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RESEARCH MEMORANDUM

EXPERIMENTAL PERFORMANCE OF LIQUID FLUORINE - LIQUID AMMONIA PROPELLANT COMBINATION IN 1000-POUND-THRUST ROCKET ENGINES

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

The performance of liquid fluorine and liquid ammonia as a propellant combination was evaluated in 1000-pound-thrust rocket engines operated at a chamber pressure of 600 pounds per square inch absolute. Values of specific impulse, characteristic velocity, thrust coefficient, and heat rejection were obtained as functions of propellant mixture ratio for each of four injectors: a triplet, a showerhead, and two like-on-like types.

Maximum performance was obtained at the following values by using like-on-like injection at 32 percent fuel by weight (oxidant-fuel ratio of 2.12): specific impulse, 290 pound-seconds per pound (85 percent of theoretical maximum for equilibrium expansion, 92 percent of theoretical maximum for frozen expansion); characteristic velocity, 6200 feet per second (87 percent of theoretical maximum for equilibrium expansion); nozzle thrust coefficient, 1.50; over-all heat rejection, 4.0 Btu per second per square inch.

Specific impulse for the showerhead injector was about 4 percent lower and heat rejection 20 percent lower than for the like-on-like injectors. In general, the showerhead data exhibited better reproducibility than the like-on-like data, where scatter in the region of highest specific impulse exceeded the limits of error of the measurements.

The flat-faced showerhead and like-on-like injectors demonstrated no tendencies to create local hot spots, either on the injector face or on the engine walls.

Unsatisfactory performance, repeated burnouts, and ultimate destruction characterized operation of the contoured-face triplet injector.

The elementary injection concepts of fine propellant atomization, homogeneous propellant distribution, and uniform thorough coverage of the injector face by propellant entry holes are emphasized.

INTRODUCTION

The aim of the present research was to investigate the performance of the liquid fluorine - liquid ammonia propellant combination as influenced by injection methods in 1000-pound-thrust engines operating at a nominal combustion pressure of 600 pounds per square inch absolute. From theoretical calculations based on equilibrium expansion, the maximum specific impulse which could be expected at this pressure is 340 pound-seconds per pound.

Work reported earlier (ref. 1) was conducted at the 100-pound thrust level at a combustion pressure of 300 pounds per square inch absolute. The maximum specific impulse achieved was 270, whereas calculations showed 311 pound-seconds per pound to be possible theoretically on equilibrium expansion from that pressure.

The engine component which affects performance most is the propellant injector. The work reported herein was confined to studies of performance obtained with three different types of injector; the selections were based on past work at this laboratory (refs. 1 and 2) and that conducted by other organizations (refs. 3 to 9). Characteristic engine length (50 in.), chamber- to throat-area ratio (11:1), and engine geometry were kept constant.

As measures of performances obtained by different injectors, three characteristics were observed:

(1) The peak performance exhibited by the injector, as indicated by specific impulse and characteristic velocity

(2) The location of peak performance with respect to mixture ratio

(3) The tendency of the injector spray pattern not to produce excessive heat transfer to the engine, either locally or over-all

The second consideration was included because a high-performance injector operating best in the fuel-rich regions would enhance regenerative cooling possibilities.

Primary data required for the above observations, and the calculation of thrust coefficients, came from measurements of propellant flow rates, developed engine thrust, combustion-chamber pressure, and coolant temperature rise and flow rate.

EQUIPMENT

Injectors. - Four injectors were used in this investigation. The first consisted of 20 triplet groups arranged in a circular pattern on a contoured face as seen in figure 1. Each group provided for two-oxidant-on-one-fuel impinging streams. The diameter of all the holes was 1/32 inch.

A showerhead injector (fig. 2) was designed with a flat face and a hole distribution of 92 fuel and 119 oxidant holes of 0.025-inch diameter to completely cover the face. Rows of fuel and oxidant holes were interspaced in a grid-like pattern. The arrangement of the holes relative to each other, the hole diameters, and the injection pressure drops were designed for a mixture ratio of 29 weight percent fuel. All holes were drilled axially.

In order to achieve finer atomization than may be expected from a straight showerhead, an injector was made which employed pairs of impinging streams of the same propellant, designated the like-on-like radial injector (fig. 3). These streams impinged at the surface of the injector face and formed a finely atomized fan-shaped spray at each pair of holes. There were 16 pairs of fuel and 28 pairs of oxidant holes. All holes were of 0.035-inch diameter. Manifolds supplying propellants to the holes were formed radially in this injector for ease in fabrication. Subsequent modifications included first countersinking the hole pairs (modification A, fig. 3) for improved atomization and later adding 24 more fuel holes (modification B, fig. 3).

The last injector was intended to combine the fine atomization of like-on-like impingement with uniform distribution and thorough coverage across a flat face. This injector had 85 pairs of fuel holes and 108 pairs of oxidant holes and was referred to as the like-on-like grid injector (fig. 4). The diameter of the holes was 0.020 inch.

Comparative photographs of water-spray patterns from the showerhead and the like-on-like grid injectors can be seen in figure 5.

The triplet and the like-on-like radial injectors were made of nickel; the showerhead and the like-on-like grid injectors were of brass. The injectors were designed for propellant pressure drops near 150 pounds per square inch at the flows required by a mixture ratio of 29 weight percent fuel.

Engine chambers. - The 50-inch-characteristic-length combustion chambers were cooled by the axial flow of water through annular passages. Figure 6 is a drawing and photograph of a cutaway section of a chamber. The technique used in fabrication of these chambers is discussed in appendix A.

Test facilities. - The assembled engine, chamber and injector, was mounted horizontally on the floating member of the thrust stand. The floating member was supported by two vertical steel flexure plates. Engine coolant water, during firing, was supplied by a pump at a pressure of 250 pounds per square inch and a flow rate of about 6 pounds per second.

The propellant flow system can best be understood by reference to figures 7 to 9. This installation was patterned basically after those used for related earlier work (refs. 1, 2, 10, and 11). All firing operations were accomplished by remotely controlled valves and pressure regulators. Flow rates were established by the extent to which the propellant tanks were pressurized with helium. Maximum working pressure was 1000 pounds per square inch. A helium purge line was connected to the oxidant flow line downstream of the oxidant valve. The helium valve was electrically interlocked with the propellant valves so that when the fuel flow valve opened, helium purged the oxidant line; when the oxidant flow valve opened, this helium valve closed.

All components of the fuel system were made of stainless steel; materials used in the oxidant system were monel, nickel, brass, and stainless steel. Teflon was used for packings, gaskets, and seats in all valves except the oxidant flow valve. This valve had no packing, employing instead a stainless-steel bellows. In order to prevent rupture of the thin bellows, both sides of it were pressurized simultaneously with the oxidant tank. The metal-to-metal seat and plug in the oxidant valve were nickel, and the gaskets were lead.

Both propellant tanks were suspended directly from cantilever arms fitted with strain-gage elements (fig. 7). The tanks were totally immersed in liquid for bouyancy; a water bath served the fuel tank and liquid nitrogen was used for the oxidant tank. The nitrogen was also necessary to maintain the oxidant temperature below its normal boiling point. Constant level of the nitrogen was assured by means of a standard water-closet ball cock and float.

Instrumentation. - Propellant flow rates were determined by change in the tank weight as indicated by the cantilevered strain gages and recorded by self-balancing potentiometers. During the latter stages of the work, venturis and rotating-vane-type flowmeters were installed; but, because of mechanical difficulties with both the flow meters and the differential pressure transducers for the venturis, consistently reliable data were not obtained from either of these latter two types of instruments during the runs. Agreement among the three methods, however, was indicated to be within ±3 percent or better during flow calibrations with liquid ammonia and liquid nitrogen.

Thrust was recorded automatically from a ring-type strain-gage element in tension and mounted on the axis of the engine.

Chamber pressure and propellant tank and line pressures were measured by Bourdon tube-type recorders and strain-gage-type static-pressure transducers.

For calculation of engine heat rejection, the coolant-water-flow rate was determined by the records from a variable-area orifice meter, and temperature rise was measured by iron-constantan thermocouples located at the inlet and outlet water tubes.

Accuracy of the thrust measurements was considered to be within ±1 percent. Other measurements were accurate within ±2 percent.

Propellants. - Both gaseous fluorine and liquid ammonia were obtained in pressurized commercial cylinders and were handled as described in reference 1. The properties of fluorine are tabulated in reference 2, and those of ammonia may be found in reference 12.

PROCEDURE

The propellants were loaded into their tanks from the manifolded supply cylinders. Ammonia was transferred as a liquid; gaseous fluorine was condensed to the liquid state in the propellant tank. Tank pressures were than preset for the flow conditions required by the run. Coolant-water flow and all instruments were turned on. Propellant flows were started by instantaneously opening both flow valves completely, with fuel leading oxidant by a fraction of a second. Ignition occurred immediately, since the propellants are self-igniting. After 8 or 10 seconds of operation, the run was stopped. If another were to be made, the tank pressures were adjusted to the new conditions and firing was repeated. Upon completion of the last run, both systems were thoroughly purged with helium and then closed up in a standby condition with helium pressure retained.

Figure 10 was taken from one frame of a color movie film and shows the engine in operation during a run with the showerhead injector.

Specific impulse values are considered to be accurate within ±3 percent, based on the accuracy of measurement of the corresponding parameters (propellant flows within ±2 percent and thrust within ±1 percent). Similarly, characteristic velocity values are probably accurate within ±4 percent, and nozzle thrust coefficients within ±3 percent.

Because of the method of fabrication of the engine combustion chambers, average deviations of the nozzle throat area from design specifications were plus 1 or 2 percent. Thermal expansion of the throat wall during running might amount to as much as 1-percent area increase. The cumulative effect of 3 percent or less would raise the characteristic velocity and lower the thrust coefficient values proportionally from those reported.

Adjustment of specific impulse values for loss of performance through heat rejection to engine walls and to account for variation of experimental combustion-chamber pressures from the nominal 600 pounds per square inch absolute amounted, in general, to about 2 percent of the measured specific impulse. Adjusted values are listed in table I. The method of computing these values was similar to that used in references 1 and 10.

RESULTS

A complete presentation of the experimental results is made in table I. No values were tabulated for the triplet injector because all its runs resulted in severe injector burning. Figures 11 to 13 give the results in terms of specific impulse, characteristic velocity, thrust coefficient, and heat rejection as functions of propellant mixture ratio. The figures show curves faired through experimental values from the showerhead injector and from combined results of the two like-on-like injectors. In addition, curves based on theoretical computations are presented (ref. 13).

