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RESEARCH MEMORANDUM

EFFECT OF FUEL DROP SIZE AND INJECTOR CONFIGURATION ON SCREAMING IN A 200-POUND-THRUST ROCKET ENGINE USING LIQUID OXYGEN AND HEPTANE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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EFFECT OF FUEL DROP SIZE AND INJECTOR CONFIGURATION ON SCREAMING IN A 200-POUND-THRUST ROCKET ENGINE USING LIQUID OXYGEN AND HEPTANE

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SUMMARY

The tendency to cause rocket screaming and the amplitude of screaming were observed for each of six different injectors in a 200-pound-thrust rocket engine using liquid oxygen and heptane. The results show that the over-all features of propellant preparation primarily determine screaming amplitude. The largest amplitudes were observed with a triplet injector. For two injectors differing only in the mean fuel drop size produced, screaming amplitude varied inversely with drop diameter.

INTRODUCTION

Screaming (high-frequency combustion pressure oscillations) continues to be one of the more important problems in rocket-engine development. The modes and results of screaming are well-chronicled (for example, ref. 1), but a generalized solution is still sought. For some engines, changes in injector design have eliminated screaming. In others, attenuation is sought through the use of baffles and other acoustical absorbers (refs. 2 and 3).

Among the factors that influence the tendency of an engine to scream are injector configuration (refs. 4 and 5), fuel type (ref. 6), and possibly combustor geometry. In reference 6, the screaming tendency of a series of fuels was correlated with the rate of propellant vaporization; the fuels with the greatest vaporization rate had the greatest screaming tendency. Recent theoretical and experimental studies of the effect of propellant drop evaporation indicate that this process may largely determine the performance efficiency of a rocket engine (ref. 7). If drop evaporation is a rate-controlling step in the combustion of liquid

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propellants, initial drop diameter also might have an appreciable effect on screaming because of the influence on the energy release rate. This report describes the results of an experimental study of the effect of fuel drop size on screaming in a 200-pound-thrust rocket engine using liquid oxygen and heptane.

Two spray nozzles of different capacities provided two mean drop sizes having a diameter ratio of about 2. A triplet and a like-on-like injector, both of conventional configuration, were used for comparison. The effect of injection at the axial midpoint of the chamber also was studied briefly. The amplitude and the frequency of chamber-pressure oscillations were measured with a high-frequency-response pressure transducer over a range of oxidant-fuel weight ratios for each injector.

APPARATUS AND PROCEDURE

The engine was designed for a thrust of 200 pounds at 300-pound-per-square-inch chamber pressure with liquid oxygen and heptane; figure 1 shows the geometry and the location of instrumentation. The uncooled chambers were made of mild steel tubing, 4 inches inside diameter by 5.5 inches outside diameter; chamber length was 16 inches. The nozzle had a convergent section only, with a water-cooled copper throat.

Injectors

The eight injectors used in this study can be catalogued under two configurations, axial and radial. The radial configurations were placed at the midpoint of the chamber as shown in figure 1(b). Two spray-nozzle injectors, a like-on-like injector, and a triplet injector were used in each configuration (shown schematically in fig. 2). The triplet and the like-on-like injectors were relatively conventional and need no further description. The spray-nozzle injectors differed only in the mean drop size produced, and therefore were used to study the effect of fuel drop size, with other factors essentially constant. These spray-nozzle injectors will be referred to as the small-drop (axial or radial) and the large-drop (axial or radial) injectors.

The spray-nozzle injectors were designed to permit change of fuel drop size by merely interchanging fuel spray nozzles. These nozzles were core-type, hollow-cone, and pressure-atomizing, like those of reference 8. The large-drop and the small-drop spray nozzles had orifice diameters of 0.076 and 0.042 inch, respectively. The following equation, obtained in reference 8, gives the mean drop diameter $\bar{D}$ produced by this type of nozzle in quiescent air, the point of measurement being 10 feet from the nozzle:

$$\bar{D} = 16.56\, d_o^{1.52}\, \dot{w}^{-0.444} \nu^{0.713} \mu^{0.159}$$

(where $\dot{w}$ is given in grams per second and d_o is given in millimeters.) All symbols are defined in appendix A. Figure 3 shows the mean drop diameter as a function of flow rate, as calculated from this equation for the large- and small-drop nozzles. The fluid properties of heptane were used. Over the range of flow rates of interest, the ratio of the mean drop diameter produced by these nozzles was about 2.5.

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Because of the large environmental differences between rocket-engine conditions and the test conditions of reference 8, this equation probably would not represent the mean drop diameter produced by these spray nozzles when used in a rocket engine. However, the ratio of diameters is the significant factor in this experiment.

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Figure 3 also gives the pressure drops across the nozzles as a function of flow rate. The points shown are the mean drop diameter and the pressure drop at the experimental average value of the flow rate per nozzle for each nozzle.

Figure 4 shows the sprays produced when operating with water at pressure drops of 25 and 225 pounds per square inch for the large- and small-capacity spray nozzles, respectively. A difference in coarseness is readily observed.

The liquid oxygen in the spray-nozzle injectors was passed through 24 flat-spray atomizing nozzles, located so that each fuel spray was surrounded by oxygen. The outer ring of oxygen sprays (axial form of the injector) was directed at an angle of 15° toward the chamber axis to minimize wetting of the wall. These injectors were designed to provide identical preparation of the propellants, except for fuel drop size. The method of introduction was expected to vaporize the oxygen rapidly and thus emphasize the effect of fuel drop size on combustion.

Ignition

For the axial injectors, ignition was accomplished with a sparkplug about 3 inches downstream of the injectors. Spark ignition was also successful for the like-on-like radial injector. Ignition with the other radial injectors, however, was difficult. For these, the sparkplug was replaced with a propane-oxygen torch (both gases) placed at the closed end of the chamber. The torch was turned off after ignition was achieved.

Instrumentation

Propellant flows were measured by rotating-vane-type flowmeters (accuracy, ±2 percent). Average chamber pressure was measured by a strain-gage-type pressure transducer (accuracy, ±2 percent).

The amplitude of chamber-pressure oscillations was measured with a flush-mounted high-frequency-response pressure pickup located as shown in figure 1. The output of this water-cooled pickup was fed into an oscilloscope and was recorded with a continuous-strip camera. The natural frequency of the pickup is of the order of 20,000 cycles per second. 4702

RESULTS

Performance

The characteristic exhaust velocity c^* was determined for each run from average values of chamber pressure, total flow rate, and nozzle throat area. Theoretical values c^*_{th} for liquid oxygen and heptane are shown in figure 5. The performance of each injector is shown in figure 6 as the ratio c^*/c^*_{th}. For most injectors, performance increased slightly as the oxidant-fuel weight ratio O/F was increased. The arithmetic average values of c^*/c^*_{th} for each injector (dashed lines in fig. 6) are summarized in table I. These values ranged from 86.9 percent for the axial large-drop injector to 93.5 percent for the axial like-on-like injector. The radial large-drop and like-on-like injectors gave performance similar to that of their axial counterparts. No data were obtained for the two remaining radial injectors. The radial triplet injector experienced seven extremely rough burning runs, one of which destroyed the exhaust nozzle, and the last of which destroyed the oxygen manifolding by internal explosion. This behavior is believed to have been caused by the drainage of fuel into the lower oxygen orifices. With the radial small-drop injector, the fuel nozzles were subject to cracking along the root diameter of the last thread. When this occurred, added fuel flow through the crack lowered the performance and decreased the oxidant-fuel ratio O/F to such an extent that the data were no longer comparable with those of the other injectors.

