RESEARCH MEMORANDUM

COMBUSTOR PERFORMANCE WITH VARIOUS HYDROGEN-OXYGEN INJECTION METHODS IN A 200-POUND-THRUST ROCKET ENGINE

By M. F. Heidmann and Louis Baker, Jr.

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SUMMARY

Characteristic velocity of liquid oxygen and gaseous hydrogen was determined as a function of mixture ratio in a nominal 200-pound-thrust variable-length rocket engine. Fourteen different injectors, which varied mixing and oxygen atomization, were evaluated. The heat-transfer rates were determined for seven of these injectors. Injector designs included (1) triplets of two hydrogen jets impinging on one oxygen jet with variations in impingement angle and orifice size, (2) concentric injection with hydrogen surrounding a jet of oxygen, (3) radial injection of oxygen with variations in hydrogen injection, and (4) oxygen atomization by two impinging jets with variations in hydrogen injection. The triplet and concentric arrangements were studied in both single and multiple units.

The degree of oxygen atomization appeared to be the primary factor affecting efficiency in agreement with a vaporization model of combustion. Increasing the oxygen-jet size generally produced a reduction in characteristic exhaust-velocity efficiency regardless of the atomization method.

A decrease in efficiency with an increase in mixture ratio was encountered with several injectors. This implies incomplete mixing for a combustion process limited by physical processes. The effect was most pronounced with large spacing between oxygen-injection orifices or poor dispersion from a single orifice. Hydrogen-injection changes also contributed to performance variations with mixture ratio. The method of hydrogen injection appeared to affect both oxygen atomization and dispersion.

Heat rejection showed no significant variation with injection method. Maximum heat-rejection rates of 3.5 to 4 Btu per second per square inch occurred near the stoichiometric mixture ratio.
INTRODUCTION

High combustion efficiency with a minimum of complexity is continually sought in the design of injectors for rocket engines. Realization of this goal depends on a better understanding of the effects of design on performance. In order to gain a greater insight into the effect of injector configuration on the combustion characteristics of the hydrogen-oxygen system, 14 injectors were studied in a 200-pound-thrust rocket engine. The configurations included triplet, concentric-tube, radial-jet, and self-impinging jet injectors. Some of these configurations were studied because they pertained to the design of a hydrogen-cooled injector for a larger thrust engine.

A previous study using similar apparatus (ref. 1) showed qualitatively that combustor efficiency depends more on oxygen atomization than on hydrogen dispersion or propellant mixing. The present study may be considered an extension of this work in that a more quantitative evaluation was made of the effect of these parameters on combustor performance.

The characteristic exhaust velocity \( C^* \) was measured for all the injectors over a range of mixture ratios. In some instances chamber-length variations were used to evaluate performance more accurately. Heat-transfer measurements were also made for seven of the injectors. Stability characteristics were studied separately and are reported in reference 2. Gaseous hydrogen at room temperature rather than liquid hydrogen was used for all tests because it more nearly simulated entrance conditions for a regeneratively cooled rocket engine.

INJECTORS

Triplet

Six triplet injectors with two hydrogen jets impinging on one oxygen jet, as shown in figure 1(a), were studied. These included four injectors with a single element, one with four elements, and one with nine elements. Orifice diameters of the single- and four-element injectors were equal. The diameters of the orifices in the nine-element injector were about one-half as large. Hydrogen-injection velocity, tabulated in figure 1, is the calculated velocity for isentropic flow assuming a total flow of 0.12 pound per second and a chamber pressure of 300 pounds per square inch.
Concentric Tube

Two concentric-tube injectors (fig. 1(b)) with an oxygen jet surrounded by a hydrogen annulus were used. These were a single- and a nine-element injector. The oxygen orifice diameter of the nine-element injector was about one-third that of the single-element injector.

Radial Jet

Two injectors with radial injection of eight oxygen jets (fig. 1(c)) were used. Hydrogen was injected from 10 centrally located orifices in one injector and from 45 distributed holes in the other.

Impinging Jet

Four injectors with oxygen injected as two impinging jets were used as shown in figure 1(d). Hydrogen-orifice arrangements varied as follows: (1) 45 distributed holes, (2) 16 peripheral holes, (3) 10 center holes, and (4) one center hole. Hydrogen injection velocity differed for these arrangements by a factor of about 3.