Values representing maximum performance from the faired curves are summarized in the following table:

	Like-on-like injector	Showerhead injector
Specific impulse, lb-sec/lb	290	278
Percent of theoretical maximum, equilibrium	85	82
Percent of theoretical maximum, frozen	92	89
Characteristic velocity, ft/sec	6200	5820
Percent of theoretical maximum, equilibrium	87	82
Nozzle thrust coefficient	1.50	1.50
Over-all heat rejection, Btu/(sec)(sq in.)	4.0	3.2
Oxidant-fuel weight ratio	2.12	2.12
Fuel, weight percent	32.0	32.0

It may be noted that, although performance was about 4 percent lower for the showerhead than for the like-on-like injectors, its heat rejection was 20 percent lower. In general, the showerhead data exhibited better reproducibility than the like-on-like data, where scatter in the region of highest performance exceeded the limits of error of the measurements.

No combustion vibrations of significant magnitude, hard starts, or excessive deposits on engine walls were encountered during the course of this work.

DISCUSSION

In preceding NACA work on the liquid fluorine - liquid ammonia propellant combination at a 100-pound thrust level, a triplet injector, providing for four groups of two-oxidant-on-one-fuel impinging streams, gave the best results (ref. 1). The triplet injector therefore offered logical extension to the present larger-scale work. The choice of 20 groups for the new triplet injector represented a compromise in scaling up to the 1000-pound thrust level on the basis of thrust per triplet group, thrust per unit of injector face area, and physical problems of the internal manifolding considered necessary for cooling. On the thrust-per-group basis, 40 groups would be needed (scale of 1:10); on the injector-face-area basis, the use of 13 groups was indicated (scale of $1:3\frac{1}{4}$). The triplet groups of the present injector differed from those of the 100-pound-thrust injector by being so positioned that resultants from the impinging jets would be directed inward to the engine axis to diminish heat rejection to the walls and to foster secondary mixing of the reacting propellants.

This injector burned out at the weld and the shoulder between the weld and outer ring of oxidant holes (fig. 1). When it was repaired, additional oxidant holes were drilled near the weld for better cooling of this section. In subsequent operation, however, severe melting occurred again at the shoulder and also in the conical recess at the center of the face. The recently added holes were then closed and new ones were located on the shoulder; also the conical-face section was cut thinner and small bleed holes were drilled through it. This modification was not successful, and the injector burned beyond repair.

The triplet injector was designed to provide for liquid mixing and, based on experience with other injectors which have been used in fluorine work (refs. 1, 2, 10, and 11), its characteristics were such as to encourage considerable recirculation and turbulence of the combustion gases on a large scale near the injector face. The injector failed through burn-outs at protruding and recessed areas on the face.

Succeeding injector types were designed with flat faces and provided with good coverage of propellant holes across the face so that recirculation over large areas was precluded and possibilities of burn-out minimized. As an added precaution against burn-outs, these injectors depended largely on gaseous diffusion for propellant mixing. Fuel and oxidant holes were arranged with the consideration of providing a total spray pattern as nearly as possible homogeneous in propellant mixture. These changes were made on the premise that inherent localized combustion turbulence at flame fronts, uniform throughout the chamber, would be equally as effective in promoting complete combustion as recirculation and turbulence involving larger, more heterogeneous bodies of gases.

The showerhead injector utilized the preceding features to good advantage. Improved propellant distribution across the injector face is believed to be the basic reason the present showerhead surpassed its predecessor in performance (refs. 1 and 10).

A showerhead injector, however, cannot necessarily be expected to provide for fine atomization of propellants immediately upon entry into the combustion chamber, as indicated by figure 5. Such atomization is of considerable importance, especially when the continuous process of propellant vaporization, mixing, activation, and combustion must reach completion in an extremely short time as required by rocket engines. Immediate and fine atomization upon injection should reduce the duration of the vaporization step and permit rapid vapor mixing. A recognized method of achieving atomization is the use of suitably arranged impinging jets of the same propellant.

The like-on-like radial injector utilized impinging jets. This injector provided fine and immediate atomization, and surpassed the showerhead in performance. While evaluation of the like-on-like radial injector was underway, tests were conducted with water-spray blocks containing several different arrangements of drilled holes to determine the most desirable design features with respect to atomization and local distribution of propellant for like-on-like impingement. (For details, see appendix B.) The diameter of the drilled holes was kept constant for all tests. Water sprays from the blocks were observed and the conclusion was drawn that best results may be obtained with (1) two holes drilled at 90° to each other and symmetrically alined for impingement; (2) a conical countersink centered on the holes with a matching cone angle (i.e., 90°) and a depth $2\frac{1}{4}$ times the diameter of the holes; (3) placement of the holes in the countersink such that their impingement point is below the flat surface of the block and that their edges are not quite tangent to each other, thus providing a slight clearance between the impingement point and the apex of the countersink; and (4) use of moderately high pressure drops (e.g., 150 lb/sq in.).

In accordance with these findings, the like-on-like radial injector was altered by countersinking (modification A, fig. 3). The one run made with this modification gave low performance, which is probably not typical of the results that could be expected. Examination of the collected data at this time indicated the possibility of increased performance with the addition of more fuel holes. The better over-all fuel distribution obtained by the additional holes (modification B, fig. 3) apparently did increase performance as indicated by the final three runs made with this injector. Insufficient data were obtained for a complete survey because the injector was destroyed by a burn-out caused by a faulty weld.

In order to utilize further the knowledge gained thus far, the like-on-like grid injector was designed to combine the fine atomization characteristic of like-on-like impingement with improved propellant distribution resulting from a grid-type arrangement of holes. Because the like-on-like grid injector combined the best features of the two preceding injectors, it was expected to exceed each of them in performance. Results from the two runs made with it, however, appeared quite comparable with those of the like-on-like radial injector.

Improvement in performance, still without burn-out, might result from injectors employing enforced liquid mixing by use of unlike impinging jets, that is, triplet groups of very short stream lengths as a means of primary mixing of propellants, but which retain the flat face, the thorough coverage, and the homogeneity of the over-all propellant spray pattern discussed previously in this section. Triplet groups, it might be noted, necessitate some sacrifice of the atomization created by doublets (see item 11, appendix B); but, because of the symmetry of two-on-one triplets, they should give satisfactory propellant mixing (consequently, satisfactory performance) over a wider range of mixture ratios than would unlike doublet jets.

SIGNIFICANCE OF RESULTS

Comparison of results from the present investigation with those from preceding work on a smaller scale and at a lower combustion pressure (ref. 1) can be seen in figure 14.

It is apparent that the specific impulse of the 1000-pound-thrust engines was higher, in general, than that of the 100-pound-thrust engines, as would be expected because of the higher combustion pressure (600 and 300 lb/sq in. abs, respectively). Characteristic velocity, however, was appreciably higher for the 100-pound-thrust engines than for the 1000-pound-thrust engines.

As a measure of combustion efficiency, characteristic velocity is more direct than is specific impulse, and it is not significantly influenced by the choice of operational combustion-pressure level. The results indicate, then, that the like-on-like injectors used in the larger-scale engines did not perform so efficiently as the triplet injector in the smaller-scale engines.

The over-all performance efficiencies of the 1000- and 100-pound-thrust engines, nevertheless, were quite comparable; they yielded 85 and 87 percent of their respective maximum theoretical specific impulse values. (Each gave about 92 percent of its highest frozen expansion theoretical value.) This comparison is accounted for by the fact that the larger-scale engines operated with thrust coefficients very near theoretical values, whereas those for the smaller-scale engines were 92 percent of theoretical for the corresponding combustion-chamber pressure.

The curves for the smaller-scale engines do not drop so rapidly at the fuel-lean and fuel-rich mixture ratios as do those for the larger-scale engines, probably because the triplet injector of the former provided for earlier and better propellant mixing than did the like-on-like injectors.

The heat rejection for the like-on-like injectors (1000-lb-thrust engines) was higher than that of the triplet injector (100-lb-thrust engines). However, it is probable that, if the same injectors were run at equivalent combustion-chamber pressures, the reverse would be true.

The combustion-chamber cross-sectional area in the 100-pound-thrust engines was 16.6 times the throat area; the corresponding value was 11.1 for the 1000-pound-thrust engines. These contraction ratios are quite high but were accepted to permit more freedom in injector design because of the larger face area. The effect of high contraction ratios may tend to widen the gaps between the performances of different injectors. It would also tend to reduce the performances of all injectors (refs. 14 and 15).

In experimental combustion, peak performance occurs fuel-rich of the mixture ratio predicted best by theory for complete combustion. For a qualitative understanding of this phenomenon, it may be reasoned that (1) peak performance with combustion less than 100-percent efficient (experimental) implies incomplete heat release from the fuel; (2) some portion of the fuel, then, offers no contribution and may be considered a diluent, altering the molecular weight and temperature of the exhaust gases; (3) the presence of this diluent portion, which may be related in magnitude to the degree of inefficiency of combustion, has the dual effect of decreasing performance, since total propellant flow is considered in the denominator of performance parameters, and of placing the observed peak performance at a mixture ratio of higher measured fuel content than would be observed with complete combustion.

SUMMARY OF RESULTS

The following results were obtained from experimentally burning the liquid fluorine - liquid ammonia propellant combination at a combustion pressure of 600 pounds per square inch absolute in 1000-pound-thrust rocket engines.

1. Flat-faced, like-on-like impingement injectors gave the best performance and were not subject to burn-out.

2. A showerhead injector gave performance about 4 percent lower and heat rejection 20 percent lower than the like-on-like injectors and showed no burn-out tendencies.

3. A single-ring triplet-type injector with a contoured face burned out repeatedly and did not give satisfactory performance.

4. The following values at maximum performance for the like-on-like and the showerhead injectors were taken from faired curves:

	Like-on-like injector	Showerhead injector
Specific impulse, lb-sec/lb	290	278
Percent of theoretical maximum, equilibrium	85	82
Percent of theoretical maximum, frozen	92	89
Characteristic velocity, ft/sec	6200	5820
Percent of theoretical maximum, equilibrium	87	82
Nozzle thrust coefficient	1.50	1.50
Over-all heat rejection, Btu/(sec)(sq in.)	4.0	3.2
Oxidant-fuel weight ratio	2.12	2.12
Fuel, weight percent	32.0	32.0

5. In general, the showerhead data exhibited better reproducibility than the like-on-like data, where scatter in the region of highest specific impulse exceeded the limits of error of the measurements.