Screaming Amplitudes

The instantaneous chamber-pressure records were scanned to determine the maximum peak-to-peak screaming amplitude ΔP for each run. The oscillations were not of constant amplitude and at times disappeared completely. The maximum amplitude reported was not that of an isolated pressure excursion, but was the maximum value over several consecutive cycles. The ratio $\mathscr{A}$ of this amplitude ΔP to the average absolute chamber pressure P_c (measured with the slower response transducer) is shown in figure 7 as a function of O/F for each injector. The line through the data is the arithmetic average value of $\mathscr{A}$ for that injector. These values, summarized in table I, ranged from 0.02 to 0.38 for the radial large-drop and axial triplet injectors, respectively. As explained under performance results, no data were obtained for the radial triplet and radial small-drop injectors.

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Oscilloscope records of typical oscillations are shown in figure 8. The predominant mode of oscillation, based on observed frequencies of 1200 cycles per second, was longitudinal with all injectors except the radial like-on-like and the axial triplet. The longitudinal mode is illustrated by the record of figure 8(a) obtained with the axial small-drop injector.

For the radial like-on-like injector, frequencies of about 1200, 6000, and 12,000 cycles per second were observed. Figure 8(b) shows the general character of these oscillations excluding the 1200-cycle-per-second oscillation. The 12,000-cycle-per-second oscillation is clearly resolved in some portions of the record and appears to persist at a diminished amplitude in other portions. Two amplitudes, not entirely independent, were determined for this injector. These amplitudes depended on the frequency of oscillation. The larger amplitude was observed at frequencies of 6000 or 12,000 cycles per second, and the smaller amplitude was observed at frequencies of 1200 or 6000 cycles per second. The two frequency-dependent amplitudes are shown as a function of O/F in figure 7(f).

For the axial triplet injector, a frequency of about 6000 cycles per second indicated a transverse mode. Figure 8(c) shows this mode and also the 1200-cycle-per-second mode superimposed on it. The occurrence (often simultaneous) of two frequencies during a run was common.

Calculation of Average Fuel Drop Diameter

The theory and the method of reference 7 were used to calculate from experimental data a mass-median fuel drop diameter $D_{g,M}$ for each injector; the equation and data are given in appendix B with limitations of the method. The drop diameters $D_{g,M}$ thus calculated are summarized in table I and are compared with the values $\overline{D}$ previously calculated for the two spray nozzles by the equation of reference 8 (given in APPARATUS AND PROCEDURE). The drop diameters ($\overline{D}$ and $D_{g,M}$) calculated by these two equations do not agree, although the ratio of diameters (large/small) is very nearly the same. The two equations do not define the same mean

diameter; however, from the frequency-size data given in reference 8, an approximate mass-median diameter that agreed closely with the log mean value $\overline{D}$ was calculated. Part of the quantitative difference in drop diameters $\overline{D}$ and $D_{g,M}$ can be attributed to the comparatively long distance available for atomization in reference 8. Other differences in spray environment (previously mentioned in the section "Injectors") would be expected to increase this discrepancy. Also, the performance measurements were those of oscillatory combustion tests and not those of the steady-state operation assumed in reference 7. If the increased average 4702
velocity of chamber gases under oscillatory conditions is considered, $D_{g,M}$ would increase; this would further increase the discrepancy between the two values ($D_{g,M}$ and $\overline{D}$) of drop diameter. A large part of the discrepancy may be due to the limitations of the analysis of reference 7, as discussed in appendix B. Although poor quantitative agreement was not found between $D_{g,M}$ and $\overline{D}$, the assumption of drop vaporization as a controlling process during combustion appears consistent, since the agreement of drop-diameter ratios is good.

DISCUSSION

The most serious screaming (based on amplitude) encountered among the axial injectors occurred with the triplet, for which amplitudes were an order of magnitude greater than for the other injectors. Also, the mode of oscillation was transverse (6000 cps) rather than longitudinal. The magnitude of oscillation observed for the axial like-on-like injector was quite similar to that produced by the spray-nozzle injectors. Apparently the propellant preparation by these injectors is very similar. The spray-nozzle injectors, designed to differ only in the mean drop size produced, afford a direct study of the effect of fuel drop diameter where other factors are essentially constant. Although the effect of fuel drop diameter appears to be secondary to that of the over-all methods of propellant preparation, nevertheless a possible explanation is of interest.

For the axial spray-nozzle injectors, the data show that the ratio of the amplitudes $\mathscr{A}_s/\mathscr{A}_l$ varied inversely with the mean fuel drop diameter for the two sprays studied. It is assumed that amplitude is proportional to the energy available per unit time to drive the instability and that this energy is proportional to the evaporation rate of fuel drops. Only the fuel was considered, since any contribution by the oxygen presumably would be the same for both drop diameters. The evaporation rate of a drop (ref. 9) is

$$\frac{dm}{dt} \propto D^{1.5}$$

For a mass-mean diameter D_m, the total energy dE/dt available per unit time is

$$\frac{dE}{dt} \propto n \frac{dm}{dt}$$

The number of drops evaporating is

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$$n \propto \frac{\dot{w}}{D_m^3}$$

Thus, if the amplitude is proportional to the energy released per unit time and if the energy is proportional to the evaporation rate of fuel drops, then

$$\mathscr{A} \propto \frac{dE}{dt} \propto \frac{\dot{w}}{D_m^3} D_m^{1.5} = \frac{\dot{w}}{D_m^{1.5}}$$

or the ratio of amplitudes $\mathscr{A}_s/\mathscr{A}_l$ for the small- and large-drop diameters is

$$\frac{\mathscr{A}_s}{\mathscr{A}_l} = \frac{\dot{w}_s}{\dot{w}_l}\left(\frac{D_{m,l}}{D_{m,s}}\right)^{1.5}$$

The experimental value of $\mathscr{A}_s/\mathscr{A}_l$ was 2.45. The calculated values, using average flow rates, were 3.0 based on $\overline{D}$ and 3.5 based on $D_{g,M}$. Thus, the calculated values compare favorably with the experimental value.

