteristic velocity, experimental, ft/sec	Characteristic velocity, theoretical[a], ft/sec	Characteristic velocity, efficiency, percent
		Hydrogen, lb/sq in.	Fluorine, lb/sq in.			Percent hydrogen	Oxidant/fuel					
121 Converging element coaxial	6	5.2	9.4	62.5	59.5	6.04	15.6	2.998	11.85	7571	7693	97.1
		5.3	20.0	61.0	58.1	6.13	15.3	3.067	11.79	7183	7697	93.3
		8.2	19.0	60.1	57.4	7.73	11.9	2.898	11.75	7483	7856	95.3
		8.9	10.2	62.9	60.1	8.06	11.4	2.915	11.83	7845	7885	99.5
		11.9	13.9	62.2	59.6	9.88	9.11	2.863	11.71	7839	8004	97.9
		13.9	12.1	64.2	61.5	9.98	9.02	2.925	11.82	7997	8020	99.7
		20.0	14.4	65.8	63.2	11.90	7.40	2.975	11.81	8077	8140	99.2
		16.3	14.7	62.5	60.1	12.02	7.32	2.803	11.67	8052	8138	98.9
		7.7	7.6	52.5	50.1	8.14	11.3	2.456	11.89	7807	7875	99.1
		6.7	13.5	50.9	48.5	8.06	11.4	2.432	11.91	7643	7865	97.2
		7.3	17.9	48.8	46.5	8.02	11.5	2.457	11.99	7298	7857	92.9
		7.3	15.9	48.8	46.6	8.23	11.2	2.381	11.83	7444	7872	94.6
		6.2	4.9	41.4	39.5	8.13	11.3	1.930	11.92	7851	7848	100.0
		6.1	9.2	39.2	37.4	8.28	11.1	1.909	11.87	7476	7851	95.2
		4.2	7.2	26.0	24.8	8.56	10.7	1.227	11.74	7633	7820	97.6
		6.0	7.3	26.0	25.0	11.03	8.07	1.179	11.72	7988	7986	100.0
		2.8	7.8	25.9	24.6	6.55	14.3	1.297	11.82	7218	7650	94.4
		3.6	7.6	20.5	19.6	8.78	10.4	.979	11.78	7595	7813	97.2
121 Element thin face coaxial	6	4.8	14.4	62.1	59.1	6.43	14.6	3.039	12.00	7510	7742	97.0
		6.9	14.6	64.4	61.4	8.10	11.3	2.995	11.97	7902	7900	100.0
		9.9	12.8	64.7	61.9	10.15	8.85	2.915	11.94	8157	8030	101.6
		13.4	14.1	64.4	61.8	12.00	7.34	2.854	11.92	8304	8142	102.0
		6.0	12.8	53.2	50.7	8.10	11.4	2.536	12.04	7740	7878	98.2
		5.9	12.5	52.7	50.2	7.98	11.5	2.543	12.09	7680	7867	97.6
		5.1	9.7	41.7	39.8	8.22	11.2	2.036	12.06	7576	7860	96.4
		5.1	9.6	41.4	39.4	8.06	11.4	2.053	12.14	7494	7848	95.5
		2.5	1.9	31.5	29.9	6.02	15.6	1.641	12.05	7073	7602	93.0
		2.7	6.6	30.9	29.3	6.12	15.3	1.637	12.23	7050	7612	92.6
		6.0	4.2	30.9	29.6	10.26	8.75	1.473	12.00	7751	7954	97.4
		2.8	5.2	30.5	29.0	6.16	15.2	1.635	12.20	6961	7618	91.4
		4.1	3.9	30.3	28.9	7.96	11.6	1.535	12.03	7283	7797	93.4
		7.5	4.9	30.6	29.4	11.95	7.36	1.444	12.11	7919	8062	98.2
		7.7	4.8	30.5	29.2	12.14	7.24	1.437	12.15	7954	8073	98.5
		5.9	4.9	30.3	29.0	10.03	8.97	1.473	12.12	7662	7937	96.5
		6.0	4.9	30.2	28.8	10.20	8.80	1.467	12.16	7683	7947	96.7
		4.3	5.2	29.8	28.4	8.05	11.4	1.542	12.23	7243	7802	92.8
		4.4	5.5	29.7	28.3	8.13	11.3	1.532	12.19	7243	7807	92.8
		3.6	4.7	25.5	24.3	8.03	11.5	1.299	12.07	7274	7783	93.5
		2.9	3.2	20.5	19.5	8.11	11.3	1.044	12.08	7265	7764	93.6
121 Parallel element coaxial	6	4.1	18.2	61.7	58.7	6.05	15.5	3.142	12.13	7291	7690	94.8
		6.4	19.3	62.2	59.3	7.98	11.5	3.032	12.20	7677	7880	97.4
		9.1	12.6	63.0	60.3	9.99	9.01	2.912	12.07	8040	8020	100.2
		12.7	15.2	62.4	60.0	11.89	7.41	2.868	12.05	8108	8130	99.7
		5.4	15.4	50.4	48.1	8.07	11.4	2.491	12.15	7546	7865	95.9
		4.7	13.4	38.8	37.0	8.16	11.3	2.011	12.17	7195	7842	91.7
		3.8	10.5	30.3	29.0	8.14	11.3	1.509	11.83	7308	7810	93.6
		3.7	9.8	30.0	28.6	8.14	11.3	1.500	12.10	7417	7808	95.0
		2.4	9.6	25.0	23.8	6.26	15.0	1.349	12.00	6808	7609	89.5
		3.5	9.0	24.5	23.4	8.25	11.1	1.259	11.86	7098	7792	91.1
		3.5	8.0	24.2	23.1	8.24	11.1	1.251	12.14	7196	7792	92.4
		4.6	7.3	24.5	23.5	10.25	8.76	1.211	11.93	7441	7929	93.9
		4.6	7.4	24.6	23.5	10.17	8.83	1.210	12.06	7540	7923	95.2
		6.2	7.3	24.9	24.0	12.20	7.20	1.189	11.90	7726	8057	95.9
		6.0	7.3	24.7	23.8	12.14	7.23	1.190	12.04	7737	8053	96.1
		2.8	8.5	20.3	19.4	8.33	11.0	1.011	11.96	7378	7780	94.8
		2.7	7.8	19.9	19.0	8.19	11.2	1.004	12.18	7415	7768	95.5
61 Converging element coaxial	6	14.7	17.9	59.4	56.7	6.33	14.8	3.097	12.15	7150	7727	92.5
		22.3	16.3	61.1	58.5	8.02	11.5	3.017	12.10	7547	7882	95.7
		32.9	13.5	62.3	59.9	9.95	9.05	2.934	12.02	7897	8008	98.6
		39.6	16.4	62.6	60.5	11.72	7.53	2.918	12.00	7999	8122	98.5
		40.0	16.6	59.4	57.5	12.25	7.16	2.840	12.42	8081	8147	99.2
		19.4	11.1	50.2	48.1	8.03	11.5	2.539	12.21	7435	7863	94.6
		16.5	6.9	40.4	38.7	8.18	11.2	2.029	12.25	7507	7849	95.6
		12.7	5.5	30.9	29.6	7.88	11.7	1.511	11.78	7419	7795	95.2
		7.3	4.7	25.5	24.3	6.11	15.3	1.374	11.90	6765	7593	89.1
		7.3	5.7	25.4	24.3	6.12	15.3	1.373	11.86	6740	7594	88.8
		10.8	4.9	25.8	24.7	8.06	11.4	1.291	11.84	7280	7786	93.5
		15.4	5.7	26.1	25.1	10.02	8.98	1.257	11.82	7600	7919	96.0
		19.9	5.0	26.1	25.2	11.79	7.48	1.213	11.80	7893	8042	98.1
		9.3	4.9	20.7	19.8	8.15	11.3	1.055	11.88	7174	7768	92.4

[a]Unpublished NASA data.

[redacted]