CONCLUDING REMARKS

From experience gained through this and previous fluorine work, certain elementary injection concepts must be followed, that is, fine propellant atomization, homogeneous propellant distribution, and uniform thorough coverage of the injector face by propellant entry holes. These concepts warrant very careful attention in spite of the high reactivity of fluorine. In addition to the preceding, a flat injector face is advantageous to minimize burnouts.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
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APPENDIX A

COMBUSTION-CHAMBER FABRICATION

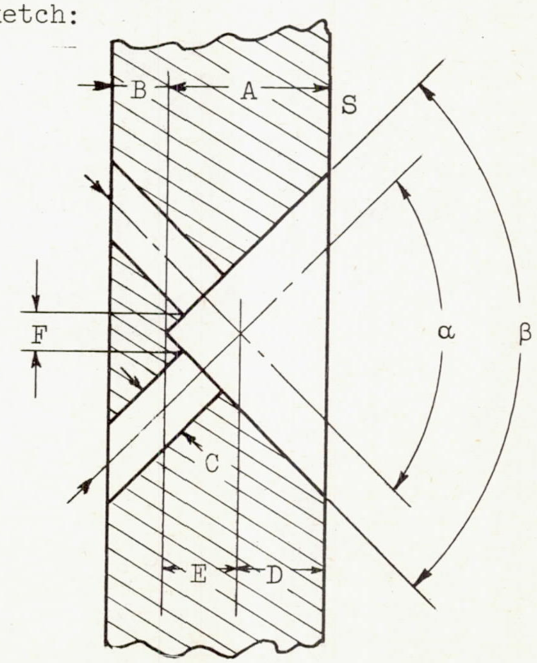
The 50-inch-characteristic-length, water-cooled combustion chamber was of unique fabrication. Three successive shells, one around another, were spun to the contour of a machined mandrel. The innermost shell was nickel of 1/8-inch thickness except at the nozzle throat, where it was thinner for better cooling during combustion. The transitions between thicknesses, as well as all weld joints, were uniformly faired during the spinning operation. A second shell, of 1/32-inch steel, was next spun tightly around the first, followed by a third one of 1/32-inch Inconel. The Inconel shell was then split longitudinally and removed. The steel was peeled off and discarded. In order to assemble the engine, axial spacer wires were tacked to the inside of the Inconel shell and this shell was welded together again around the inner wall. Thus, a uniform coolant passage was achieved between the nickel and Inconel walls. Finally, the flange, pressure tap, and water tubes were welded on to complete the rocket combustion chamber. (See fig. 6.)

APPENDIX B

WATER-SPRAY TESTS WITH LIKE-ON-LIKE IMPINGEMENT

In order to study spray patterns formed by pairs of like-on-like impinging jets, brass test blocks were made containing several different arrangements of drilled holes. Water sprays from these blocks were observed visually to determine qualitatively which conditions produced best atomization and most uniform local distribution of the water droplets.

The arrangement and nomenclature of the brass test blocks are shown by the following sketch:



The following conditions were used and observations made:

(1) Angle α was held constant at 90°, based on references 16 and 17.

(2) Angle β was tested at 90° and 100°. Angle of countersunk cone of 100° gave no better atomization or distribution throughout the resulting spray fan than the 90° angle but did produce more dripping down the surface S of the test block.

(3) Distance A was tested at 0, 0.070, and 0.195 inch. Best results were obtained at 0.070 inch. At 0, atomization and distribution were poorer and the fan was not sharply defined; at 0.195 inch, a considerable amount of dripping occurred.

(4) Distance B was kept constant. A + B would be determined by structural strength and cooling requirements of the injector.

(5) Diameter C was held constant at 1/32 inch.

(6) Distance D was tested at positive and negative values. Jets impinging below surface S showed better atomization and fan shape than those impinging beyond the surface.

(7) In one test at $D = 0$, countersinking was omitted. Good results were obtained, but when countersinking was added atomization became finer and the fan had fewer random sprays.

(8) Distance E was tested at $E \rightarrow A$, $E \rightarrow 0$, and where E permitted a slight clearance (0.008 or 0.010 in.) between the jet holes and the apex of the countersunk cone. When $E \rightarrow A$, the spray was coarse and dripping was relatively great; at $E \rightarrow 0$, atomization was coarse but the distribution of the spray was uniform with very little dripping; when E permitted clearance between the jets and the apex, atomization was good and distribution was uniform with negligible dripping.

(9) Distance F varied with E. Spacing of drilled holes tangentially ($F = 0$) or slightly separated showed better atomization than when center lines of holes intersected at surface S ($D = 0$) with no countersink.

(10) In an attempt to develop a spray cone instead of a fan, a second set of holes was added at 90° to the first and on the same axis. When the four jets impinged at a common point, a solid stream with very little atomization was produced; location of the second pair of holes as far as possible from the first improved the spray.

(11) A third hole was added to an original pair where $D = 0$ and countersinking was omitted (as in item 7). Center lines of the three holes intersected at surface S, and the third hole was drilled perpendicular to surface S (bisecting the angle between the two original holes). Atomization from the triplet group was poorer than from the original doublet, the angle of the spray fan was decreased, and distribution through the fan was shifted to give a greater portion at center than at edges.

(12) Pressure drops from 20 to 150 pounds per square inch were used. All patterns functioned well through the range but were best at the higher pressure drops.

The following conclusions are based on the preceding observations: Best results may be obtained with (1) two holes drilled for subsurface jet impingement; (2) a 90° angle between the holes; (3) countersinking with an angle to match the holes, that is, 90°; (4) depth of the conical countersinking equal to $2\frac{1}{4}$ times the diameter of the holes; (5) holes spaced in countersinking such that their edges are not quite tangent, thus providing a slight clearance between the impingement point and the apex of the countersunk cone; and (6) moderately high pressure drops, that is, near 150 pounds per square inch.

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TABLE I. - SUMMARY OF EXPERIMENTAL PERFORMANCE OF LIQUID FLUORINE - LIQUID AMMONIA PROPELLANT COMBINATION

Injector	Fuel, weight percent	Oxidant-fuel weight ratio, O/F	Total propellant flow, lb/sec	Thrust, lb	Combustion-chamber pressure, lb/sq in. abs	Specific impulse, lb-sec/lb	Characteristic velocity, ft/sec	Thrust coefficient	Average heat rejection rate to engine, Btu/(sec)(sq in.)	Specific impulse adjusted for heat rejection and pressure deviations, lb-sec/lb	Run time, sec
Like-on-like radial	26.5	2.78	3.70	948	555	257	5490	1.51	3.61	262	7
	38.3	1.61	3.22	876	515	272	5850	1.50	3.40	280	13
	39.7	1.52	3.29	876	515	267	5730	1.50	3.44	275	11
Countersinks (modification A)	33.9	1.95	3.89	1005	580	258	5450	1.53	4.18	263	9
Added fuel holes (modification B)	32.0	2.12	3.27	978	575	299	6430	1.50	----[b]	304	7
	33.0	2.03	3.66	1008	577	276	5770	1.54	3.55	280	9
	36.3	1.76	3.25	979	575	301	6470	1.50	3.54	306	12
Like-on-like grid	28.8	2.47	3.55	988	595	280	6120	1.47	3.99	283	11
	30.3	2.30	3.60	1007	595	280	6040	1.49	----[b]	283	6
Showerhead	23.7	3.22	3.89	922	545	237	5120	1.49	2.39	241	10
	25.5	2.92	4.19	988	575	236	5020	1.51	2.70	239	8
	25.7	2.90	4.04	924	525	229	4750	1.55	2.50	234	7
	27.1	2.69	3.60	977	565	271	5730	1.52	2.77	275	8
	27.9	2.58	3.96	1025	591	259	5460	1.53	2.92	262	8
	29.7	2.36	3.78	1037	595	274	5750	1.54	3.18	277	12
	31.1	2.21	3.71	926	535	249	5270	1.53	2.65	255	9
	32.6	2.07	3.24	865	500[a]	267	5640[a]	1.53[a]	2.37	274[a]	8
	32.8	2.05	3.75	1080	615	288	5990	1.55	3.07	290	13
	35.1	1.85	3.55	936	535	264	5510	1.54	2.67	270	8
	37.1	1.69	3.78	935	545	247	5270	1.51	2.56	252	9
	38.0	1.63	2.98	703	415	236	5090	1.49	2.37	248	15

[a]Chamber pressure calculated from thrust coefficient value selected from faired curve for this injector.

[b]Temperature records not obtained.

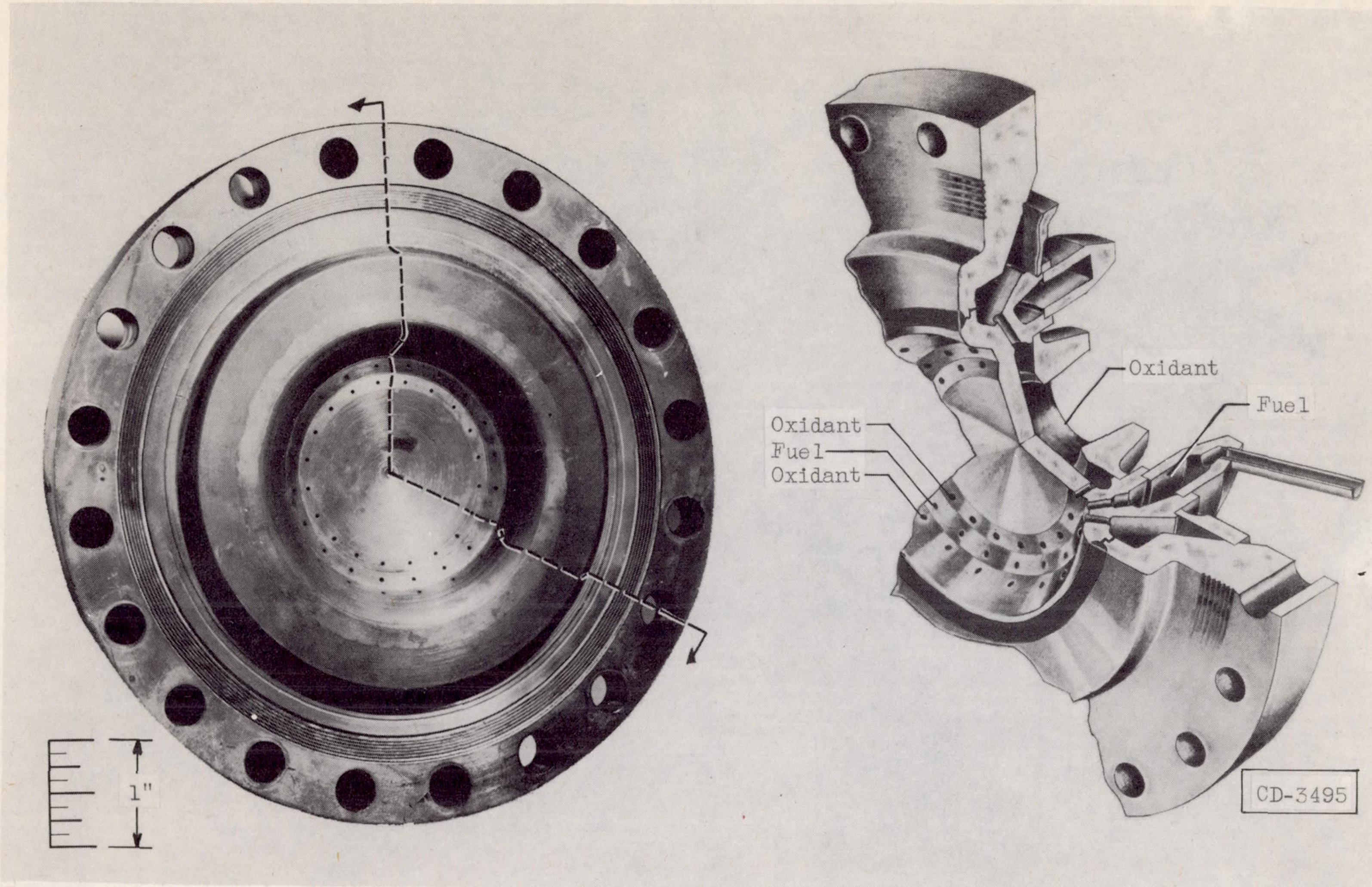


Figure 1. - Injector providing for 20 sets of two-oxidant-on-one-fuel impinging jets in a circular array on a contoured face.