Midpoint injection did not appear to produce any significantly different results with the radial large-drop injector. Longitudinal oscillations might be expected to occur as the second harmonic with midpoint injection. Energy dissipation for the second harmonic is larger than for the fundamental, and therefore lower amplitudes would be expected. However, from the observed frequencies, the second harmonic did not occur. The 12,000-cycle-per-second oscillation observed with the radial like-on-like injector does not correspond in frequency to that expected for a transverse mode. The record (fig. 8(b)) suggests that two waves, each of 6000 cycles per second, were traveling independently about the chamber. The amplitudes of the two waves varied randomly but generally in the same direction. The significance of this result is rather obscure. From presently accepted theories of acoustic oscillations in a cylindrical chamber, it seems unlikely that two independent waves could exist simultaneously in the chamber. Both radial injectors gave smaller amplitudes than their axial counterparts when only the longitudinal frequencies are compared. Following the preceding arguments on drop size, this result could be caused by the agglomeration of drops, since the sprays converge at the center of the chamber. It might also result from the fact that the axial midpoint of the chamber, where injection occurs, corresponds to an acoustical pressure node for the first harmonic in a simple system. An acoustic wave presumably cannot be driven by heat addition at such a point.

In previous studies, the tendency for screaming with triplet-type injectors has been explained in terms of a driving mechanism. Possibly the damping of the system also is affected by injector design; a discussion of the effect on damping follows. 4702

The most obvious difference between the triplet injector and any of the other injectors is that it forces liquid-phase contact of the propellants. As a result, the triplet might be expected to produce a better mixed and more concentrated propellant distribution, compared with other injectors. The data of reference 5 substantiate these considerations by showing that a triplet injector gives a very rapid and localized heat release. Assuming that the mixture preparation theory is correct, then a more uniform temperature (or density) distribution would exist in the chamber. In the case of a reflected shock wave interacting with transverse temperature and velocity gradients in a shock tube, the shock strength was attenuated (ref. 10). Assuming that the oscillations under consideration here behave similarly leads to the speculation that, compared with the other injectors, less damping of the oscillation occurred with the triplet. That the triplet injector was able to sustain a higher frequency oscillation also indicates that this injector produces a propellant mixture that has a shorter combustion time delay than the mixture produced by other injectors.

CONCLUDING REMARKS

The results indicate that the method of injection is of prime importance in determining amplitude. Fuel drop size appeared to be of secondary importance, compared with the general character of propellant preparation. For example, instability was much more severe with a triplet injector than with other injectors. This result may be attributed to more uniform mixing of propellants by the triplet injector, with attendant uniform temperature or density throughout the chamber.

For the spray nozzle injectors pressure amplitude varied inversely with mean fuel drop diameter. This relation appears to support a hypothesis that the combustion energy available to drive the oscillations is influenced by the vaporization rate of the fuel. This conclusion was previously reached in reference 4 from tests with fuels having large differences in latent heat of vaporization.

Injection at the axial midpoint of the chamber increased stability slightly, if longitudinal modes are compared; however, the radial like-on-like injector gave large amplitudes at frequencies of 6000 and 12,000 cycles per second. The exact role of midpoint injection is not clearly defined from these experiments.

Simultaneous occurrence of both longitudinal and transverse oscillations was frequently observed and, based on frequency relations only, the oscillations appeared to act independently of each other.

Among the large number of additional parameters that may affect engine stability are chamber geometry and mass distribution of propellant, and the numerous possible interaction effects. These additional complexities make it evident that oscillatory combustion problems in rocket engines require much work before a solution can be applied *a priori* to new engine developments.

SUMMARY OF RESULTS

An investigation of combustion instability in a 200-pound-thrust rocket engine has indicated the following results for liquid oxygen and heptane propellants:

1. Instability was most pronounced with an impinging-jet-type injector that gave pressure amplitudes an order of magnitude greater than the other injectors.

2. Although it appeared to be a second-order effect, amplitude varied inversely with mean fuel drop diameter under conditions where other factors were constant. This relation was explained in terms of the rate of energy release by evaporating drops.

3. Injection of propellants radially in from the circumference at the axial midpoint of the chamber had no stabilizing effect.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, January 28, 1958

APPENDIX A

SYMBOLS

$\mathscr{A}$	ratio $\Delta P/P_c$
c^*	characteristic exhaust velocity, ft/sec
c^*_{th}	theoretical characteristic exhaust velocity, ft/sec
D	drop diameter
$\bar{D}$	mean drop diameter, $\dfrac{\sum nD^3 \log D}{\sum nD^3}$ (ref. 8), microns
$D_{g,M}$	mass-median drop diameter, microns
D_m	mass-mean drop diameter
d_o	injector orifice diameter, in. except where noted
$\dfrac{dE}{dt}$	total energy per unit time
L	chamber length, in.
L_{eff}	effective chamber length, in.
$M_{g,M}$	mass-median drop radius, in.
$\dfrac{dm}{dt}$	drop mass evaporation rate
n	number of drops evaporating
O/F	oxidant-fuel weight ratio
ΔP	maximum peak to peak screaming amplitude, lb/sq in.
P_c	average chamber pressure, lb/sq in.
T	fuel injection temperature, °R

u_{fin} theoretical final gas velocity, ft/sec

v_0 injection velocity, in./sec

$\dot{w}$ flow rate of fuel, lb/sec except where noted

μ viscosity, centipoise

ν surface tension, dynes/cm

ρ fuel density, lb/cu ft

Subscripts:

l large drop

s small drop

APPENDIX B

CALCULATION OF MEAN FUEL DROP DIAMETER

The theoretical study of reference 7 relates the percentage of fuel vaporized to drop diameters. The range of test conditions in the present study differed appreciably from those assumed in the theoretical analysis, particularly in the final theoretical gas velocity and in the injection velocity. Thus, drop diameters calculated by this theory are 4702
approximate.

From this theory, the effective chamber length required to vaporize a given fraction of the fuel can be calculated for any drop diameter. The analysis also included the effect of drop-size distribution. The percent fuel vaporized was assumed to be proportional to c^*/c^*_{th}. For the present case a geometric standard deviation of 2.3 (ref. 7) was assumed; and, for the average values of c^*/c^*_{th} (percent fuel vaporized), values of effective chamber length were obtained from figure 10 of reference 7 for each injector. A mass-median drop diameter was calculated from the following equation:

$$L_{eff} = \frac{L P_c^{0.55} u_{fin}^{0.25} T^{0.25} (4.15\times10^{-5})}{M_{g,M}^{1.45} v_0^{0.75}}$$

Average experimental values of these parameters were used in the calculation. The chamber length was somewhat indeterminate with the radial injectors, and the calculation was not made. The injection velocity v_0 for the spray nozzles was calculated by the Bernoulli theorem and the average value of the pressure drop across the nozzles (shown in fig. 3).

The velocity coefficient was assumed to be 0.95. For the other injectors, injection velocity was obtained from the continuity equation. These values and the results are given for the axial injectors only in the following table:

[Density, 42.7 lb/cu ft; final gas velocity, 1380 in./sec; fuel injection temperature, 530° R; chamber length, 16 in.]