TABLE I. - Concluded. INJECTOR CHARACTERISTICS AND PERFORMANCE WITH GASEOUS HYDROGEN AND LIQUID FLUORINE

Injector type	Thrust-chamber length, in.	Injector pressure drop		Chamber pressure at injector face, lb/sq in. abs	Chamber pressure corrected to nozzle entrance, lb/sq in. abs	Propellant proportions		Total flow rate, lb/sec	Nozzle throat area, sq in.	Characteristic velocity, experimental, ft/sec	Characteristic velocity, theoretical[a], ft/sec	Characteristic velocity, efficiency, percent
		Hydrogen, lb/sq in.	Fluorine, lb/sq in.			Percent hydrogen	Oxidant/fuel					
31 Converging element coaxial	6	13.9	43.8	64.4	61.5	6.46	14.5	3.438	12.24	7044	7755	90.8
		14.4	35.1	61.3	58.6	6.94	13.4	3.198	12.14	7159	7797	91.8
		19.6	36.0	65.7	63.0	8.26	11.1	3.222	12.08	7598	7907	96.1
		27.0	35.9	66.3	63.9	10.16	8.84	3.129	12.01	7884	8033	98.1
		35.4	----	66.7	64.6	12.15	7.23	3.077	11.91	8046	8153	98.7
		16.7	----	53.3	51.0	8.21	11.2	2.716	12.34	7451	7880	94.6
		14.0	----	42.0	40.2	8.41	10.9	2.188	12.39	7318	7870	93.0
		10.4	----	31.3	30.0	8.15	11.3	1.619	11.68	6974	7815	89.2
		11.4	----	31.2	30.0	8.36	11.0	1.651	11.68	6825	7828	87.2
		9.4	16.2	25.9	24.8	8.30	11.1	1.381	11.82	6820	7805	87.4
		12.7	12.8	26.5	25.5	10.10	8.93	1.330	11.82	7294	7925	92.0
		15.6	20.6	26.0	25.1	12.00	7.35	1.278	11.68	7390	8049	91.8
		5.9	16.3	20.8	19.8	6.90	13.3	1.169	11.96	6526	7660	85.3
31 Converging element coaxial with swirlers	6	10.5	41.4	59.7	56.9	5.99	15.7	3.222	12.17	6918	7663	90.3
		11.1	34.6	59.5	56.9	6.41	14.6	3.075	12.05	7170	7721	92.9
		15.5	34.2	59.3	56.8	7.94	11.6	2.959	12.18	7525	7873	95.6
		16.0	35.4	61.2	58.6	8.04	11.4	2.986	12.03	7597	7884	96.4
		23.0	29.4	62.5	60.2	9.89	9.11	2.932	11.98	7917	8007	98.9
		31.5	32.3	62.7	60.7	11.86	7.42	2.870	11.95	8127	8132	99.9
		13.9	23.8	50.5	48.4	8.09	11.4	2.498	12.09	7534	7867	95.8
		11.6	16.9	39.7	38.0	8.16	11.3	2.021	12.12	7336	7844	93.5
		4.5	25.1	32.5	31.0	5.99	15.7	1.736	11.95	6872	7603	90.4
		5.0	24.3	31.9	30.4	6.10	15.4	1.721	11.98	6802	7617	89.3
		7.0	39.9	32.4	31.0	7.77	11.9	1.647	11.94	7234	7797	92.8
		7.1	26.5	31.1	29.9	8.10	11.4	1.593	11.97	7230	7809	92.6
		10.0	29.6	32.5	31.3	10.23	8.78	1.525	11.96	7894	7967	99.1
		12.5	27.5	32.6	31.5	11.41	7.76	1.577	11.97	7679	8020	95.7
		12.6	33.0	32.5	31.4	11.85	7.44	1.527	11.95	7913	8030	98.5
		12.9	24.3	31.5	30.4	12.18	7.21	1.494	11.98	7845	8082	97.1
		6.1	22.5	26.2	25.0	8.12	11.3	1.354	11.99	7132	7792	91.5
		6.1	28.3	26.8	25.6	8.15	11.3	1.374	11.92	7155	7798	91.8
		5.4	19.7	20.3	19.4	8.20	11.2	1.096	12.00	6925	7771	89.1
		5.0	22.2	21.8	20.9	9.01	10.1	1.132	11.93	7082	7833	90.4
31 Converging element coaxial	12	5.6	15.0	28.4	27.0	6.13	15.3	1.479	12.00	7058	7607	92.8
		5.5	17.0	26.8	25.5	6.19	15.2	1.404	12.01	7024	7610	92.3
		8.3	11.0	27.0	25.8	8.25	11.1	1.321	11.99	7540	7803	96.6
		12.0	14.0	26.8	25.8	10.15	8.86	1.295	11.99	7688	7930	97.0
		15.2	9.0	26.8	25.9	11.63	7.60	1.273	11.98	7829	8026	97.6
Showerhead a	12	6.2	18.5	62.0	59.1	6.26	14.99	3.197	12.04	7164	7722	92.8
		9.4	14.9	63.2	60.2	7.98	11.53	3.046	12.02	7645	7885	97.0
		11.3	15.0	62.6	59.8	8.16	11.26	3.186	12.03	7263	7892	92.0
		----	----	62.5	59.7	10.22	8.78	2.906	12.01	7932	8025	98.8
		15.2	14.1	62.6	59.9	10.80	8.26	2.918	12.02	7944	8062	98.5
		----	----	62.3	59.6	12.31	7.12	2.859	12.00	8044	8152	99.9
	6	6.4	19.9	64.2	61.1	5.74	16.41	3.535	12.00	6676	7643	87.4
		6.7	----	62.9	59.9	6.08	15.40	3.269	11.93	6994	7700	90.8
		7.6	16.5	61.9	58.9	6.98	13.32	3.113	12.00	7312	7801	93.7
		11.7	17.6	60.7	57.9	7.80	11.81	3.313	11.99	6748	7865	85.8
		11.8	----	63.2	60.4	8.03	11.50	3.325	11.90	6953	7888	88.1
		12.7	17.2	60.7	58.0	8.69	10.52	3.125	11.99	7161	7925	90.4
		14.9	15.0	60.4	57.8	9.92	9.08	2.919	11.98	7638	8002	95.5
		14.9	----	62.5	59.9	9.91	9.09	2.988	11.88	7656	8007	95.6
		17.3	15.2	60.7	58.2	11.70	7.55	2.833	11.98	7931	8112	97.6
		17.4	----	62.6	60.1	11.81	7.47	2.880	11.86	7968	8126	98.1
Showerhead b	6	5.1	7.1	65.4	62.2	6.04	15.57	3.229	11.94	7405	7694	96.2
		6.9	12.4	65.1	61.9	5.97	15.75	3.708	11.92	6411	7683	83.4
		8.4	10.3	64.5	61.5	8.04	11.44	3.139	11.92	7520	7886	95.4
		12.0	9.1	64.5	61.7	10.12	8.88	3.016	11.90	7844	8021	97.8
		15.8	9.4	65.4	62.7	11.99	7.34	2.970	11.90	8094	8136	99.5
Showerhead b F_2 system change	6	2.1	8.0	26.6	25.3	5.58	16.92	1.398	11.91	6932	7505	92.4
		2.3	7.5	26.2	24.9	6.24	15.01	1.318	11.91	7250	7615	95.2
		2.9	9.2	27.1	25.8	7.97	11.55	1.304	11.89	7569	7786	97.2
		4.2	8.2	26.2	25.0	8.58	10.65	1.253	11.89	7639	7825	97.6
		7.1	22.6	27.5	26.5	11.82	7.46	1.305	11.92	7772	8038	96.7
		7.0	24.8	26.8	25.7	11.90	7.41	1.260	11.92	7823	8041	97.3
		7.1	13.5	25.3	24.4	12.03	7.31	1.268	11.92	7363	8048	91.5
		6.6	13.6	27.3	26.3	12.11	7.26	1.263	11.92	7978	8056	99.0
		5.3	9.0	58.4	55.6	6.62	14.10	2.940	12.07	7342	7755	94.7
		7.9	12.0	60.0	57.2	8.25	11.13	2.931	12.02	7551	7895	95.6
		12.3	11.2	61.2	58.6	9.95	9.05	3.003	11.97	7516	8004	93.9
		14.1	14.0	62.4	60.1	12.03	7.31	2.942	11.89	7812	8137	96.0

[a]Unpublished NASA data.

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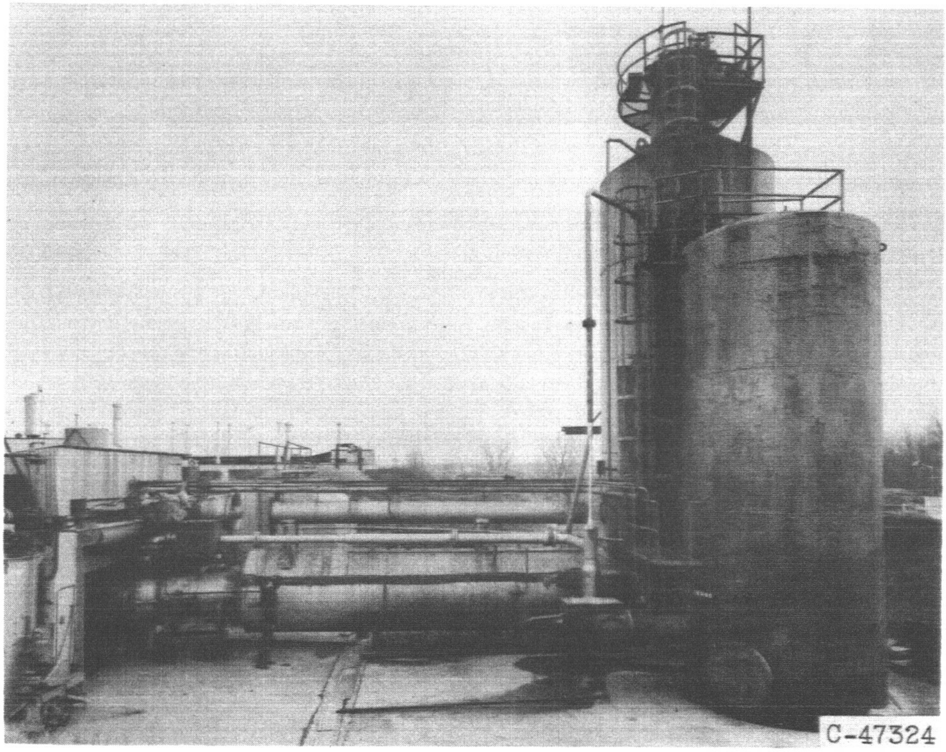