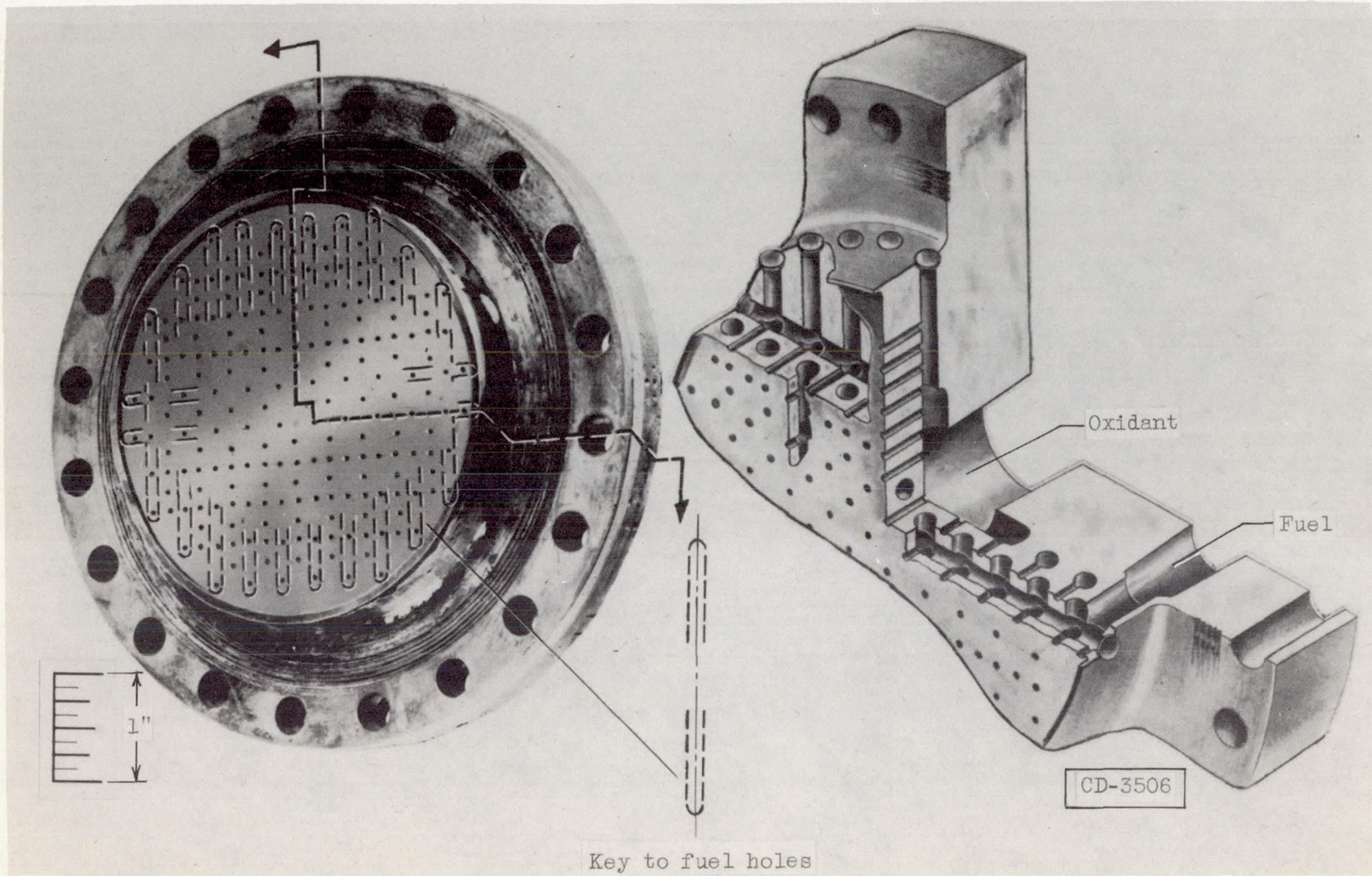


Figure 2. - Showerhead injector providing for 92 fuel and 119 oxidant axial-flow nonimpinging jets in a grid array on a flat face.

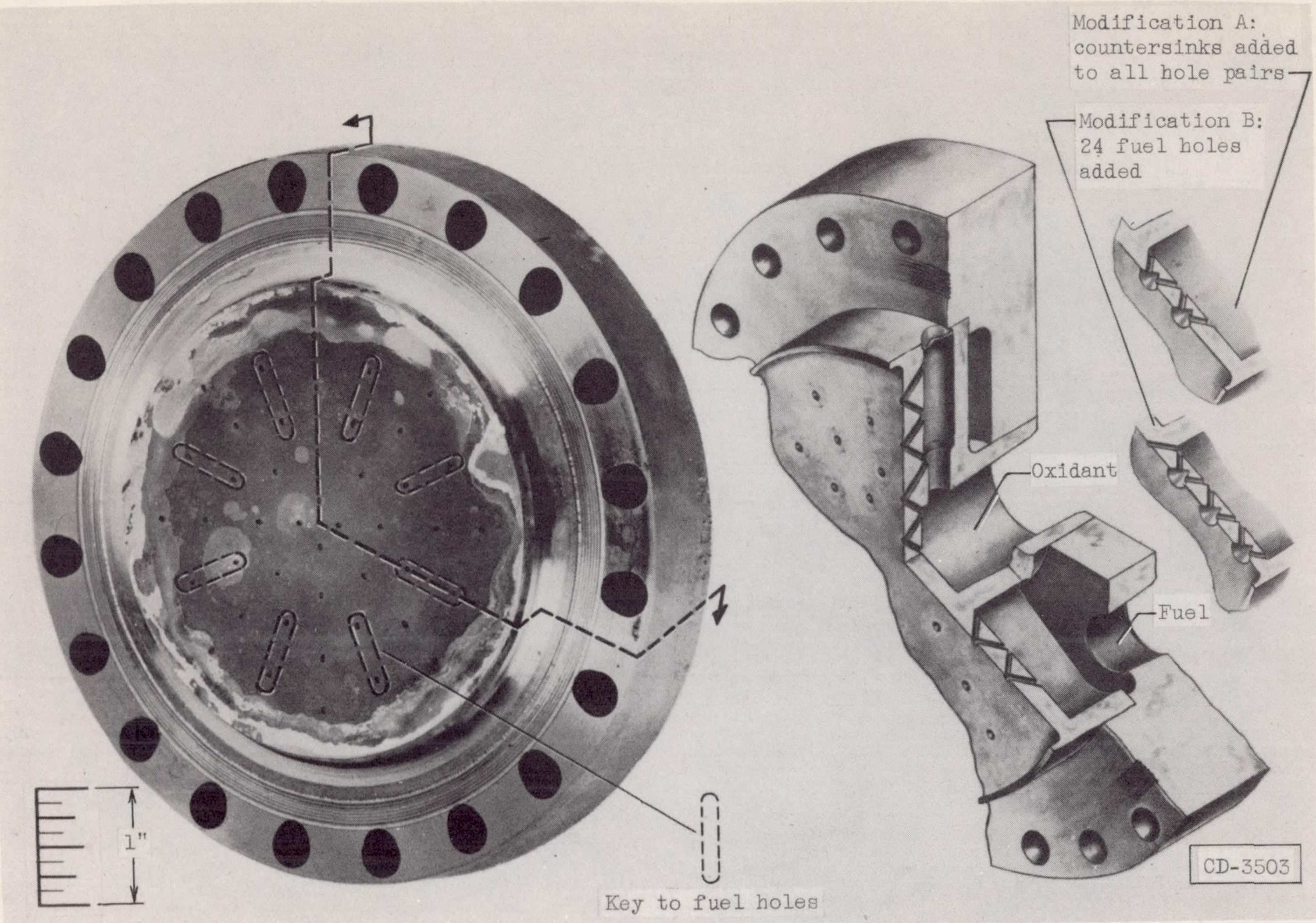


Figure 3. - Injector providing for 16 pairs of fuel and 28 pairs of oxidant like-on-like impinging jets in a radial array on a flat face.