APPARATUS AND PROCEDURE

Test Facilities

Small-scale test facilities similar to those described in references 1 and 3 were used. Hydrogen, at approximately ambient temperature, was delivered to the rocket engine from high-pressure storage cylinders after one stage of pressure regulation. The flow rate, which was limited to a total flow of about 0.12 pound per second, was measured with a Venturi meter. Liquid oxygen at 140° R was supplied from a pressurized tank immersed in liquid nitrogen. Two rotary-vane-type flow meters were used to indicate oxygen flow rate. Chamber pressure was determined from the average indication of two strain-gage pressure transducers.

The combustor consisted of an injector, uncooled cylindrical chamber, and water-cooled convergent nozzle in separable units. A chamber diameter of 2 inches and a nozzle throat diameter of 0.750 inch (contraction ratio of 7.0) were used in all of the tests.

Heat-transfer rates were measured in a 2-inch long, water-cooled chamber segment adjacent to the exhaust nozzle, shown in figure 2.
Water-air spray photographs were obtained for all the injectors to show qualitatively their atomization and dispersion characteristics. The mean operating mass flow rates were simulated. This approximated jet velocity and momentum for both oxygen and hydrogen except in the region where airflow was greater than critical.

Performance Evaluation

Engine firings from 3- to 5-seconds duration, sufficient to establish steady-state operation, were used. A series of oxidant-fuel mixture ratios was run for each of several hydrogen flow rates. In this manner a mixture-ratio range of about 2 to 10 and total flow rates of about 0.4 to 0.8 pound per second were covered. Chamber lengths (cylindrical sections) from 3 to 24 inches were used. The range of operating conditions and chamber lengths differed somewhat for the various injectors.

The characteristic exhaust velocity \( C^* \) and mixture ratio \( o/f \) were evaluated for each test condition. Experimental values, expressed as \( C^* \) efficiency, are percentages of the theoretical values shown in figure 3.

Total heat transfer during a finite time interval was reduced to heat-transfer rate per unit area. The reported values were normalized to 300 pounds per square inch absolute chamber pressure by assuming direct proportionality between the heat-transfer rate and the pressure.

RESULTS AND DISCUSSION

The experimental performance values obtained with the 14 injectors are presented in table I. Performance curves, water-air spray photographs, and injector designs are shown for each injector in figures 4 to 7.

General Observations

The \( C^* \) (characteristic exhaust velocity) efficiency was generally greater than 70 percent for all injectors. As observed in reference 1 the efficiency is higher than that obtained with heptane-oxygen combination for similar injection methods (ref. 3). The result agrees with the hypothesis that propellant vaporization is a controlling process in liquid-propellant combustors. Analytical studies based on this hypothesis (ref. 4) have shown that for a given chamber length the heptane vaporization rate is about one-third that for liquid oxygen for the same initial drop size distributions.
Injectors with 0.04- to 0.047-inch-diameter oxygen orifices gave the best performance. These included the nine-element triplet, nine-element concentric-tube, and radial-jet injectors. Of these, the triplet gave the highest performance. The C* efficiency exceeded 95 percent in a 12-inch chamber length and remained above 90 percent in a 3-inch chamber length. The performance with injectors having larger oxygen orifices was generally lower. The result attests to the importance of oxygen atomization.

The performance with several injectors depended on hydrogen distribution and injection velocity. This effect was shown in the impinging oxygen-jet injector where changes in the size and orientation of the hydrogen jet caused 15-percent changes in C* efficiency.

Several of the injectors showed a pronounced decrease in C* efficiency with an increase in mixture ratio o/f. This characteristic will be subsequently discussed in the performance analysis of individual injectors.

High-frequency combustion instability was observed during some test conditions. This condition primarily occurred with high-efficiency performance. These stability characteristics were studied separately and are reported in reference 2.

**Combustion Model**

A combustion model proved useful in previous experimental studies (refs. 4 to 8) assumed propellant vaporization as the rate-controlling step in the combustion process. Reference 8 is particularly applicable to this study. It shows that the shape of the curve of characteristic exhaust velocity against oxidant-fuel ratio indicates whether the oxidant or fuel is completely vaporized. If some constant fraction of the oxidant is not vaporized, the C* efficiency is relatively constant with changes in o/f. A constant fraction of unvaporized fuel gives a pronounced decrease in efficiency with an increase in o/f.