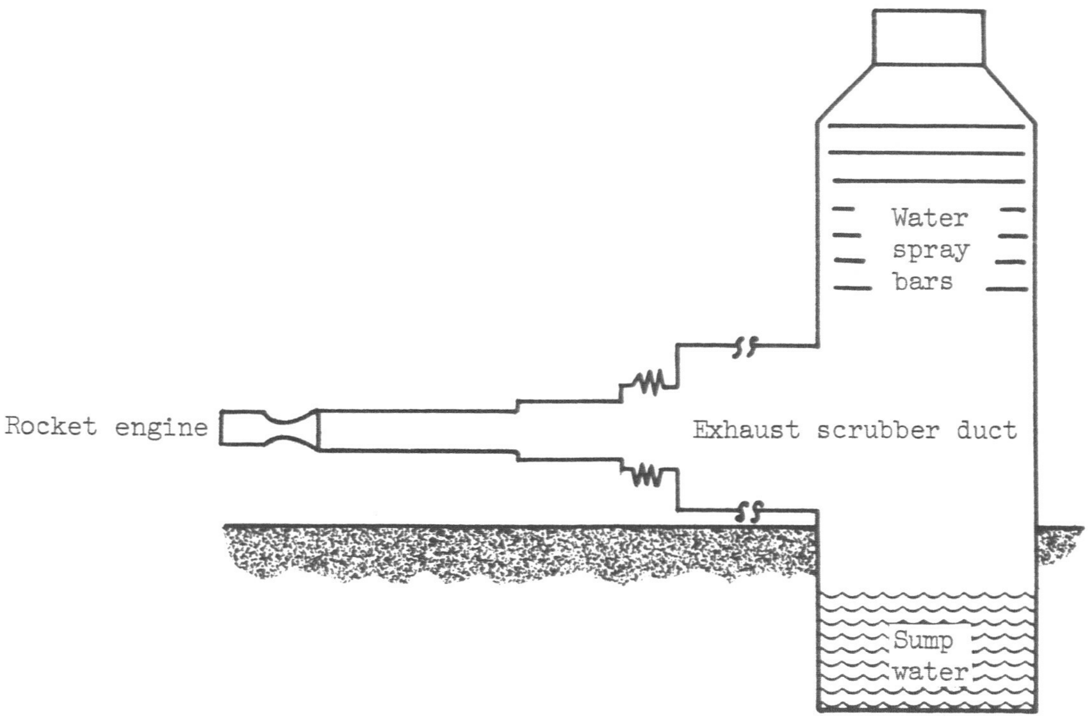

Figure 1. - General arrangement of rocket-engine test facility.

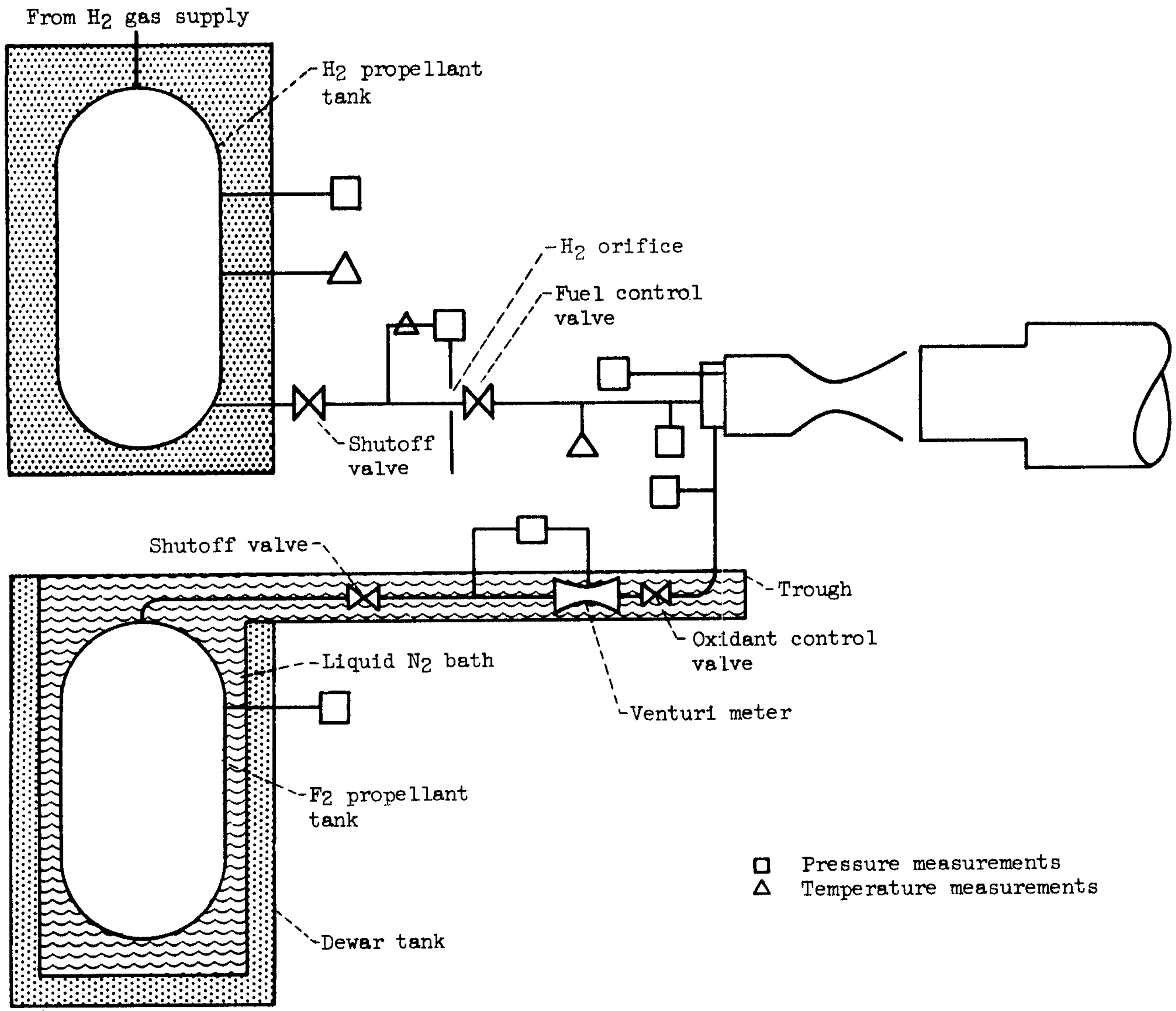

Figure 2. - Engine and propellant system including instrumentation.

[redacted]

[redacted]

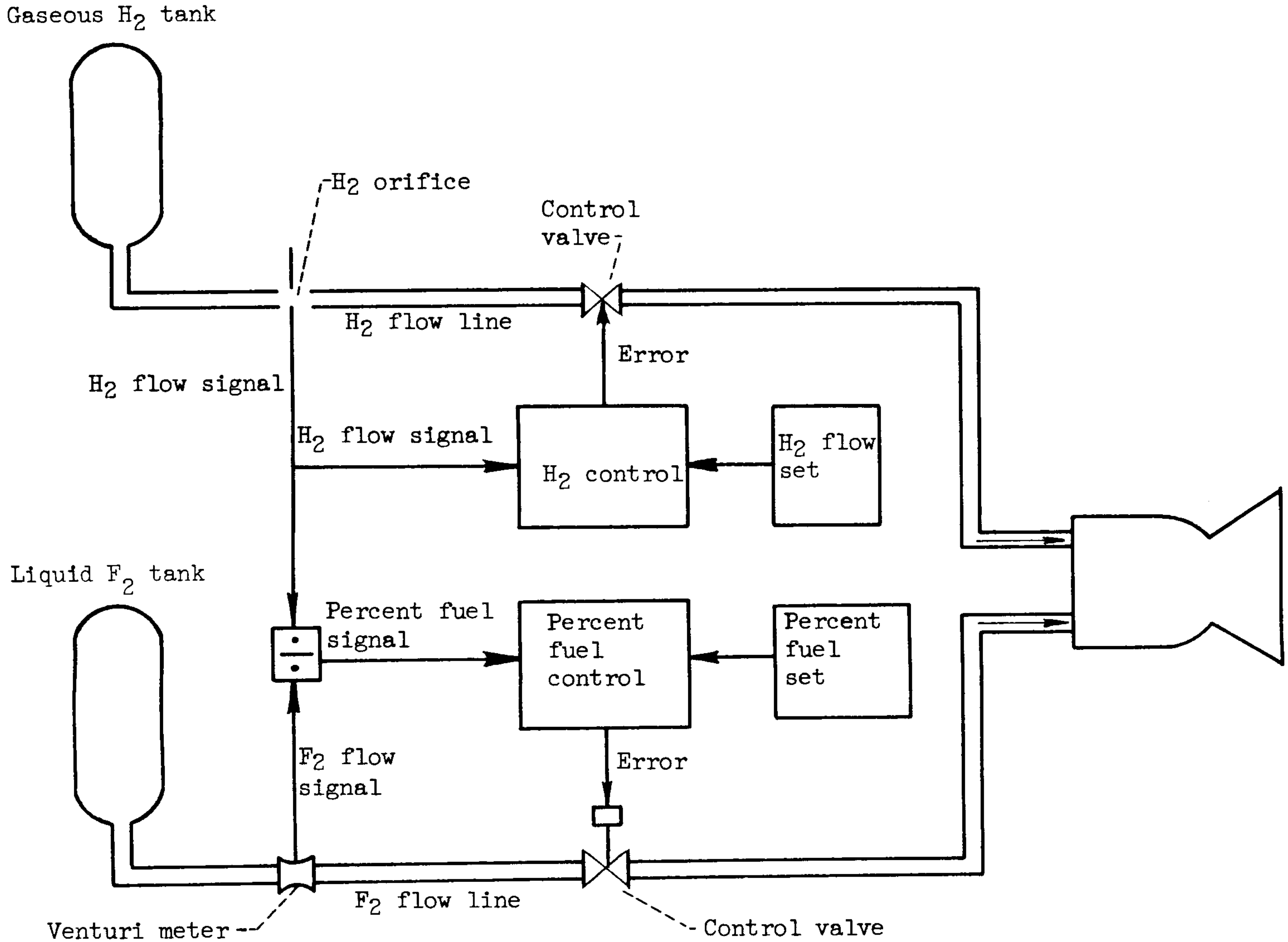

Figure 3. - Control system.