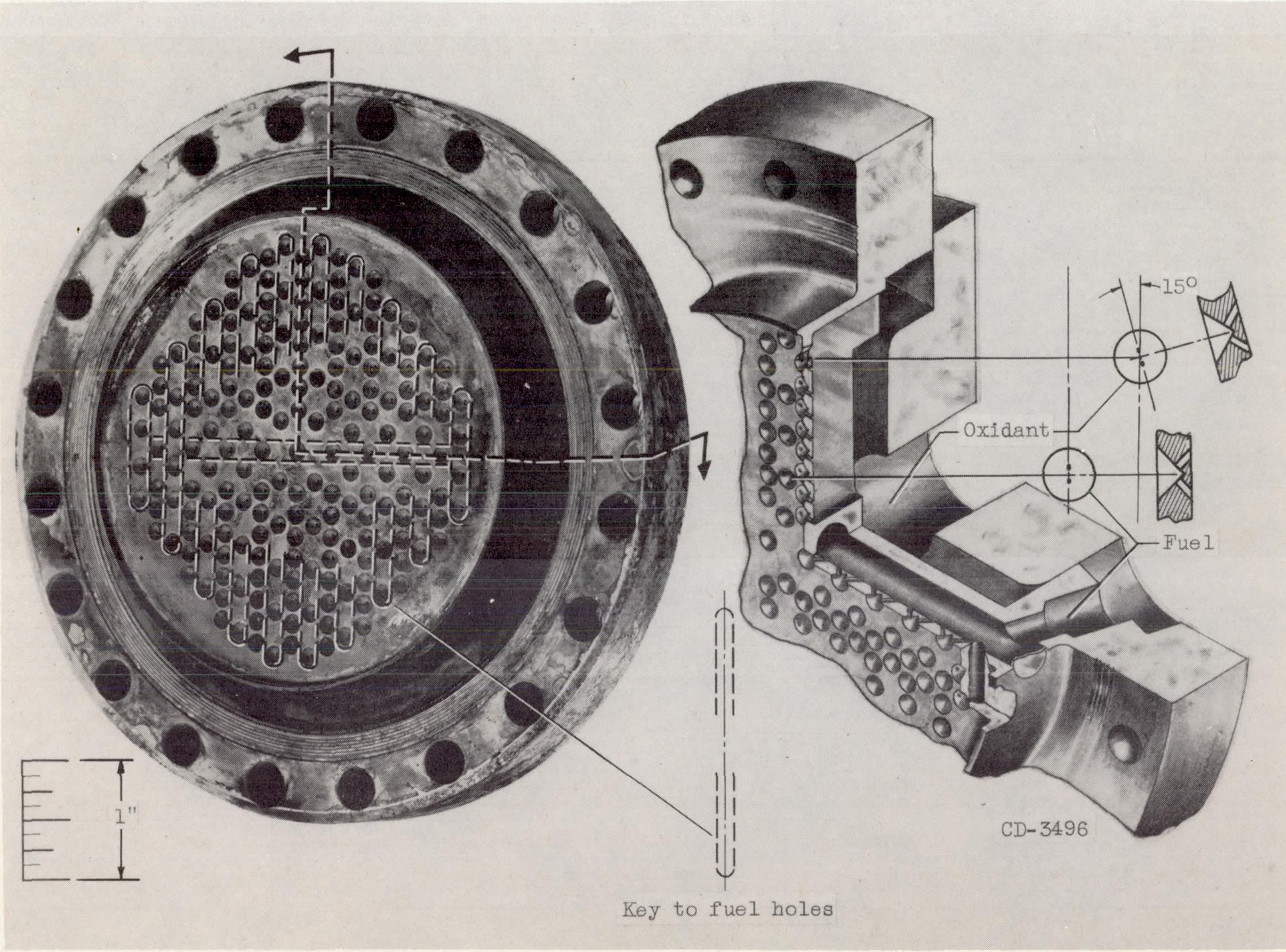
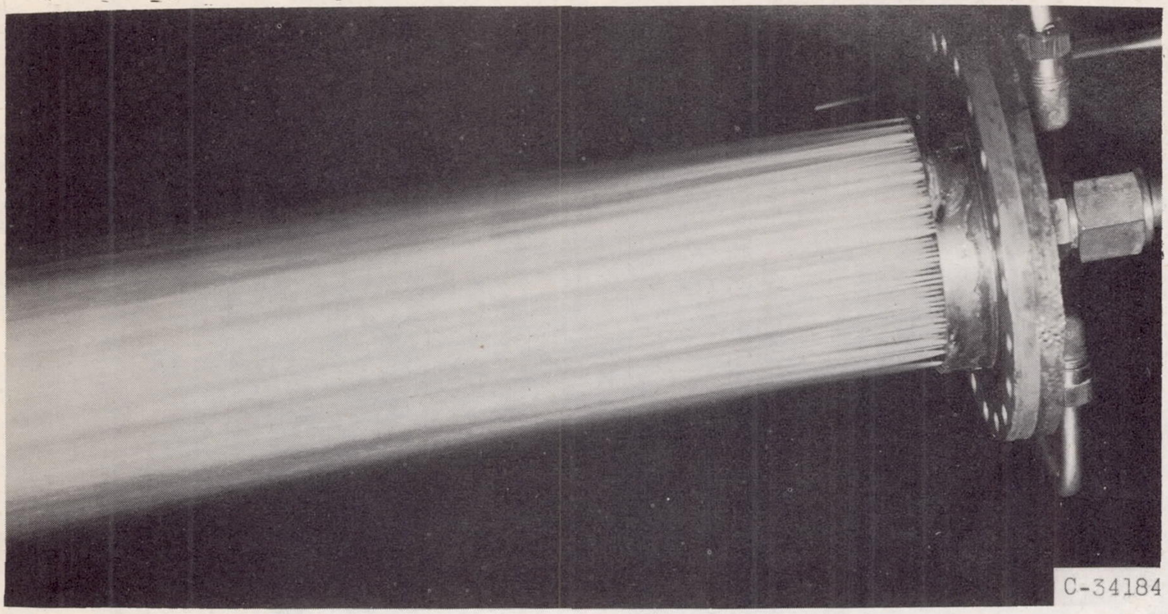
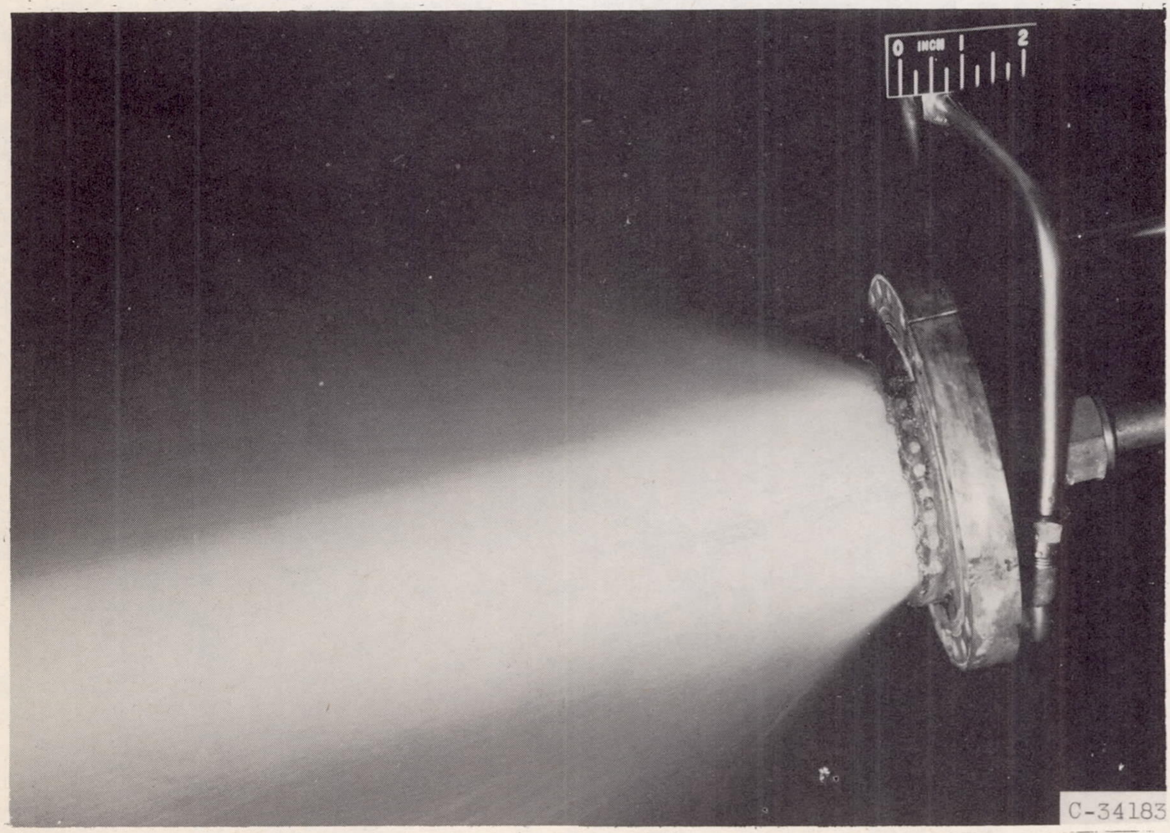


Figure 4. - Injector providing for 85 pairs of fuel and 108 pairs of oxidant like-on-like impinging jets in a grid array on a flat face.



(a) Showerhead injector.



(b) Like-on-like grid injector.

Figure 5. - Water-spray patterns from two fluorine-ammonia injectors at pressure drop of 100 pounds per square inch.

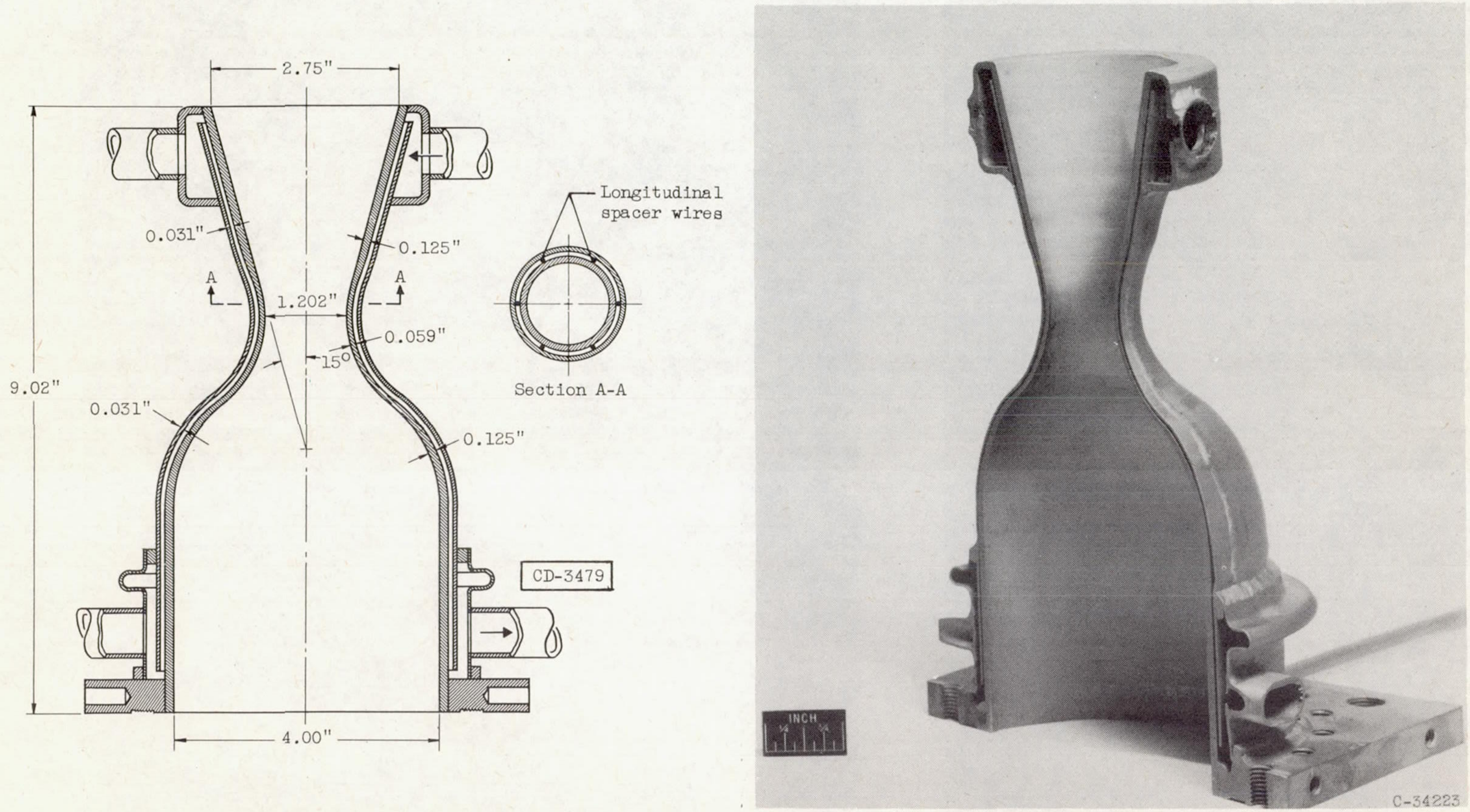


Figure 6. - Diagram and photograph of cutaway section of chamber and nozzle assembly of 1000-pound-thrust rocket engine.