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	Injector			
	Small-drop	Large-drop	Like-on-like	Triplet
c^*/c^*_{th}, percent	93.0	86.9	93.5	90.6
L_{eff}, in. (ref. 7, fig. 10)	11.7	8.5	12.3	10.4
$\dot{w}$, lb/sec	0.236	0.283	0.311	0.286
$\dot{w}$ per hole, lb/sec	0.0295	0.0354	0.0194	0.0357
v_0, in./sec	4100	1075	1656	1680
P_c, lb/sq in.	260	273	332	289
$M_{g,M}$, in.	0.0013	0.0034	0.0023	0.0024
$D_{g,M}$, microns	66	173	117	122

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TABLE I. - SUMMARY OF TEST DATA

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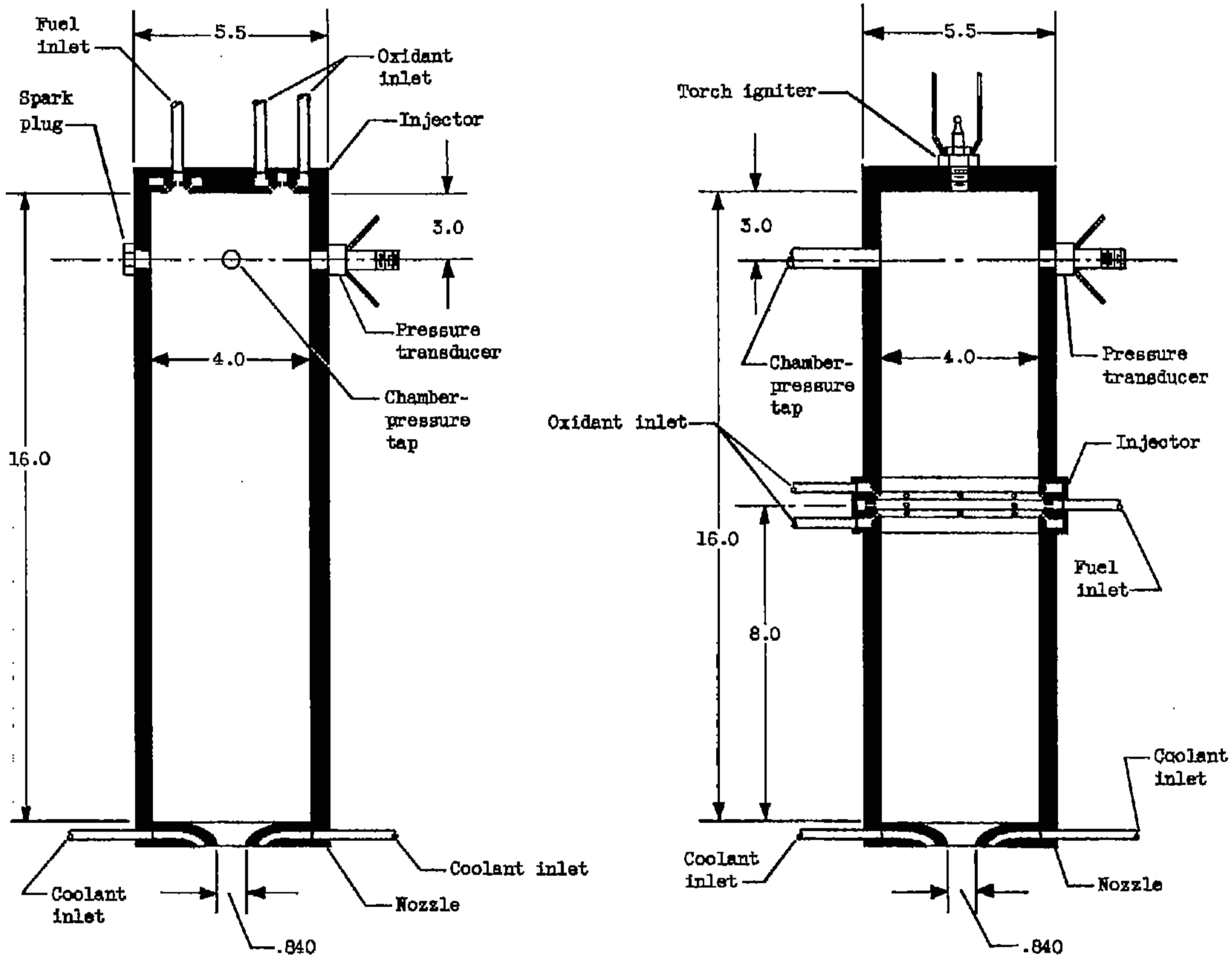
Injector	$D_{g,M}$ (ref. 7)	$\bar{D}$ (ref. 8)	$\frac{c^*}{c^*_{th}}$, percent	$\mathscr{A}$
Axial small-drop	66	42	93	0.076
Axial large-drop	173	98	86.9	.031
Axial like-on-like	117	--	93.5	.083
Axial triplet	122	--	90.6	.38
Radial large-drop	[a]173	98	87.2	.020
Radial like-on-like	[a]117	--	91.4	.038 .26

[a]Assumed to have same value as axial injector; length of chamber indeterminate.



(a) Axial injection.

(b) Radial injection.

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Figure 1. - Rocket engine geometry. (All dimensions in inches.)