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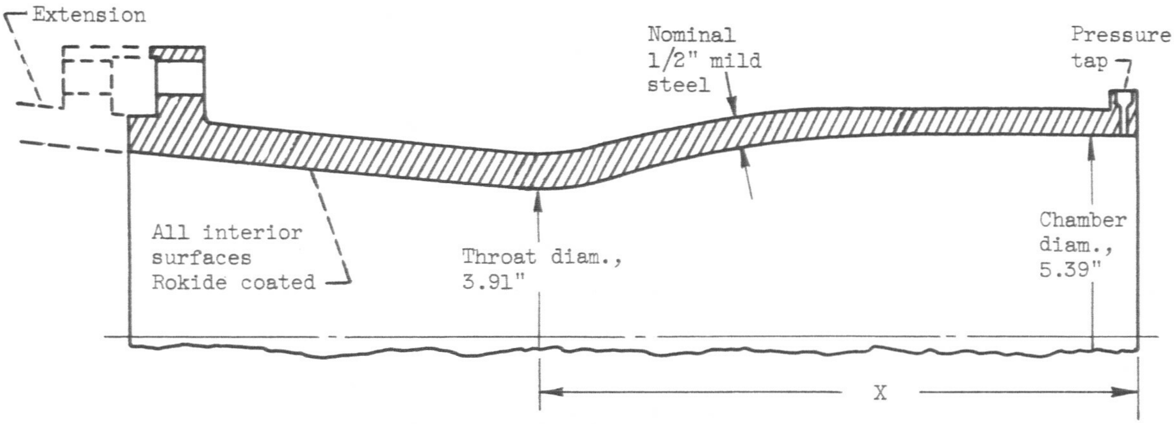

Contraction ratio, 1.90

X	L^*
6	8.8
12	20.2

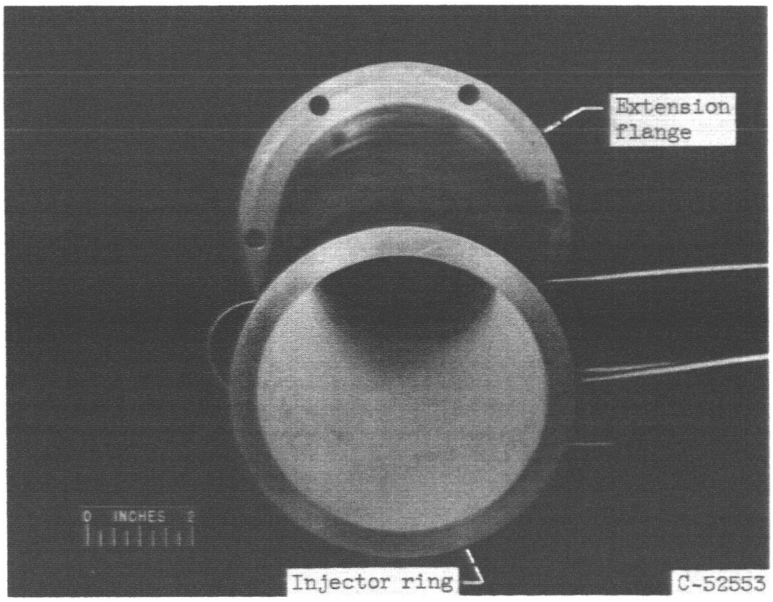

Figure 4. - Heat-sink engine used for combustion studies.

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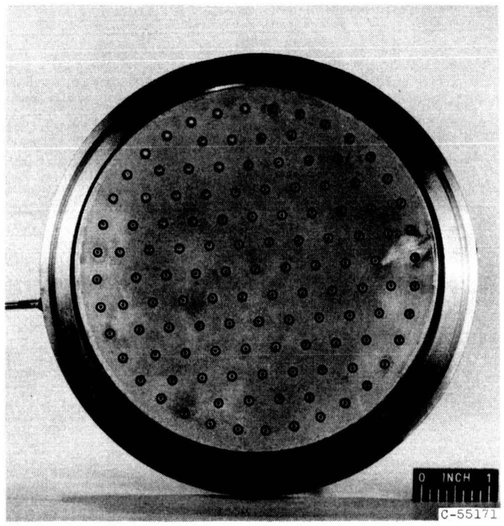
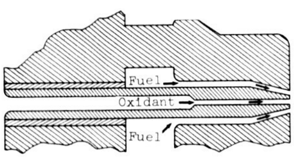
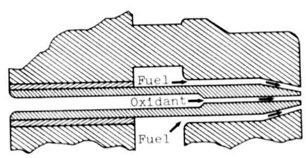




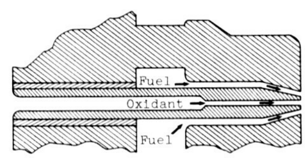
	Oxidant	Fuel	
		O.D.	I.D.
Hole diameter, in.	0.042	0.1405	0.084
Total area, sq in.	.1677	1.205	

(a) 121 Converging element.



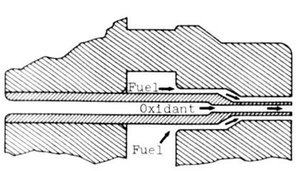
	Oxidant	Fuel	
		O.D.	I.D.
Hole diameter, in.	0.067	0.165	0.110
Total area, sq in.	.215	0.725	

(b) 61 Converging element.



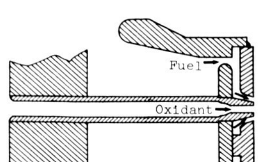
	Oxidant	Fuel	
		O.D.	I.D.
Hole diameter, in.	0.067	0.234	0.152
Total area, sq in.	.1093	0.771	

(c) 31 Converging element.



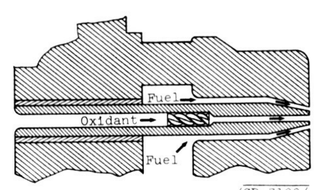
	Oxidant	Fuel	
		O.D.	I.D.
Hole diameter, in.	0.042	0.1405	0.084
Total area, sq in.	.1677	1.205	

(d) 121 Parallel element.



	Oxidant	Fuel	
		O.D.	I.D.
Hole diameter, in.	0.043	0.1405	0.084
Total area, sq in.	.1757	1.205	

(e) 121 Converging element (thin face).



	Oxidant	Fuel	
		O.D.	I.D.
Hole diameter, in.	0.073	0.234	0.152
Total area, sq in.	.1297	0.771	

(f) 31 Converging element with swirler.

Figure 5. - Coaxial injectors.

[redacted]

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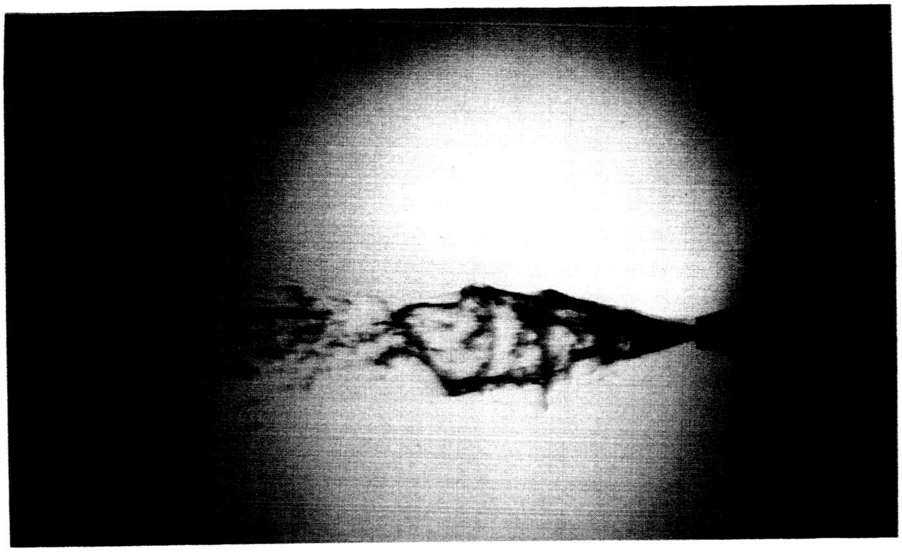
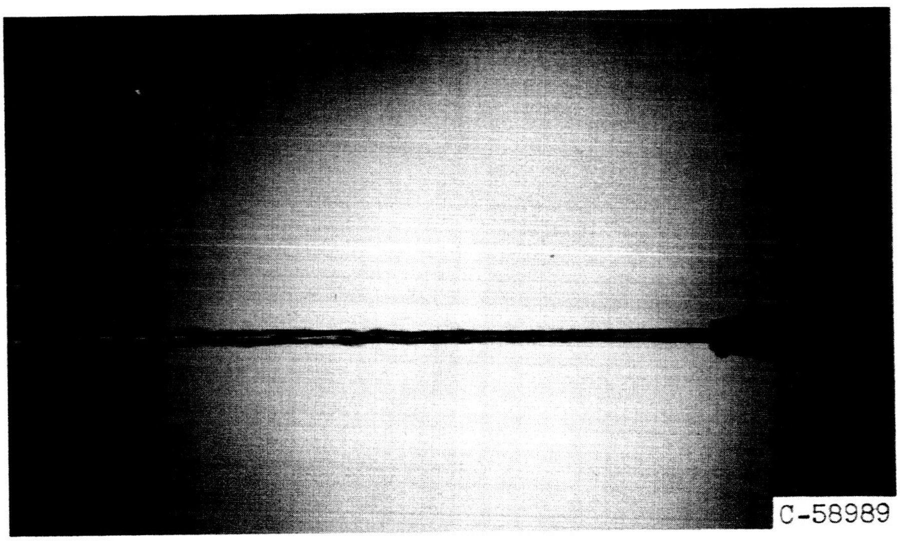


(a) 0.25-Inch length swirler.