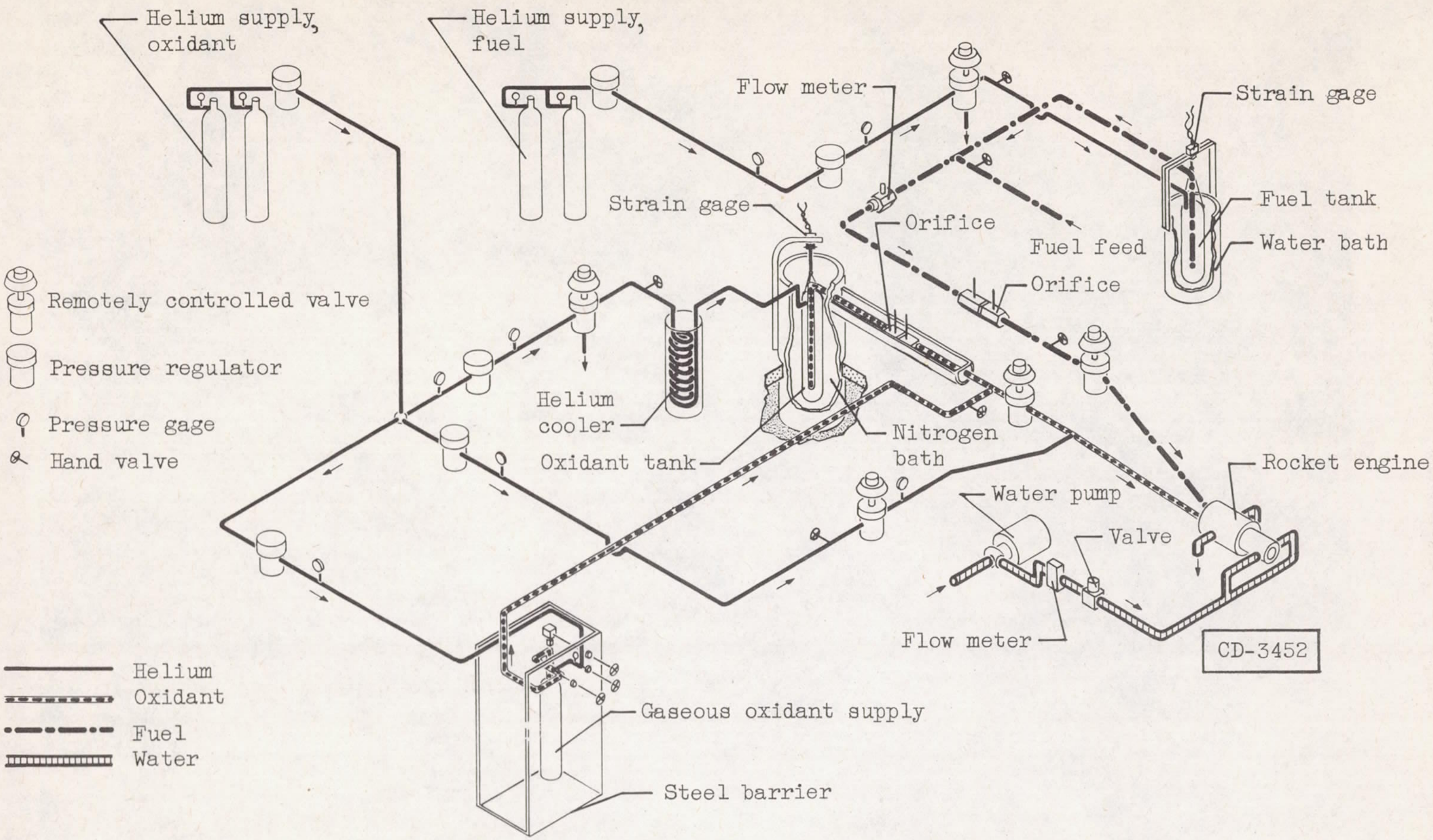


Figure 7. - Diagram of 1000-pound-thrust fluorine-ammonia rocket test facility.

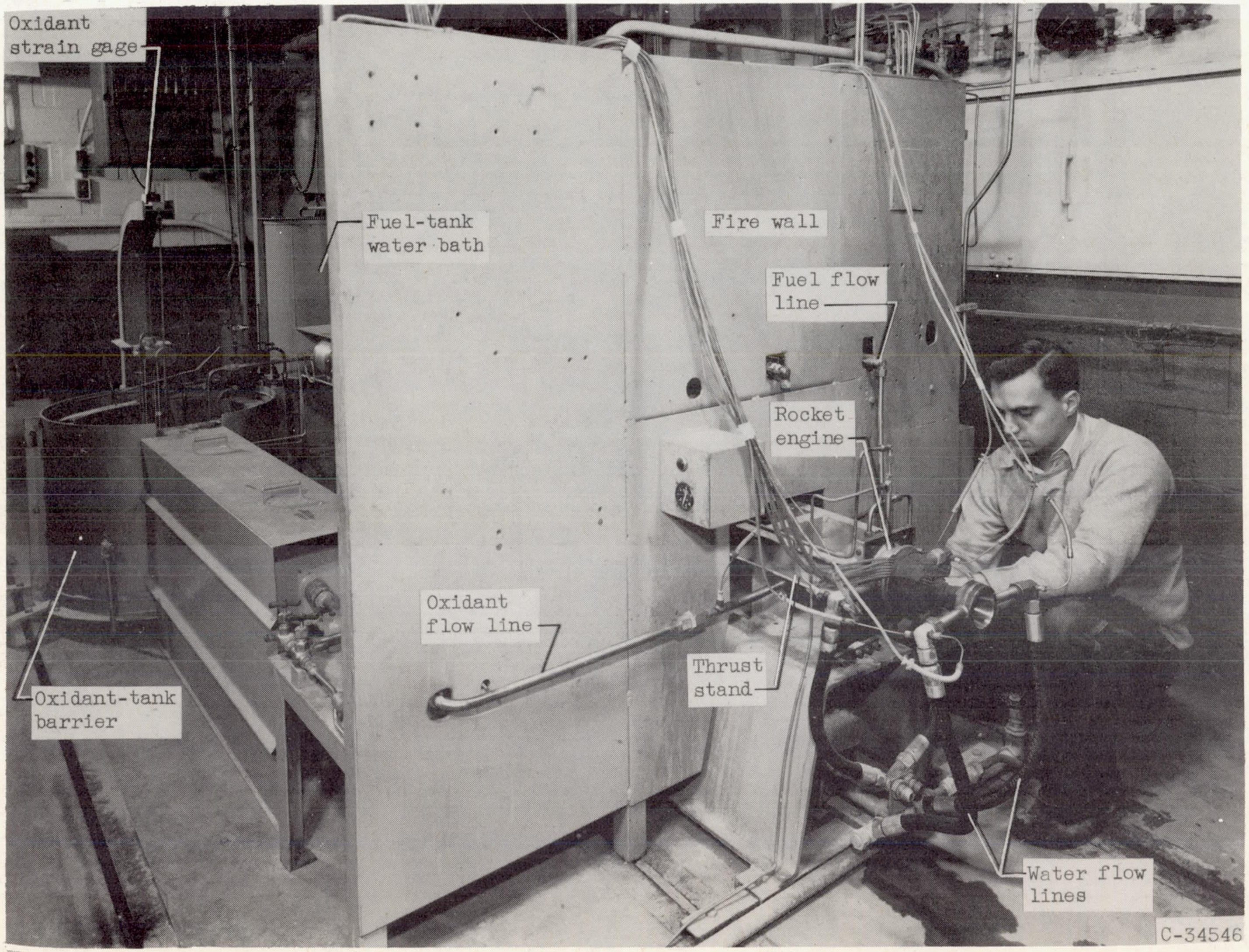


Figure 8. - Test-stand facilities for 1000-pound-thrust fluorine-ammonia rocket engine.

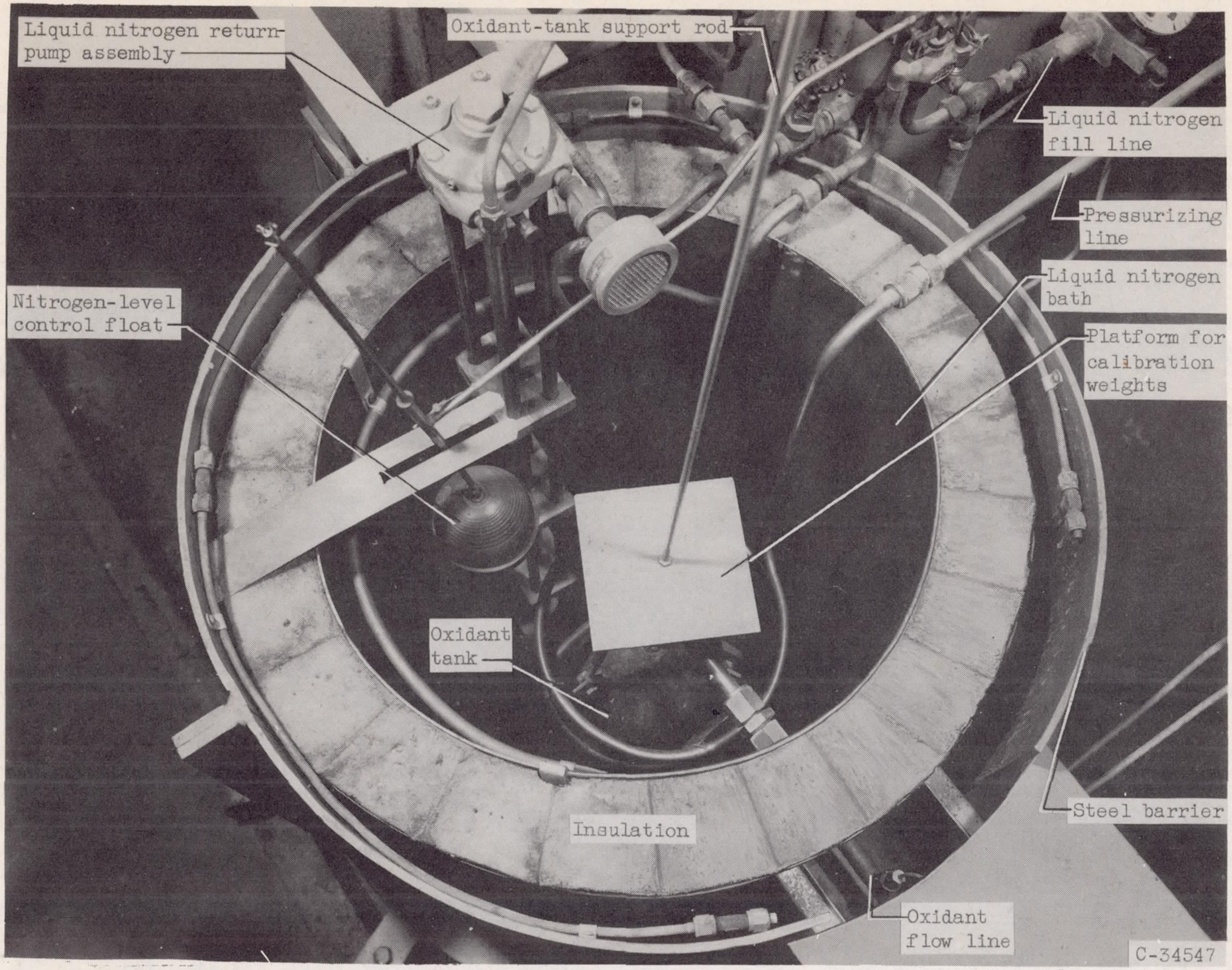


Figure 9. - Top view of oxidant tank assembly.