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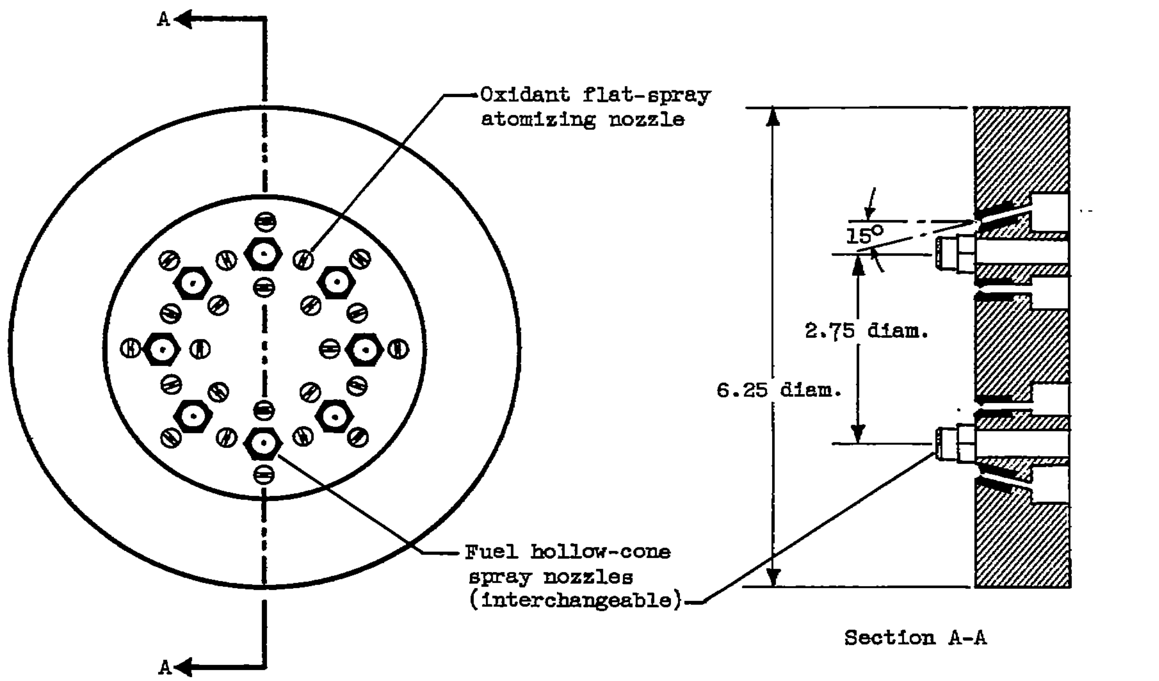
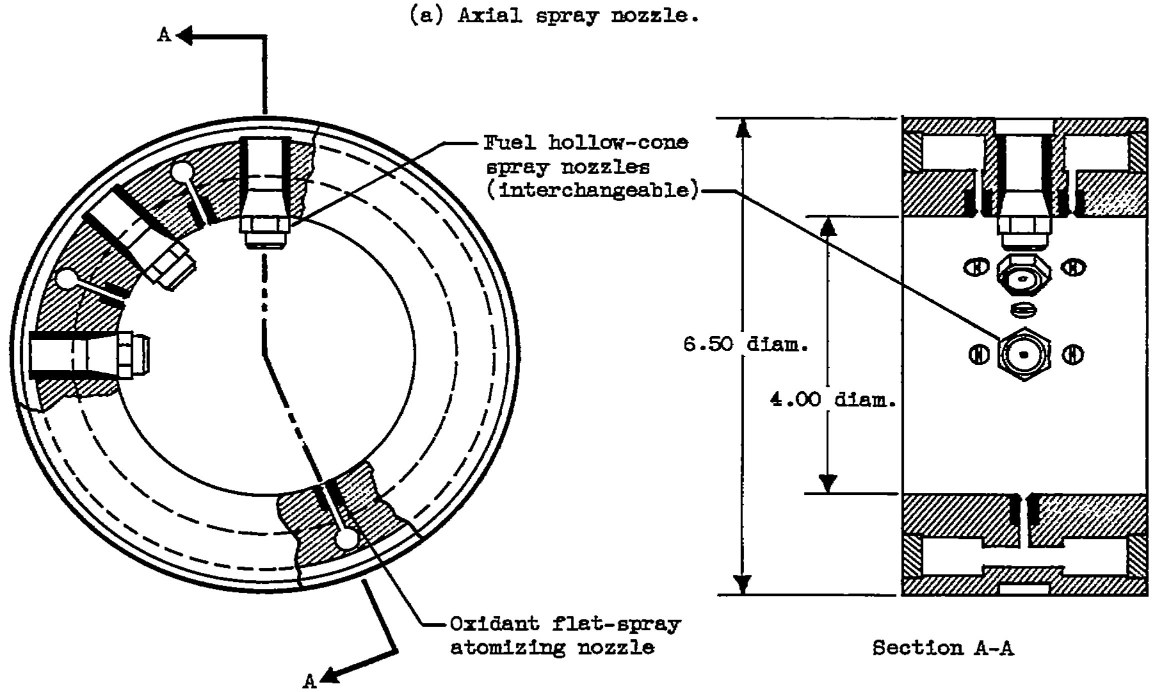


(a) Axial spray nozzle.



(b) Radial spray nozzle.

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Figure 2. - Injectors. (All dimensions in inches.)

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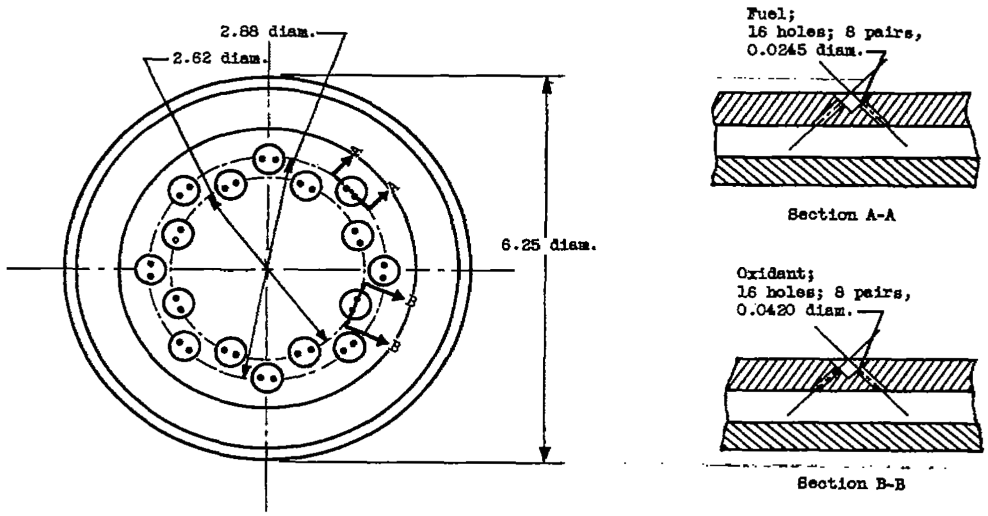
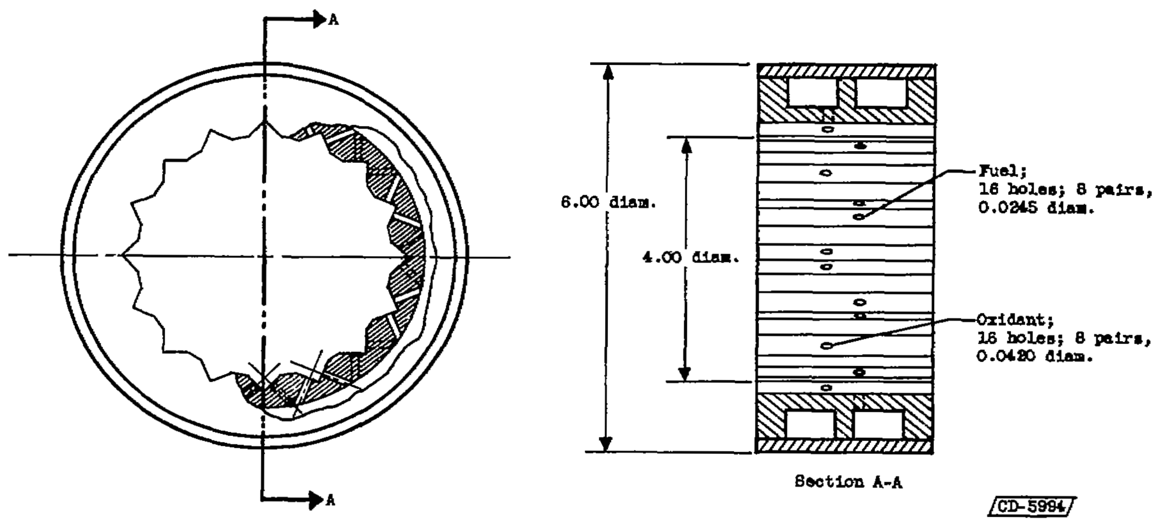


(c) Axial like-on-like.