(b) No swirler.

Figure 6. - Water flow patterns for a pressure drop of 10 pounds per square inch and a flow rate of 0.045 pound per second.

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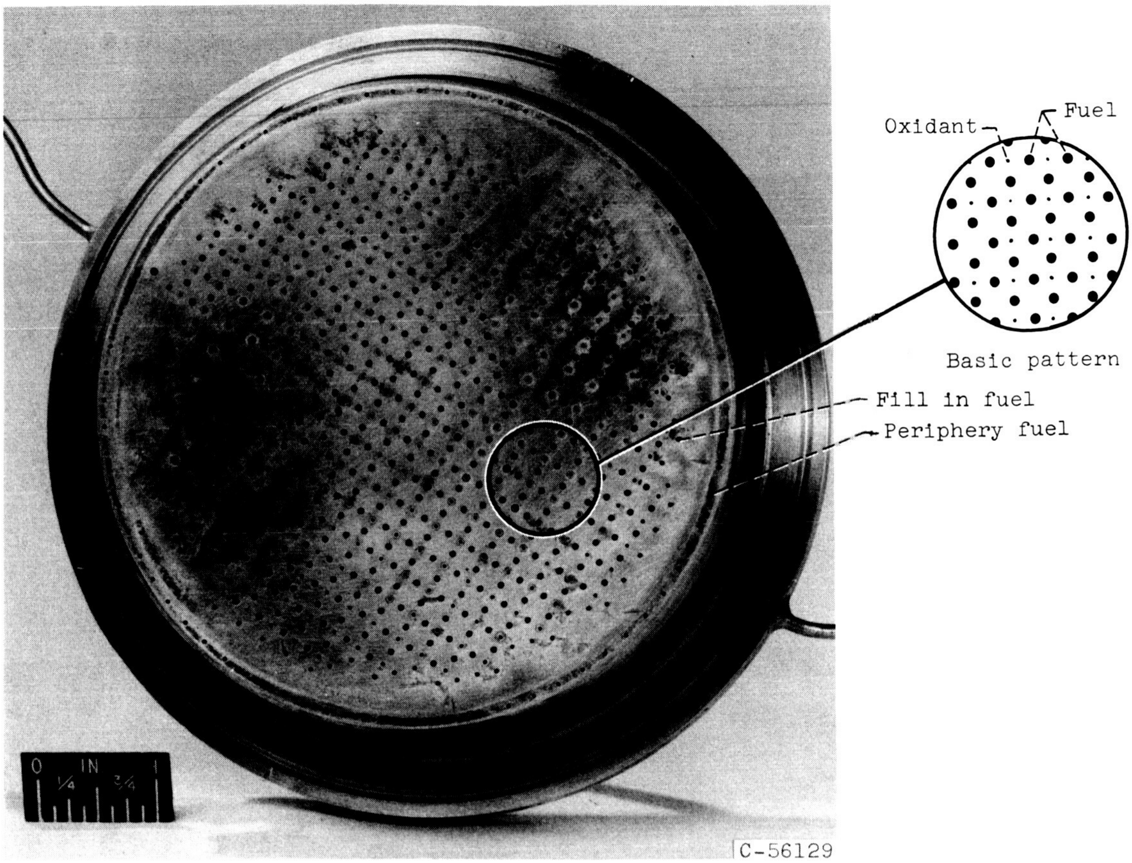

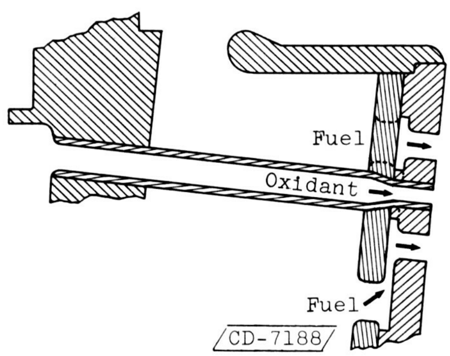

Showerhead, dished face	Oxidant		Fuel, Injectors a and b		
	Injector a	Injector b	Basic pattern	Fill in	Periphery
Number of holes	277	277	516	76	72
Hole diameter, in.	.025	.0313	0.052	0.038	0.030
Total area, sq in.	.136	.212	1.224		

Figure 7. - Showerhead injectors.

[redacted]

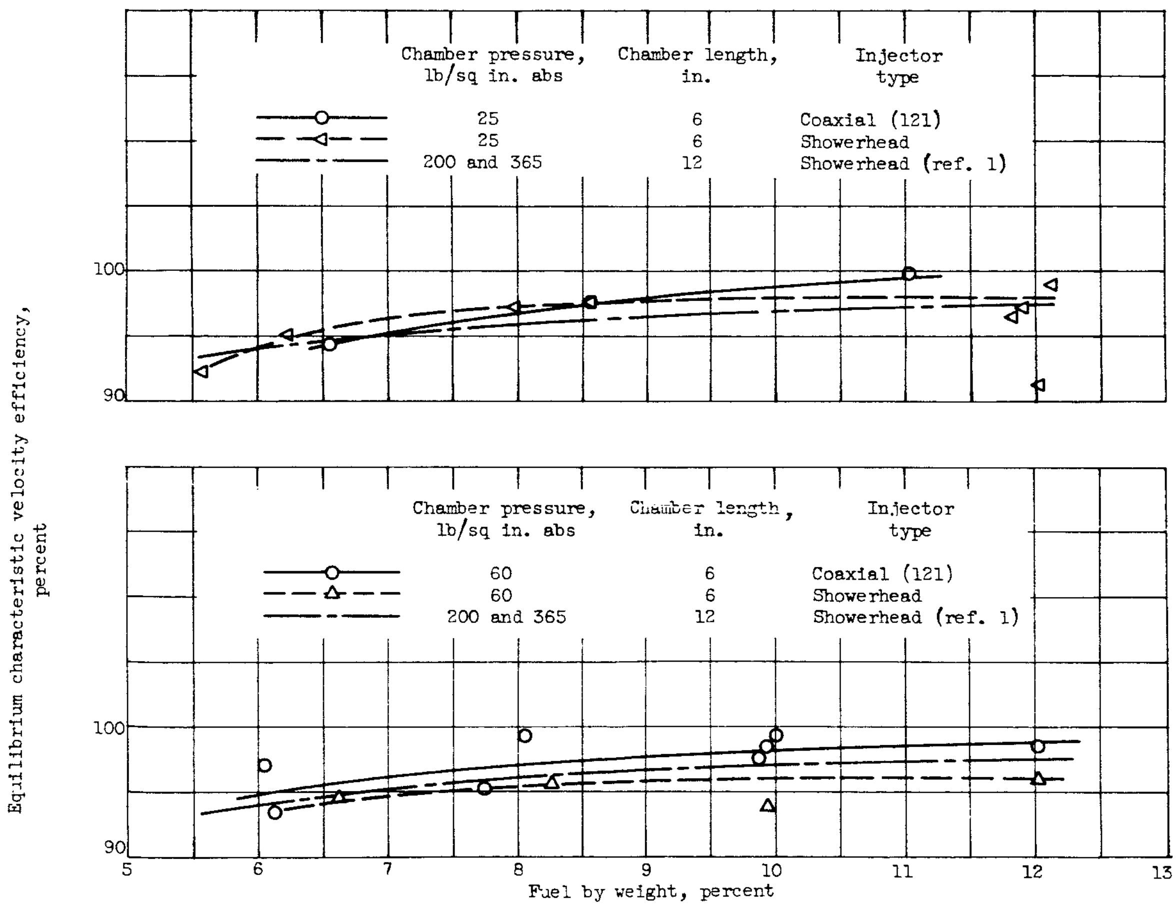

Figure 8. - Comparison of low-chamber-pressure characteristic velocity efficiency with that from reference 1 at higher chamber pressures.