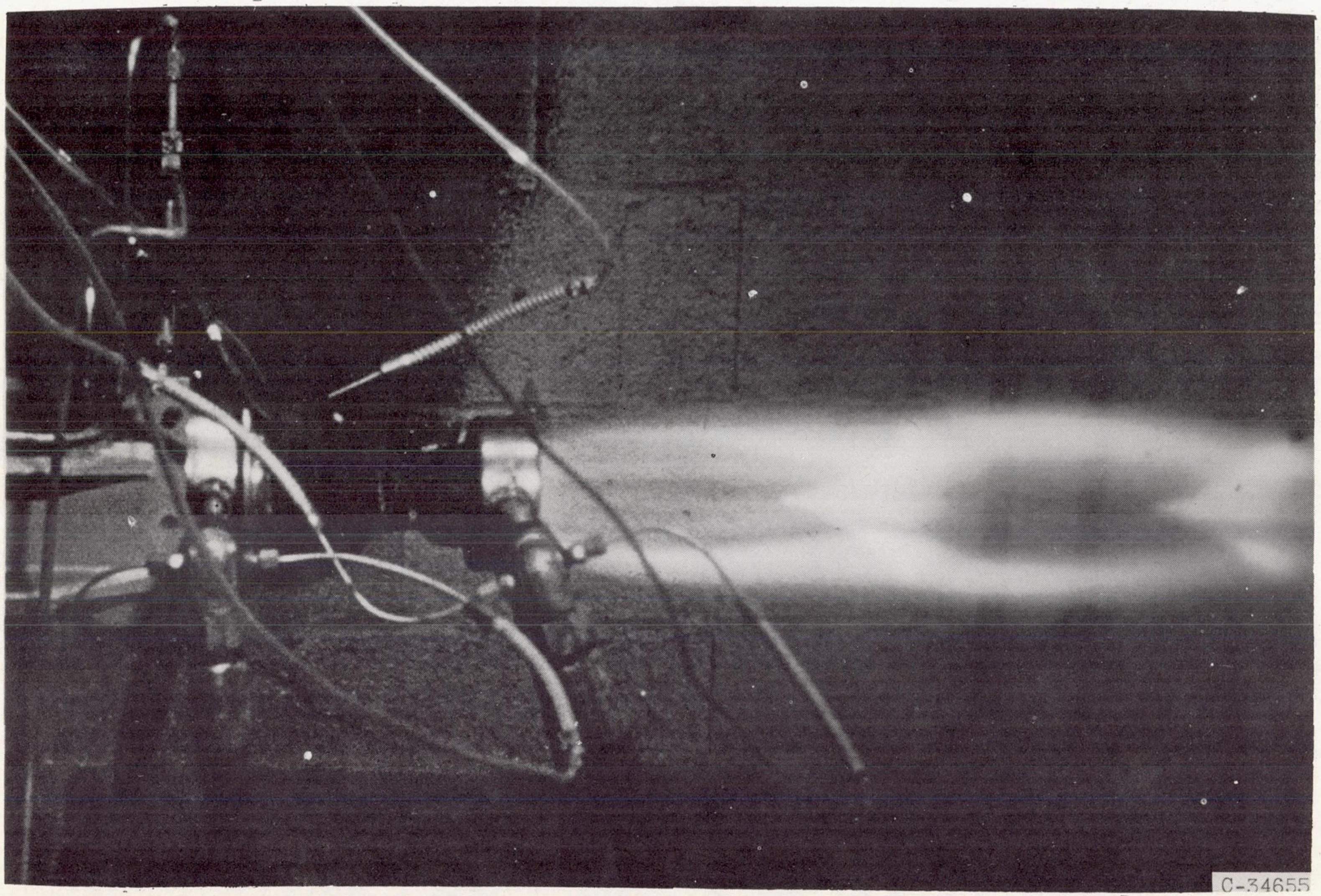


Figure 10. - Photograph of 1000-pound-thrust fluorine-ammonia rocket engine in operation.

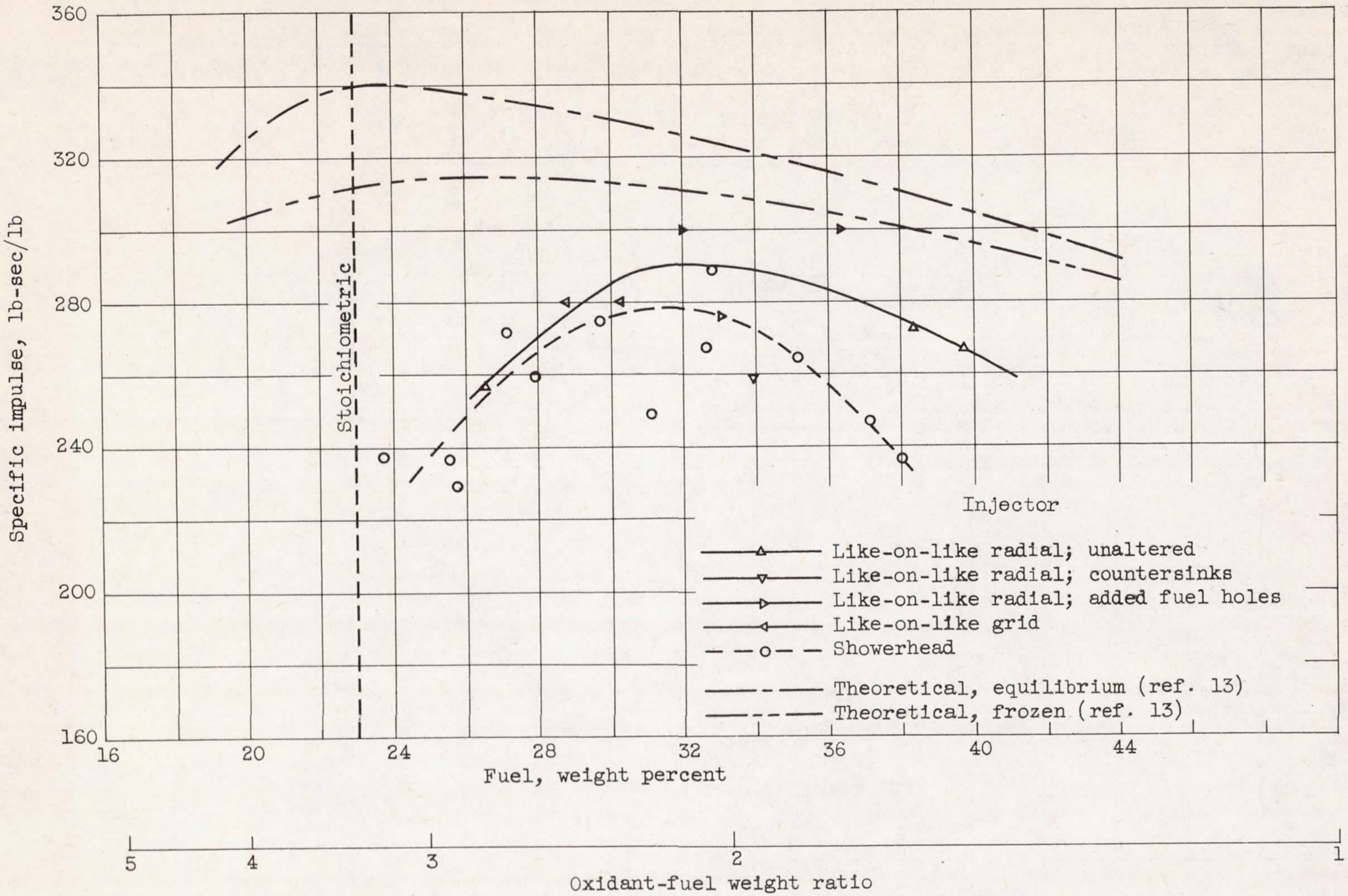


Figure 11. - Experimental and theoretical specific impulse of liquid fluorine - liquid ammonia propellant combination at combustion pressure of 600 pounds per square inch absolute. Rocket engine thrust, 1000 pounds.