(d) Radial like-on-like.

Figure 2. - Continued. Injectors. (All dimensions in inches.)

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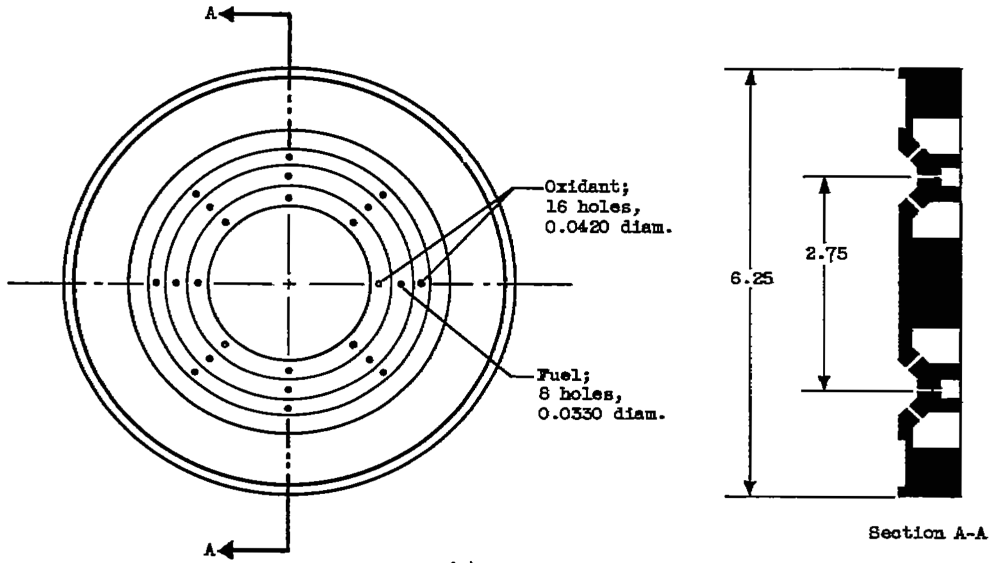
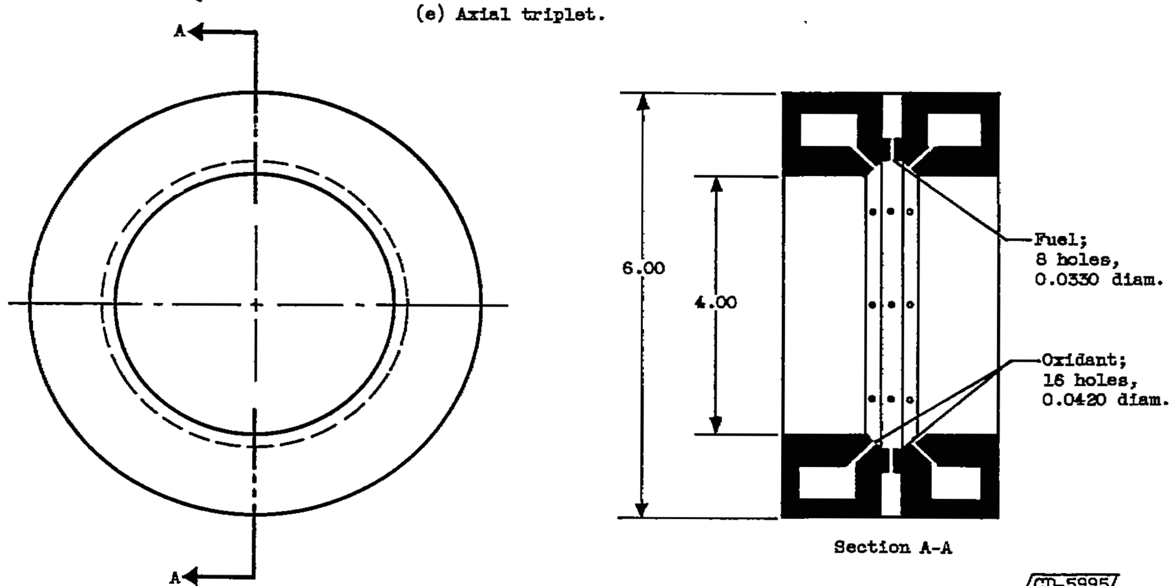


(e) Axial triplet.



(f) Radial triplet.

Figure 2. - Concluded. Injectors. (All dimensions in inches.)

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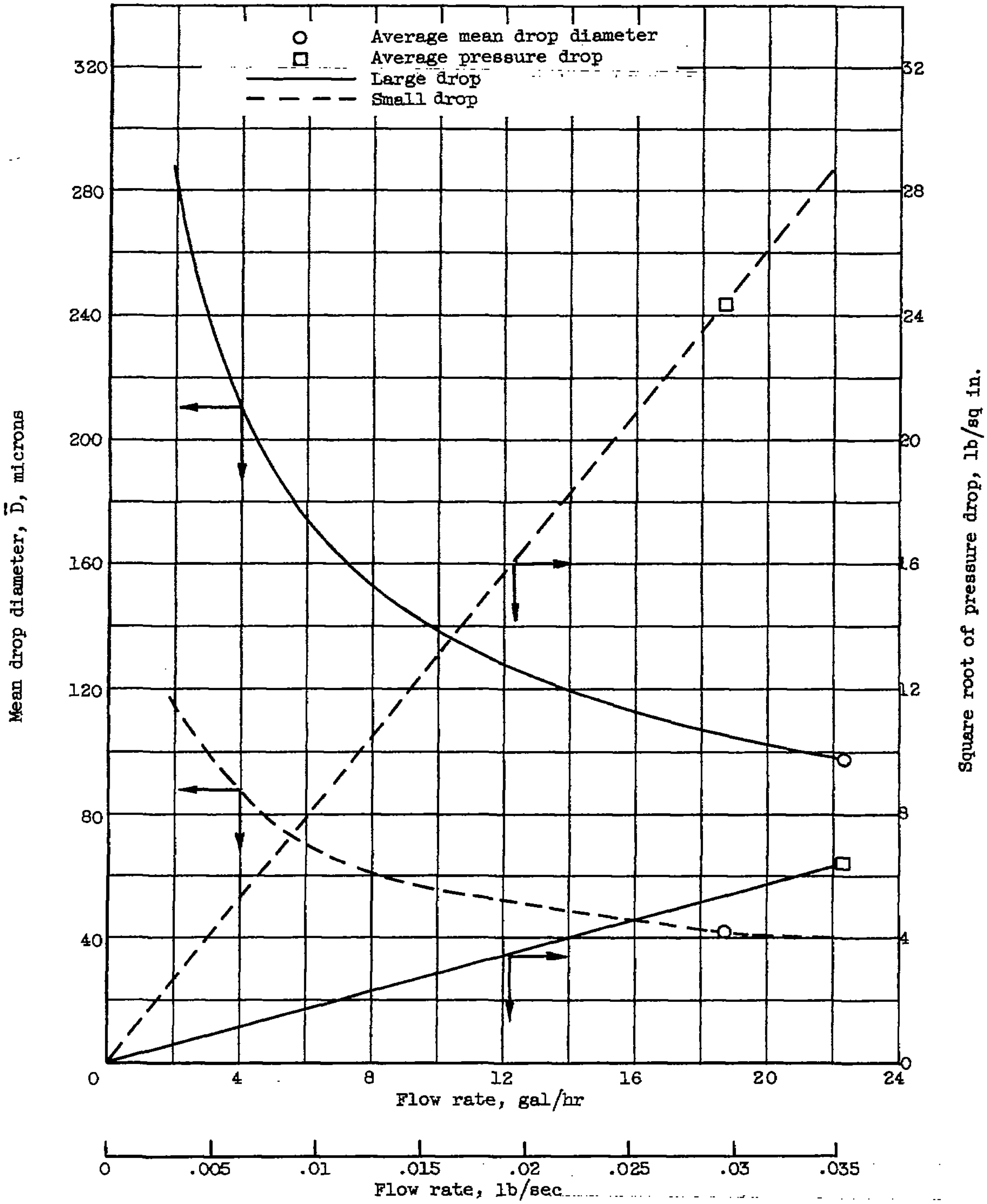