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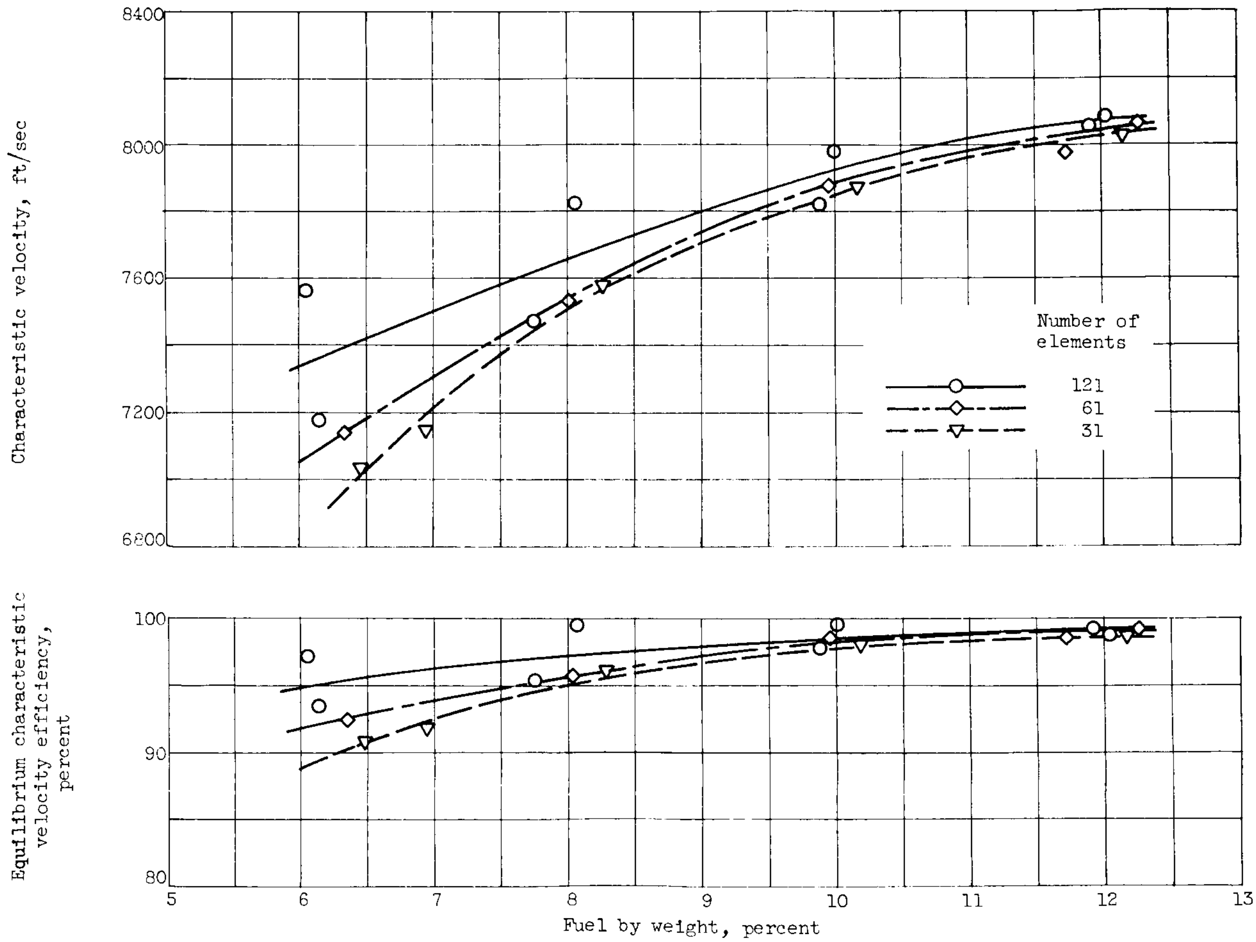
E-1464

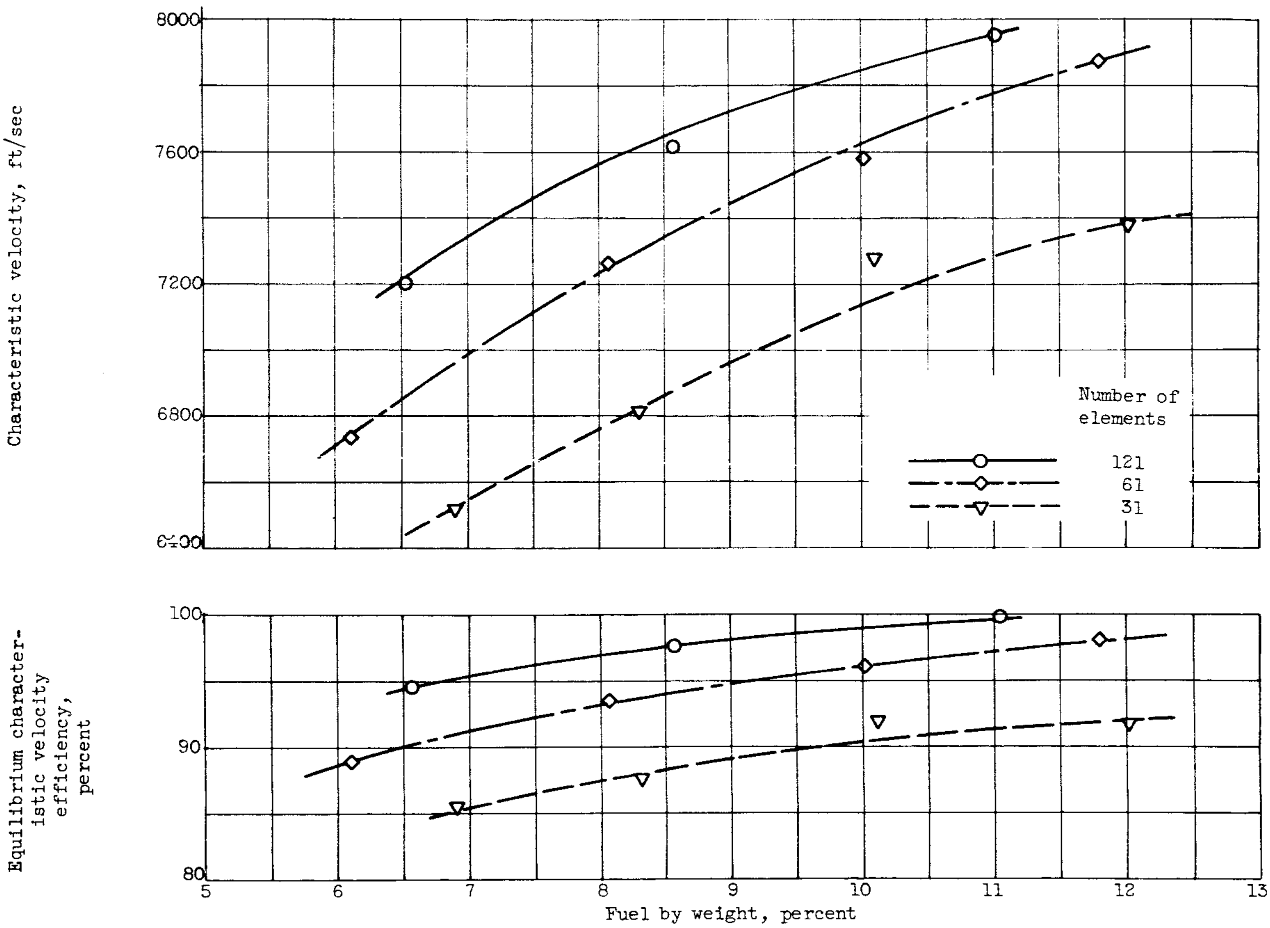


(a) Chamber pressure, 60 pounds per square inch absolute.

Figure 9. - Combustion performance with coaxial injectors.

[redacted]