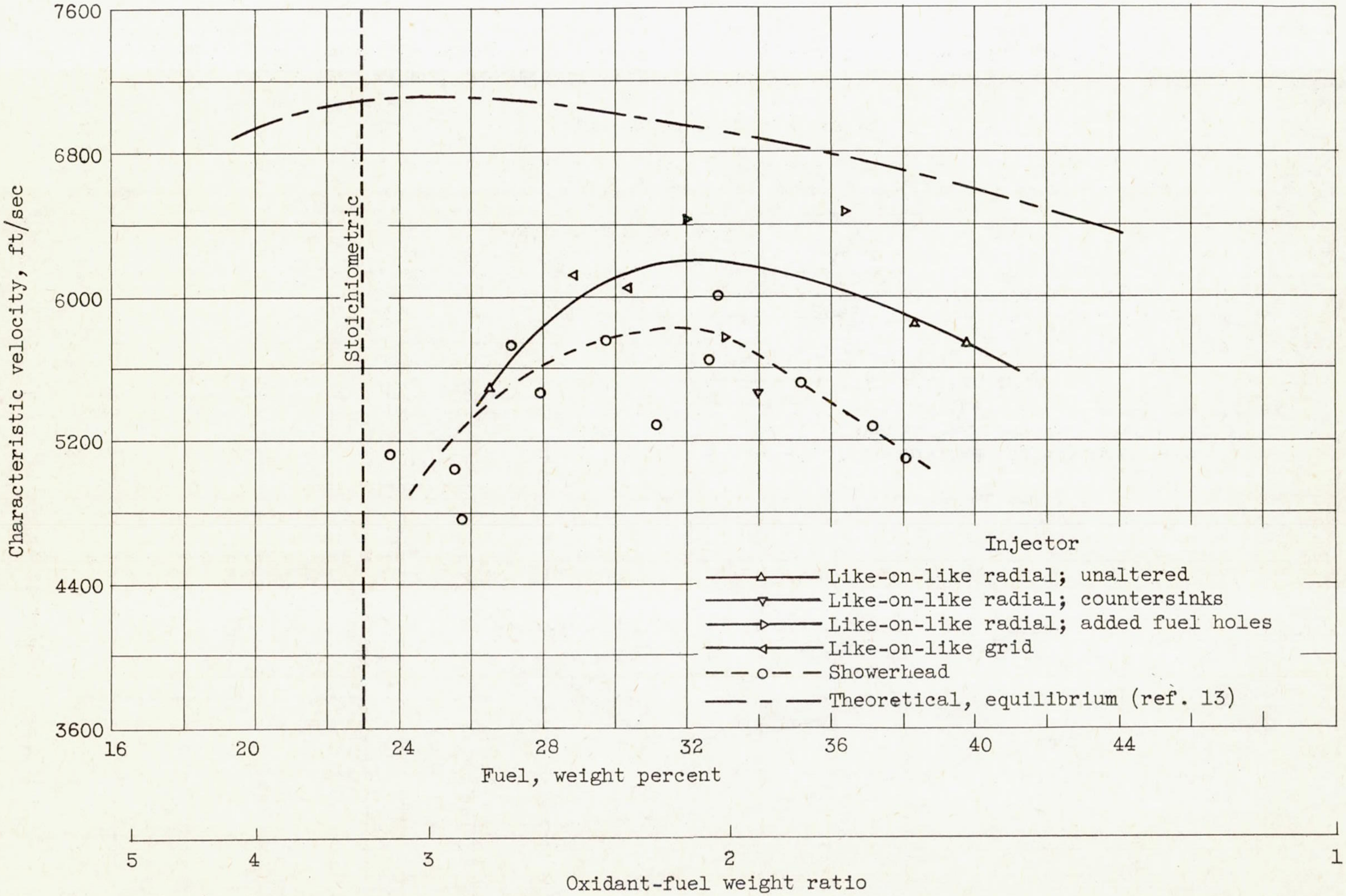
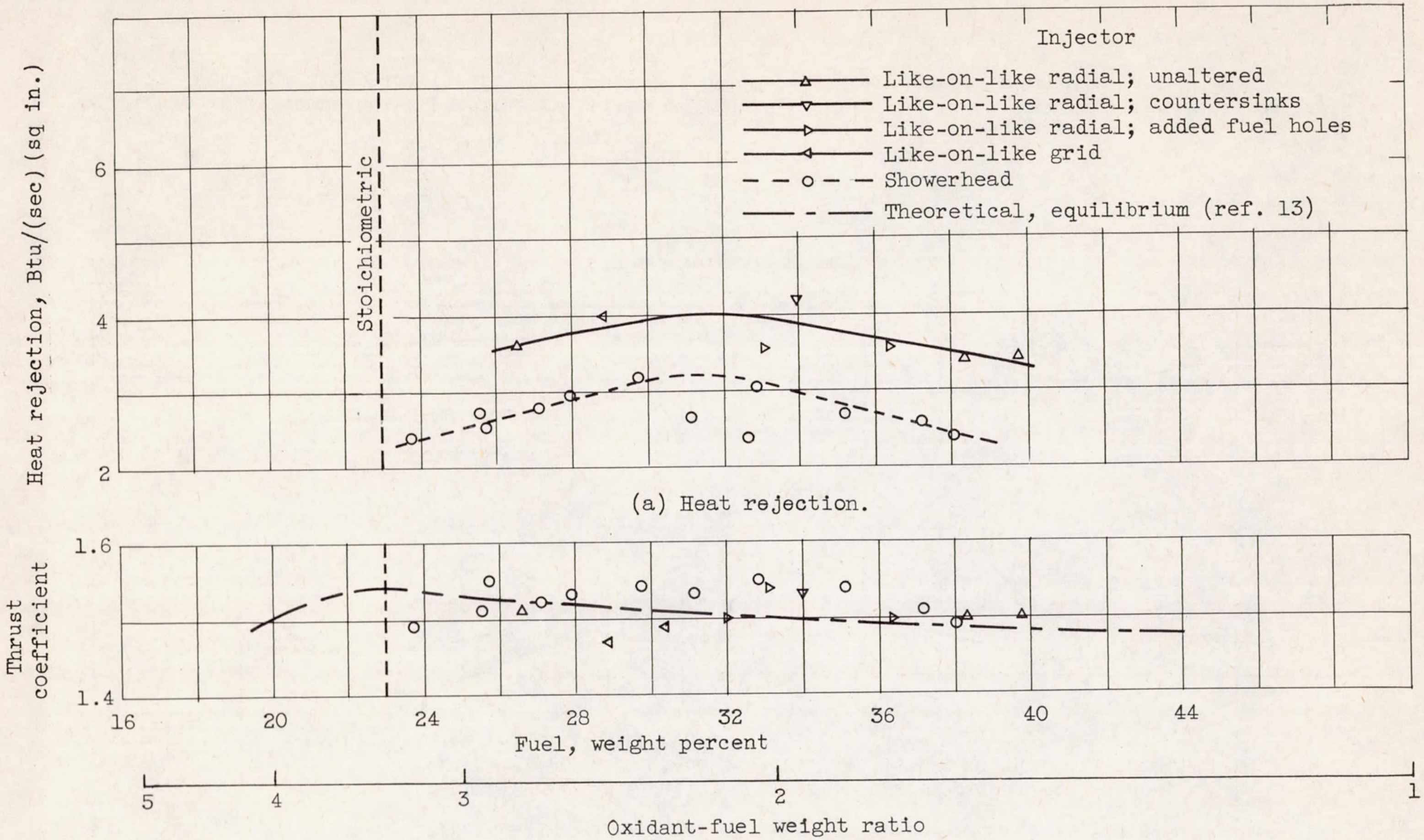


Figure 12. - Experimental and theoretical characteristic velocity of liquid fluorine - liquid ammonia propellant combination at combustion pressure of 600 pounds per square inch absolute. Rocket engine thrust, 1000 pounds.



(b) Thrust coefficient.

Figure 13. - Experimental heat rejection and experimental and theoretical thrust coefficient to engine by liquid fluorine - liquid ammonia propellant combination at combustion pressure of 600 pounds per square inch absolute. Rocket engine thrust, 1000 pounds.

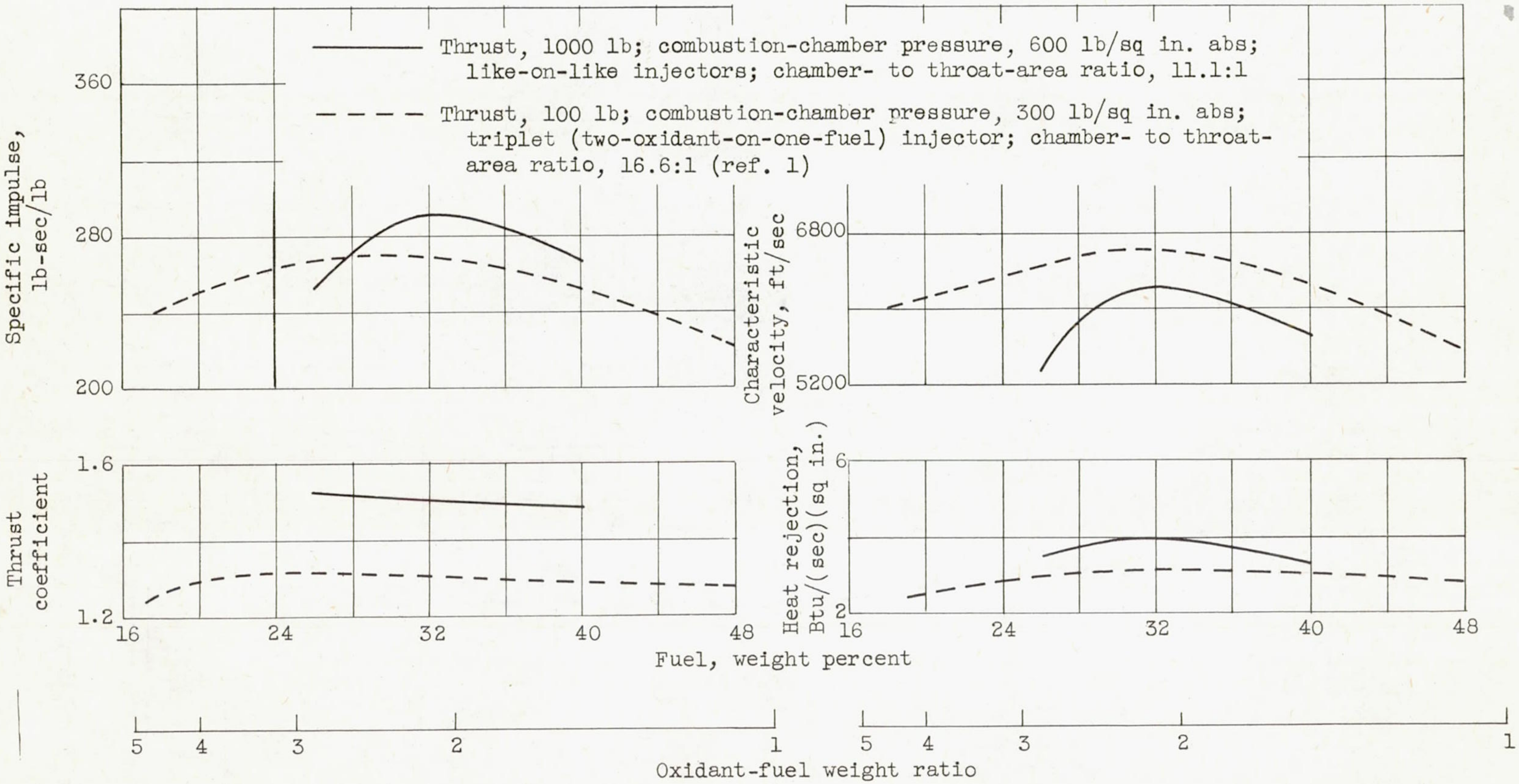


Figure 14. - Comparative performance curves of liquid fluorine - liquid ammonia propellant combination in 1000- and 100-pound-thrust rocket engines of 50-inch characteristic length.