This analysis was extended to the case of gaseous hydrogen and liquid oxygen. The assumptions used differed from those of reference 8 in the following manner: Hydrogen was assumed incompletely mixed rather than incompletely vaporized, and this unused hydrogen was assumed to have a finite volume rather than a negligible volume. The C* variations with o/f obtained with these assumptions (fig. 8) are similar to those of reference 8, that is, a constant fraction of unmixed hydrogen in the exhaust causes a decrease in C* efficiency with o/f, whereas a constant fraction of oxygen escaping unvaporized causes a constant or gradually increasing efficiency with o/f. These performance trends will aid in interpreting the experimental data.
Performance Analysis of Characteristic Exhaust Velocity

Triplet injector. - The $C^*$ performance obtained in a 12-inch chamber with the triplet injectors is summarized in figure 9(a). With single elements the performance level was nearly identical for 20° and 40° impingement angles. This represents about a 20-percent increase over nonimpinging streams. The spray photographs (fig. 4) show a comparable change in that the improvement in atomization and dispersion is more pronounced for an impingement-angle change of 0° to 20° than for a change of 20° to 40°. The higher $C^*$ efficiency observed with the nine-element injector than for the four-element injector may also be attributed to better spray properties. Increasing the number of orifices and decreasing the diameter of the orifices should improve atomization and dispersion of oxygen.

All the single-element injectors show a decrease in $C^*$ efficiency with an increase in oxidant-fuel ratio. This implies incomplete propellant mixing. With single elements the liquid oxygen is concentrated along the chamber axis and hydrogen is dispersed over a 1-inch radial distance from this axis. Mixing processes, therefore, must take place over a lateral distance of 1 inch for complete mixing. Therefore, improved mixing would be expected from a decrease in this lateral mixing distance. The four-element injector is an example of such a change. In this case, four elements identical to the single element were used in the 2-inch-diameter chamber. The lateral mixing distance was reduced considerably; the gradual rise in $C^*$ efficiency with o/f obtained experimentally is evidence of a marked increase in mixing.

The performance obtained with the off-center single-element injector is another example of a change in lateral mixing distance. The effective mixing distance is larger than that of an equivalent central element. The decrease in efficiency obtained may be attributed to poor mixing.

An example of a change in mixing with chamber length is shown by the nine-element-injector performance in figures 4(d) and (e). As chamber length is reduced, injector performance develops a trend of decreasing $C^*$ efficiency with o/f which indicates less complete mixing in short chambers.

A decrease in $C^*$ efficiency with o/f was also observed in reference 1. This primarily occurred when one instead of two oxygen orifices were used. The larger lateral mixing distance with single orifice would account for this performance trend.

Analyzing the data in this manner shows that lateral mixing in some instances is a rate-limiting process in combustion. Generalizing the results for triplets shows that the chamber length at which mixing is complete varies with spacing between oxygen orifices. Interpolation of
the experimental data shows that complete mixing is obtained in a length of 8 inches with 3/8-inch spacing, 13 inches with 0.7-inch spacing, and considerably more than 12 inches for a single element representing a 2-inch spacing. As a rough rule-of-thumb, therefore, chamber length must be about 20 times larger than the spacing between oxygen orifices in order to assure complete mixing.

**Concentric-tube injector.** - The performance of the concentric-tube injectors is summarized in figure 9(b). Qualitatively the performance is similar to that obtained with triplet injectors for equivalent size oxygen orifices. Single-element performance again decreases rapidly with an increase in o/f indicating incomplete mixing. The poorer dispersion with the single-element injector than with the nine-element injector is shown by the spray photographs in figure 5 and suggests inefficiency caused by incomplete lateral mixing. Therefore, for concentric-tube injectors dispersion of the oxygen as well as atomization is required for high performance.

**Radial-jet injector.** - The performance obtained with radial oxygen jets is summarized in figure 9(c). Hydrogen was concentrated near the chamber axis with one injector and uniformly distributed with the other. By adjusting for the differences in chamber lengths used the C* efficiency was about the same for both injectors in the high o/f region, but centrally injected hydrogen was definitely better in the low o/f region. Apparently, oxygen atomization differed in this region. With central injection the hydrogen jets were of higher velocity and orientated for a greater exchange of momentum with the oxygen than with distributed injection. As a result, oxygen atomization was improved as shown by the photographs in figure 6. This difference apparently affected performance only when a high proportion of hydrogen to oxygen existed (low o/f region).