E-1464

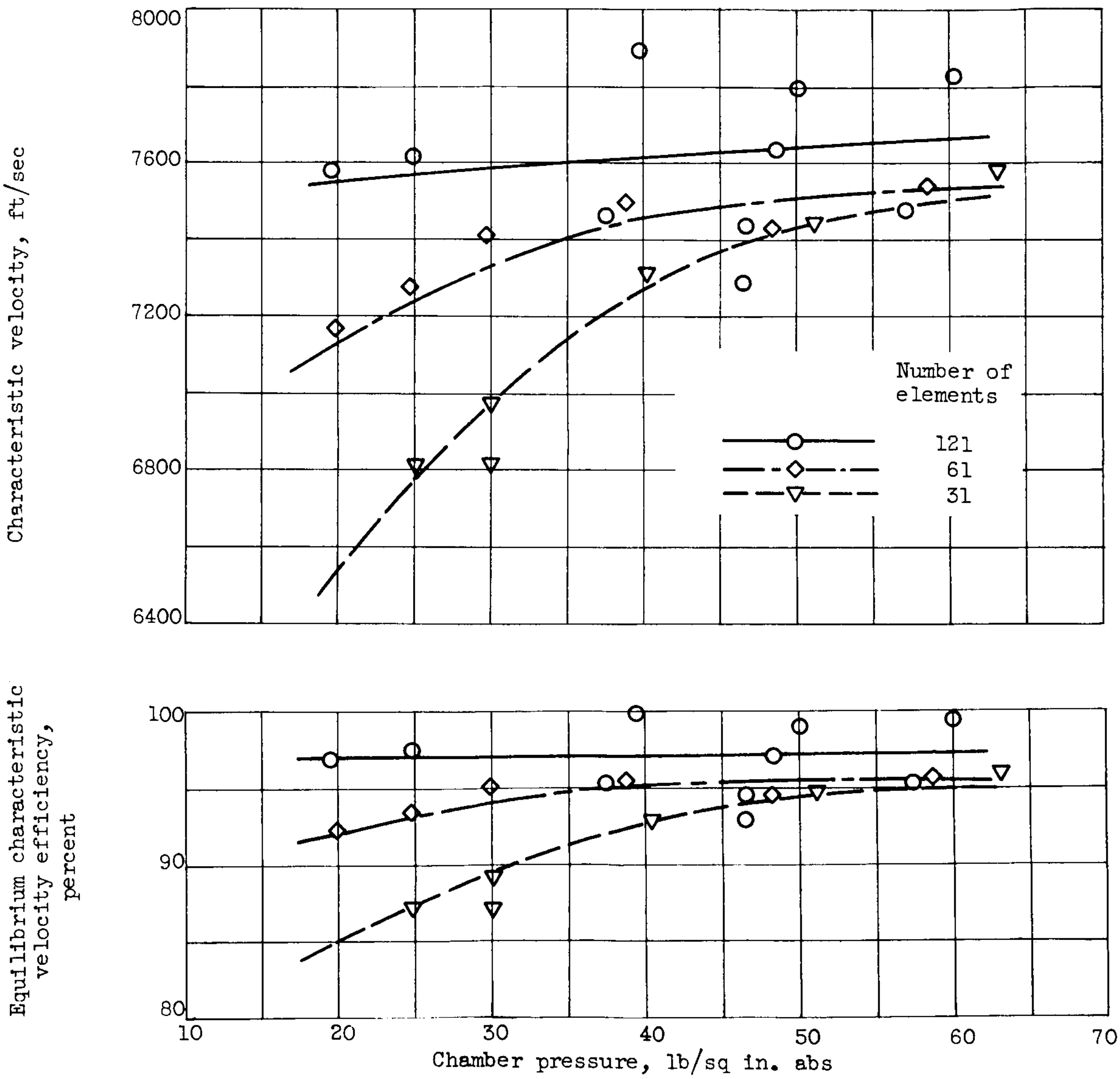


(b) Chamber pressure, 25 pounds per square inch absolute.

Figure 9. - Continued. Combustion performance with coaxial injectors.

[redacted]

E-1464

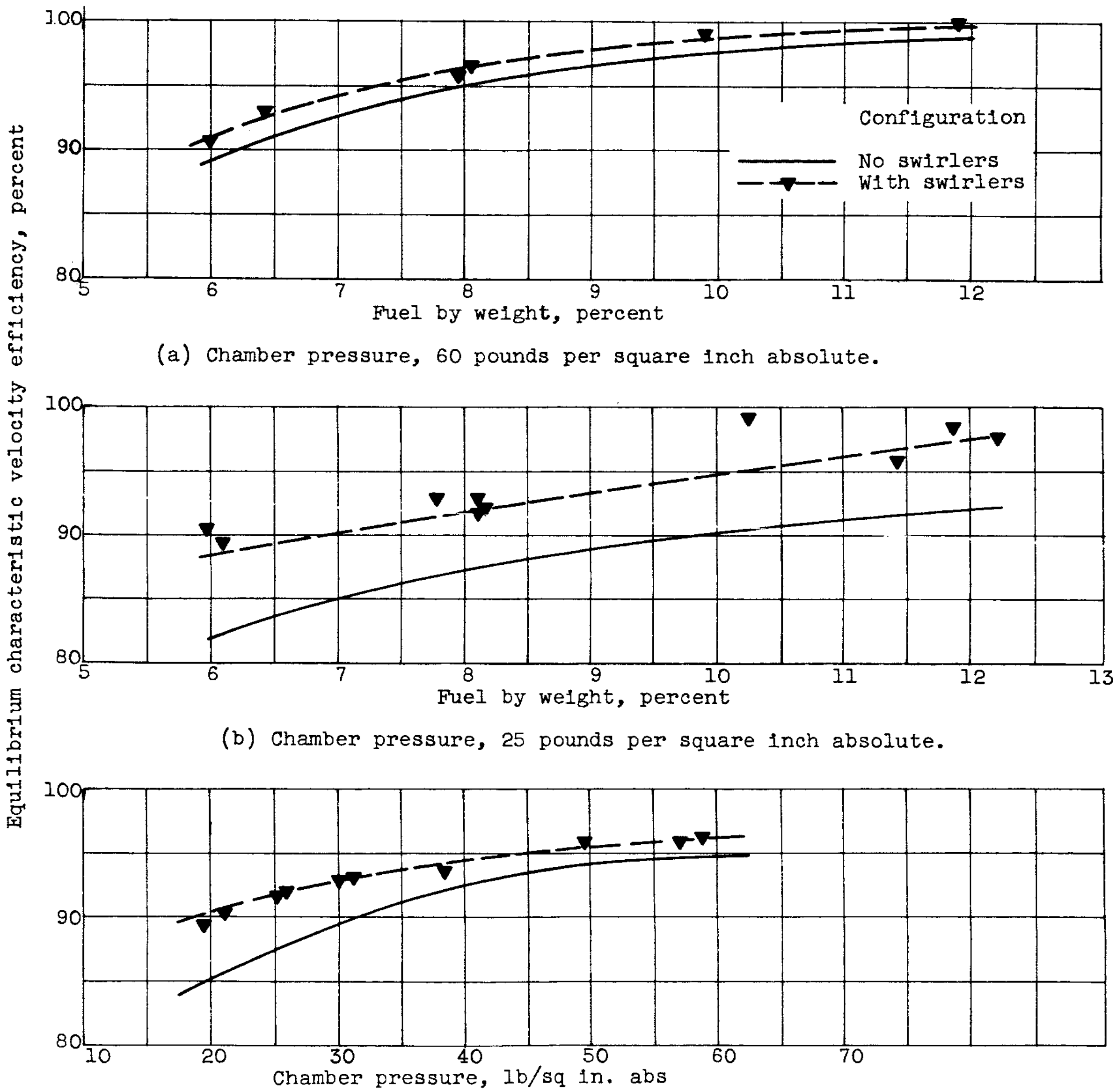


(c) Fuel by weight, 8 percent.

Figure 9. - Concluded. Combustion performance with coaxial injectors.

[redacted]

E-1464



(a) Chamber pressure, 60 pounds per square inch absolute.

(b) Chamber pressure, 25 pounds per square inch absolute.

(c) Fuel by weight, 8 percent.

Figure 10. - Effect of adding swirlers in oxidant tubes of 31-element coaxial injector.

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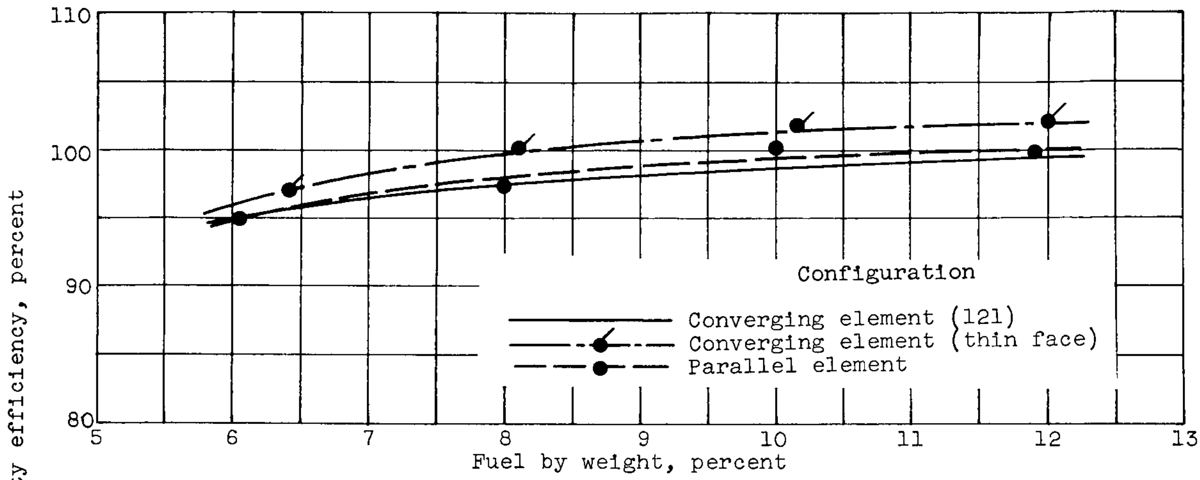
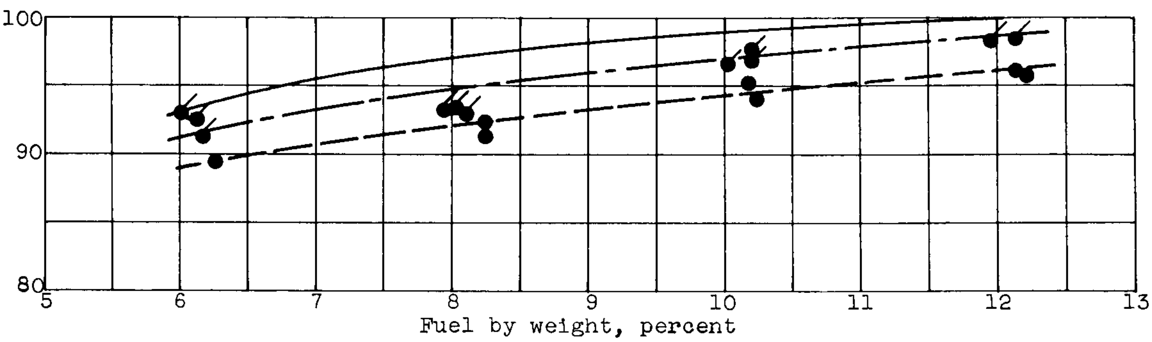
[redacted]

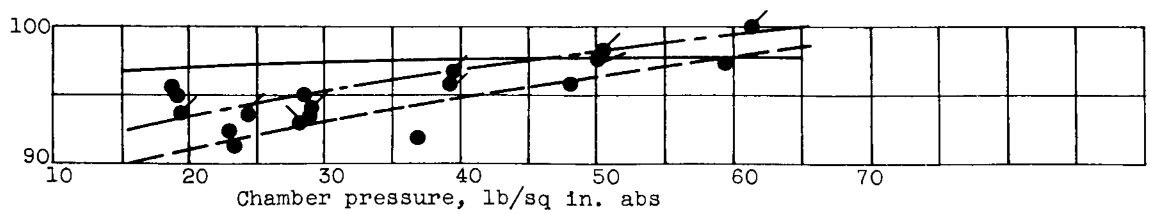
E-1464



(a) Chamber pressure, 60 pounds per square inch absolute.