Figure 3. - Variation of mean drop diameter with flow rate of large- and small-drop nozzles (calc. from ref. 8) with pressure drop across nozzles as function of flow rate.

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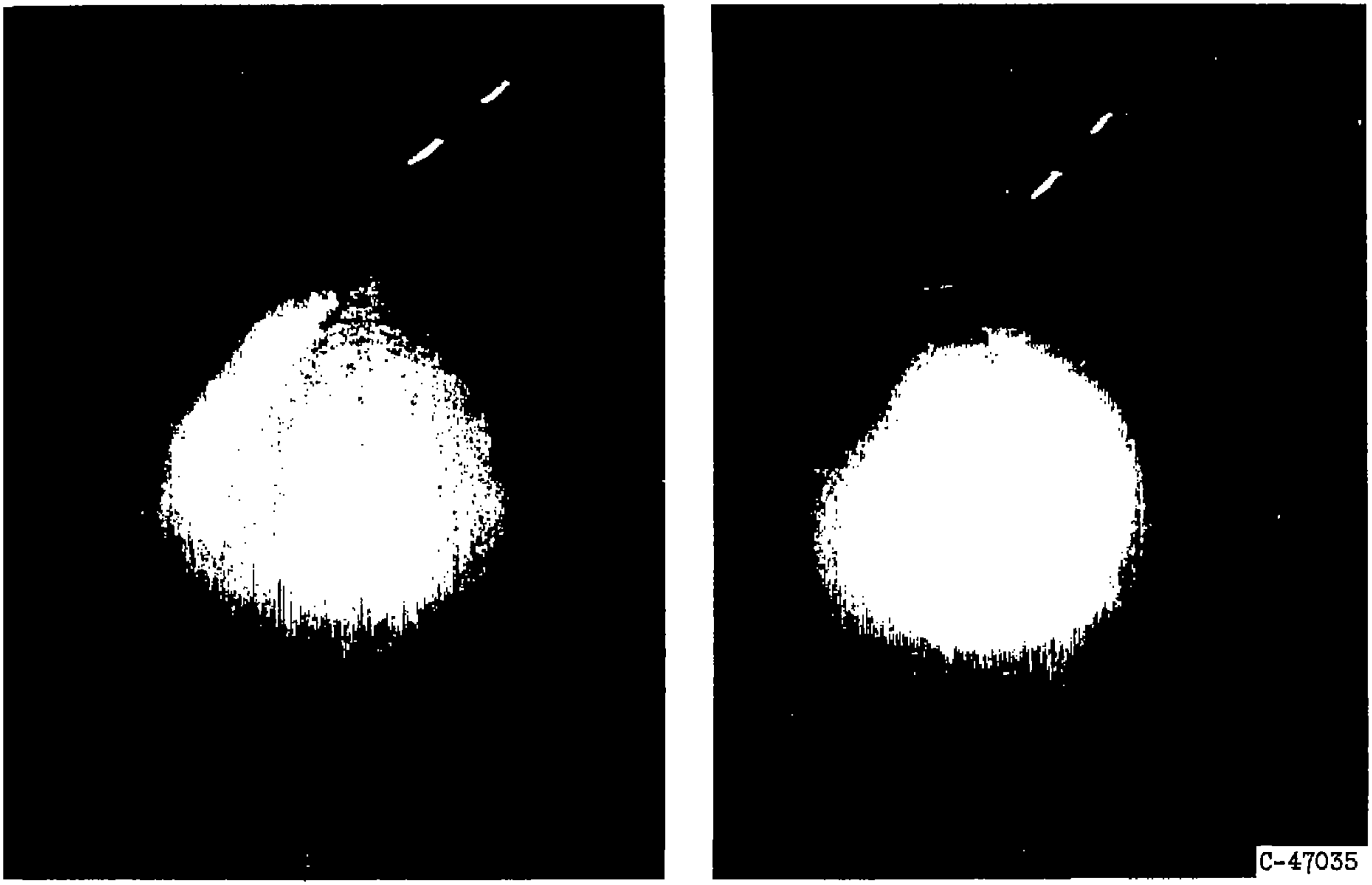

(a) Large nozzle; pressure drop, 25 pounds per square inch.

(b) Small nozzle; pressure drop, 225 pounds per square inch.

Figure 4. - Water sprays showing difference in coarseness.