**Impinging oxygen-jet injector.** - The performance of the impinging oxygen-jet injectors in which hydrogen was injected in various orientations is summarized in figure 9(d).

Injecting hydrogen through a 45-hole plate gave a C* efficiency of 88 percent with no significant change with o/f. On the basis of the combustion model, incomplete oxygen vaporization is implied with full utilization of the hydrogen. This injector introduced the hydrogen uniformly and at a low velocity. The spray photographs (figs. 7(a) and (b)) show no effect of hydrogen flow on the atomization process. This C* performance, therefore, will be used as a reference condition in evaluating the effect of changes in hydrogen injection.
The C\* efficiency level was less than 85 percent with hydrogen injected from 16 peripheral holes. Such a hole arrangement suggests poorly mixed propellants. The rising C\* efficiency with o/f, however, implies incomplete oxygen vaporization rather than incomplete mixing. The efficiency level is also lower than with the 45-hole plate indicating less complete oxygen vaporization. Corresponding changes in oxygen atomization are not evident in the spray photographs of figures 7(a) to (d); however, conditions may differ considerably within the combustor.

Incomplete mixing is implied by the performance curve obtained with hydrogen injected centrally from 10 holes. The high performance level, however, also indicates improved oxygen atomization. The spray photographs (figs. 7(e) and (f)) show that oxygen atomization is affected by hydrogen flow and that oxygen is directed away from the axis of the chamber which may contribute to poor mixing.

Hydrogen injected from a single center hole gave an increase in C\* efficiency with an increase in o/f. The spray photographs (figs. 7(g) and (h)) again show that oxygen atomization is affected by hydrogen flow. This effect presumably varies with o/f. The over-all effect on C\* efficiency is not clear, however, because changes in drop size, drop acceleration, and oxygen dispersion would occur simultaneously with changes in o/f. At low o/f values, such interaction apparently causes performance losses.

Heat Transfer

The heat-transfer data are summarized in figure 10. The rates reported are the average values for a 2-inch chamber segment installed near the exhaust nozzle. Heat-transfer rates were usually of the order of 3 to 4 Btu per second per square inch. The maximum rate was obtained near the stoichiometric oxidant-fuel ratio of 8. The higher performance injectors generally gave the highest heat-injection rates. The results deviate from this trend in the low mixture ratio region, and the distinction between injectors is less evident. A heat-transfer rate of 3.08 Btu per second per square inch at an o/f of 3.2 was computed theoretically for this engine configuration. A gas-side wall temperature of 450° F and gas-film properties at 2300° F were assumed for these calculations. Experimental rates at this o/f are within 10 percent of this value.

A greater differentiation between injectors would be expected for average values for the entire chamber length. Measurements for different chamber lengths were obtained for several injectors. The C\* efficiency changes with length, however, were small and did not significantly affect heat transfer at the measuring station.
A heat-transfer rate from 3 to 4 Btu per second per square inch results in a loss in performance of about 1 percent per 6 inches of chamber length. The C* efficiencies have not been corrected for these losses. The corrections become significant when performance changes with chamber length are analyzed.

SUMMARY OF RESULTS

A study of propellant atomization and distribution with 14 different injectors using liquid oxygen and gaseous hydrogen has shown that C* performance primarily depends on the effectiveness of oxygen atomization. Injecting oxygen by a 0.040-inch-diameter jet gave a C* efficiency of about 90 percent in a 3-inch chamber length. Increasing the oxygen-jet size generally gave a reduction in efficiency regardless of the injection method.

Variations in design of specific injection methods gave the following results.

(1) Triplet: Single-element performance increased with impingement angle up to an included angle of 20°. Multiple elements showed less variations in C* efficiency with o/f than single elements. Element spacing or oxygen dispersion appeared important in these variations implying that lateral mixing limits the combustion-rate process.

(2) Concentric tube: Performance level was comparable with that obtained with triplet injectors.

(3) Radial jet: An orientation of hydrogen and oxygen jets to give maximum interchange of momentum gave the highest C* efficiency.

(4) Impinging jet: Variations in hydrogen distribution and injection velocity affected both C* efficiency level and variations in efficiency with o/f. Compared with the condition of uniformly distributed hydrogen at low injection velocity, the interaction between hydrogen jets and oxygen sprays in some instances caused performance losses.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 14, 1958
REFERENCES


TABLE I. SUMMARY OF EXPERIMENTAL INJECTOR PERFORMANCE
(a) Triplet injector

[One axial liquid-oxygen jet, two impinging hydrogen jets per element.]