(b) Chamber pressure, 25 pounds per square inch absolute.



(c) Fuel by weight, 8 percent.

Figure 11. - Effect of directing fuel into oxidant with 121-element coaxial injector.

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E-1464

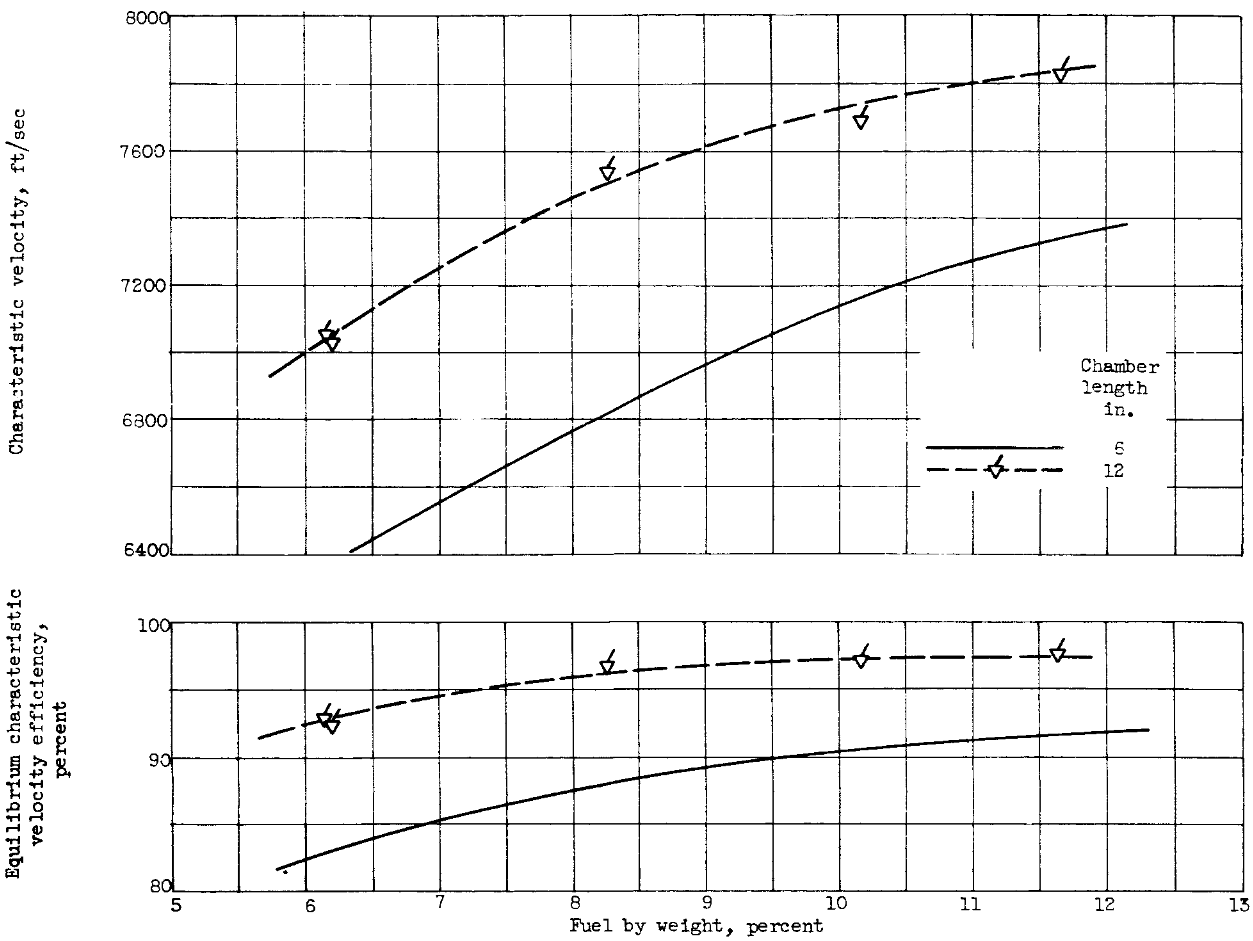
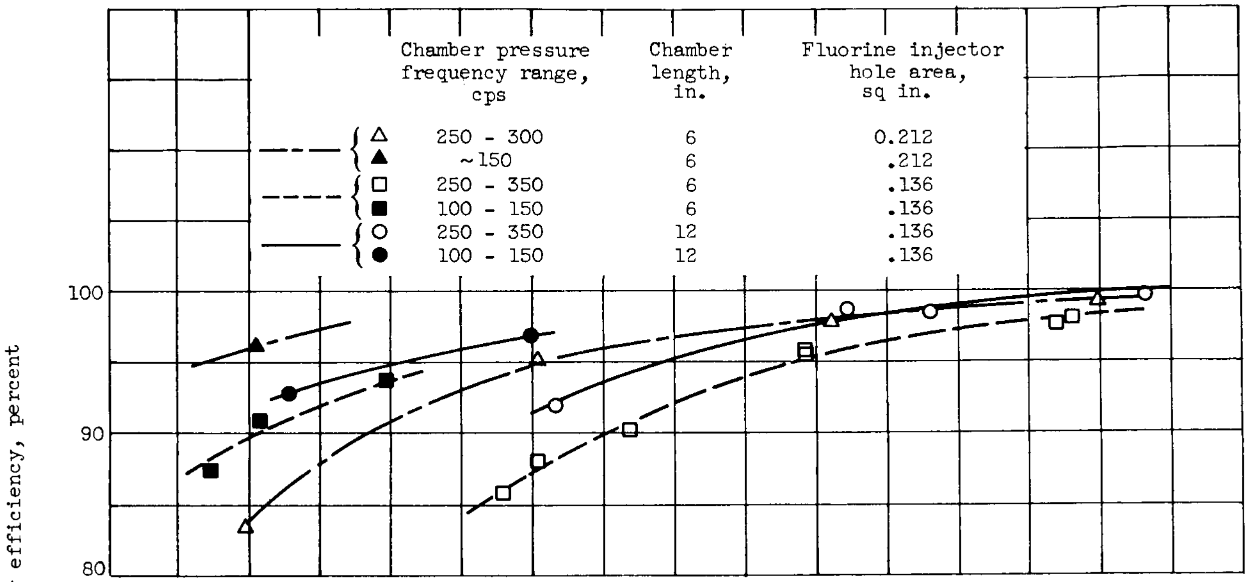
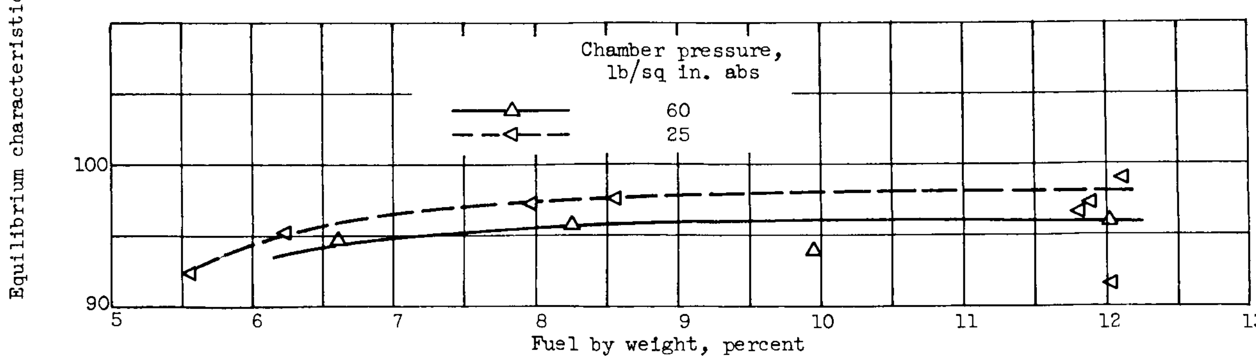


Figure 12. - Effect of chamber length on combustion performance with 31-element coaxial injector at chamber pressure of 25 pounds per square inch absolute.

[redacted]



(a) Two different flourine injector hole areas and two engine lengths; chamber pressure, 60 pounds per square inch absolute.



(b) Reduced volume in fluorine flow system; fluorine injector hole area, 0.212 square inch; chamber length, 6 inches.

Figure 13. - Combustion performance of showerhead injectors.

[redacted]