<table>
<thead>
<tr>
<th>Run</th>
<th>Chamber length, in.</th>
<th>Impingement angle, deg</th>
<th>Fuel injection flow, lb/sec</th>
<th>Fuel injection velocity, ft/sec</th>
<th>Oxidant injection flow, lb/sec</th>
<th>Oxidant injection velocity, ft/sec</th>
<th>Total weight flow, lb/sec</th>
<th>Total weight flow, lb/sec abs</th>
<th>Chamber pressure, lb/sq in. abs</th>
<th>Oxidant weight ratio</th>
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<th>Percent of theoretical</th>
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Single element; oxygen flow area, 0.0075; hydrogen flow area, 0.0433

Four elements; oxygen flow area, 0.0302; hydrogen flow area, 0.1731

Nine elements; oxygen flow area, 0.0113; hydrogen flow area, 0.0951
### TABLE I. - Continued. SUMMARY OF EXPERIMENTAL INJECTOR PERFORMANCE

#### (b) Concentric-tube injector

<table>
<thead>
<tr>
<th>Run</th>
<th>Chamber length, in.</th>
<th>Fuel weight flow, lb/sec</th>
<th>Fuel-injection velocity, ft/sec</th>
<th>Oxidant weight flow, lb/sec</th>
<th>Total weight flow, lb/sec</th>
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#### Nine elements; oxygen flow area, 0.0113; hydrogen flow area, 0.0839

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<th>Hydrogen flow area, 0.0490</th>
<th>Hydrogen flow area, 0.0136 sq in.</th>
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#### (c) Radial-jet injector

<p>| Hydrogen injection plate 2 (nine center holes); area, 0.1668 sq in. |
|--------------------------|---------------------------------------------------------------|</p>
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<tr>
<td>261</td>
<td>0.0134</td>
<td>210</td>
</tr>
</tbody>
</table>

---

### Footnotes

- *C* refers to the characteristic velocity of the exhaust. The values are based on theoretical calculations and experimental measurements.
TABLE I. - Concluded. SUMMARY OF EXPERIMENTAL INJECTOR PERFORMANCE
(d) Impinging-jet, series I injector

<table>
<thead>
<tr>
<th>Run</th>
<th>Chamber length, weight flow, lb/sec</th>
<th>Fuel injection length, weight flow, ft/sec</th>
<th>Oxidant weight flow, lb/sec</th>
<th>Total weight flow, lb/sec</th>
<th>Chamber pressure, lb/sq in</th>
<th>Oxidant-fuel ratio</th>
<th>Characteristic exhaust velocity, C, ft/sec</th>
<th>Percent of theoretical rate, Btu/(sec sq in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>82</td>
<td>14</td>
<td>0.1063</td>
<td>0.422</td>
<td>0.528</td>
<td>255</td>
<td>3.97</td>
<td>6830</td>
<td>85.6</td>
</tr>
<tr>
<td>77</td>
<td>0.0922</td>
<td>350</td>
<td>0.471</td>
<td>0.594</td>
<td>259</td>
<td>3.82</td>
<td>5795</td>
<td>72.7</td>
</tr>
<tr>
<td>69</td>
<td>0.0877</td>
<td>355</td>
<td>0.475</td>
<td>0.594</td>
<td>259</td>
<td>3.82</td>
<td>5795</td>
<td>72.7</td>
</tr>
<tr>
<td>86</td>
<td>0.0705</td>
<td>3100</td>
<td>0.355</td>
<td>0.424</td>
<td>224</td>
<td>5.01</td>
<td>7470</td>
<td>96.4</td>
</tr>
<tr>
<td>88</td>
<td>0.0866</td>
<td>3450</td>
<td>0.567</td>
<td>0.634</td>
<td>291</td>
<td>8.51</td>
<td>6490</td>
<td>94.6</td>
</tr>
</tbody>
</table>

Hydrogen injection plate 1 (one center hole); area, 0.056 sq in.

Hydrogen injection plate 2 (nine center holes); area, 0.166 sq in.

Hydrogen injection plate 3 (16 peripheral holes); area, 0.1965 sq in.

Hydrogen injection plate 4 (45 holes); area, 0.6286 sq in.
Figure 1. - Injector designs.

(a) Triplet injector.
### Table

<table>
<thead>
<tr>
<th></th>
<th>Single element</th>
<th>Nine element</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total flow area, sq in.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.0108</td>
<td>0.0113</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.0490</td>
<td>0.0939</td>
</tr>
<tr>
<td><strong>Oxygen orifice diam., in.</strong></td>
<td>0.117</td>
<td>0.040</td>
</tr>
<tr>
<td><strong>Hydrogen annular width, in.</strong></td>
<td>0.0825</td>
<td>0.044</td>
</tr>
<tr>
<td><strong>Hydrogen-injection velocity, ft/sec (0.12 lb/sec)</strong></td>
<td>2985</td>
<td>1675</td>
</tr>
</tbody>
</table>

(b) Concentric-tube injector.

Figure 1. - Continued. Injector designs.
(c) Radial-jet injector.

Figure 1. - Continued. Injector designs.
(d) Impinging oxygen-jet injector.

**Figure 1.** Concluded. Injector designs.
Figure 2. - Water-cooled chamber segment used for heat-rejection measurements showing section view of coolant passages.
Figure 3. - Theoretical variation of characteristic exhaust velocity with mixture ratio for hydrogen and oxygen.
Single element; impingement angle, $\alpha$, 0° (parallel jets), 20°, and 40°

Single element offcenter; impingement angle, $\alpha$, 20°

(a) Single-element configuration; chamber length, 12 inches.

Figure 4.- Performance of triplet injectors.
No airflow  Impingement angle, 0°  Impingement angle, 20°  Impingement angle, 40°

(b) Single-element configuration. Flow rates: water, 0.211 pound per second; air, 0.036 pound per second.

Figure 4. - Continued. Performance of triplet injectors.
Figure 4. - Continued. Performance of triplet injectors.

(c) Four-element configuration.
(d) Nine-element configuration.

Figure 4. - Continued. Performance of triplet injectors.
(e) Nine-element configuration. Flow rates: water, 0.370 pound per second; air, 0.058 pound per second.

Figure 4. - Concluded. Performance of triplet injectors.
(a) Single-element configuration.

Figure 5. - Performance of concentric-tube injector.
(b) Single-element configuration. Flow rates: water, 0.330 pound per second; air, 0.040 pound per second.

Figure 5. - Continued. Performance of concentric-tube injector.
(c) Nine-element configuration.

Figure 5. - Continued. Performance of concentric-tube injector.
(d) Nine-element configuration. Flow rates: water, 0.370 pound per second; air, 0.032 pound per second.

Figure 5. - Concluded. Performance of concentric-tube injector.
(a) 45-Distributed-hole plate.

Figure 6. - Performance of radial-jet injectors.
Figure 6. - Continued. Performance of radial-jet injectors.
Figure 6. - Continued. Performance of radial-jet injectors.
(d) Nine-center-hole plate. Flow rates: water, 0.320 pound per second; air, 0.105 pound per second.

Figure 6. - Concluded. Performance of radial-jet injectors.
Figure 7. - Performance of impinging oxygen-jet injectors.

(a) 45-Distributed-hole plate.
(b) 45-Distributed-hole plate. Flow rates:
water, 0.305 pound per second; air, 0.110
pound per second.

Figure 7. - Continued. Performance of im-
pinging oxygen-jet injectors.
Figure 7. - Continued. Performance of Impinging Oxygen-Jet Injectors.

(a) 16-perforated-hole plate.
(d) 16-Peripheral-hole plate. Flow rates: water, 0.305 pound per second; air, 0.107 pound per second.

Figure 7. - Continued. Performance of impinging oxygen-jet injectors.
Figure 7. - Continued. Performance of impinging oxygen-jet injectors.

(e) Nine-center-hole plate.
(f) Nine-center-hole plate. Flow rates: water, 0.300 pound per second; air, 0.103 pound per second.

Figure 7. - Continued. Performance of impinging oxygen-jet injectors.
(g) One-center-hole plate.

Figure 7. - Continued. Performance of impinging oxygen-jet injectors.
(h) One-center-hole plate. Flow rates: water, 0.305 pound per second; air, 0.020 pound per second.

Figure 7. - Concluded. Performance of impinging oxygen-jet injectors.
Figure 8. The effect of incomplete oxygen vaporization and incomplete hydrogen mixing on characteristic exhaust velocity.
Figure 9. - Summary of injector performance.
Figure 9. - Concluded. Summary of injector performance.
Figure 10. - Summary of heat rejection for various injectors.