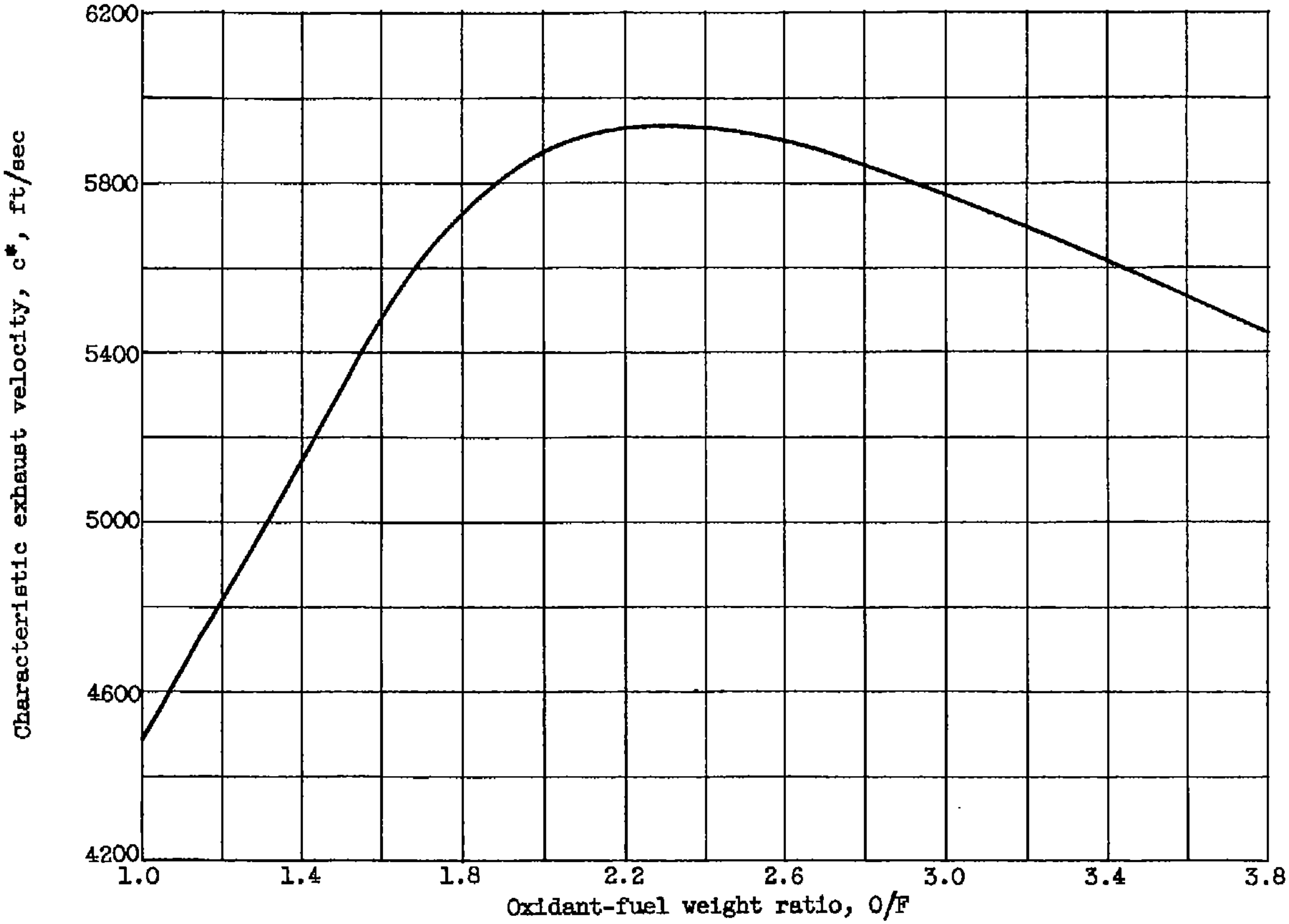

Figure 5. Theoretical equilibrium characteristic exhaust velocity for liquid oxygen - heptane.

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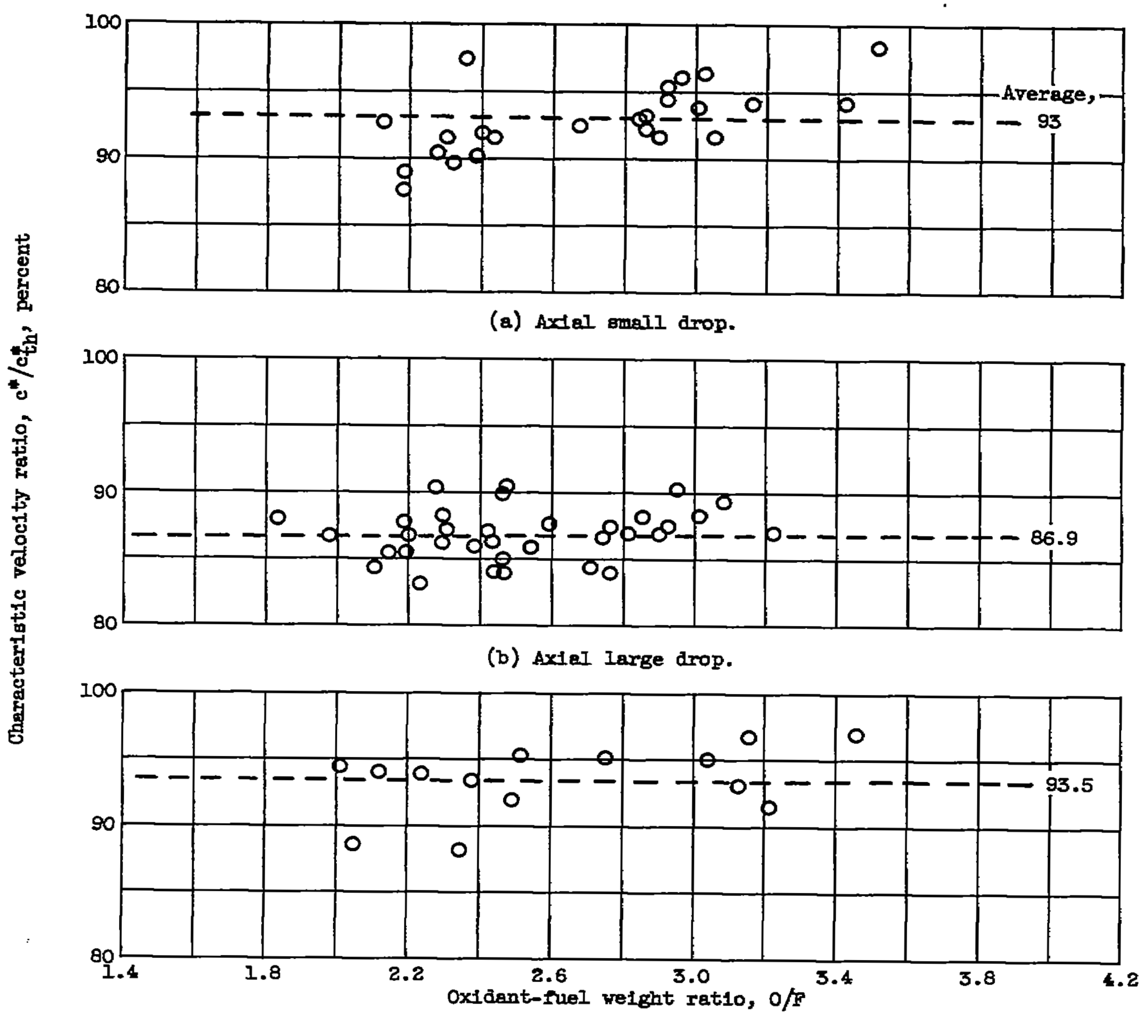

(c) Axial like-on-like.

Figure 6. - Injector performance.

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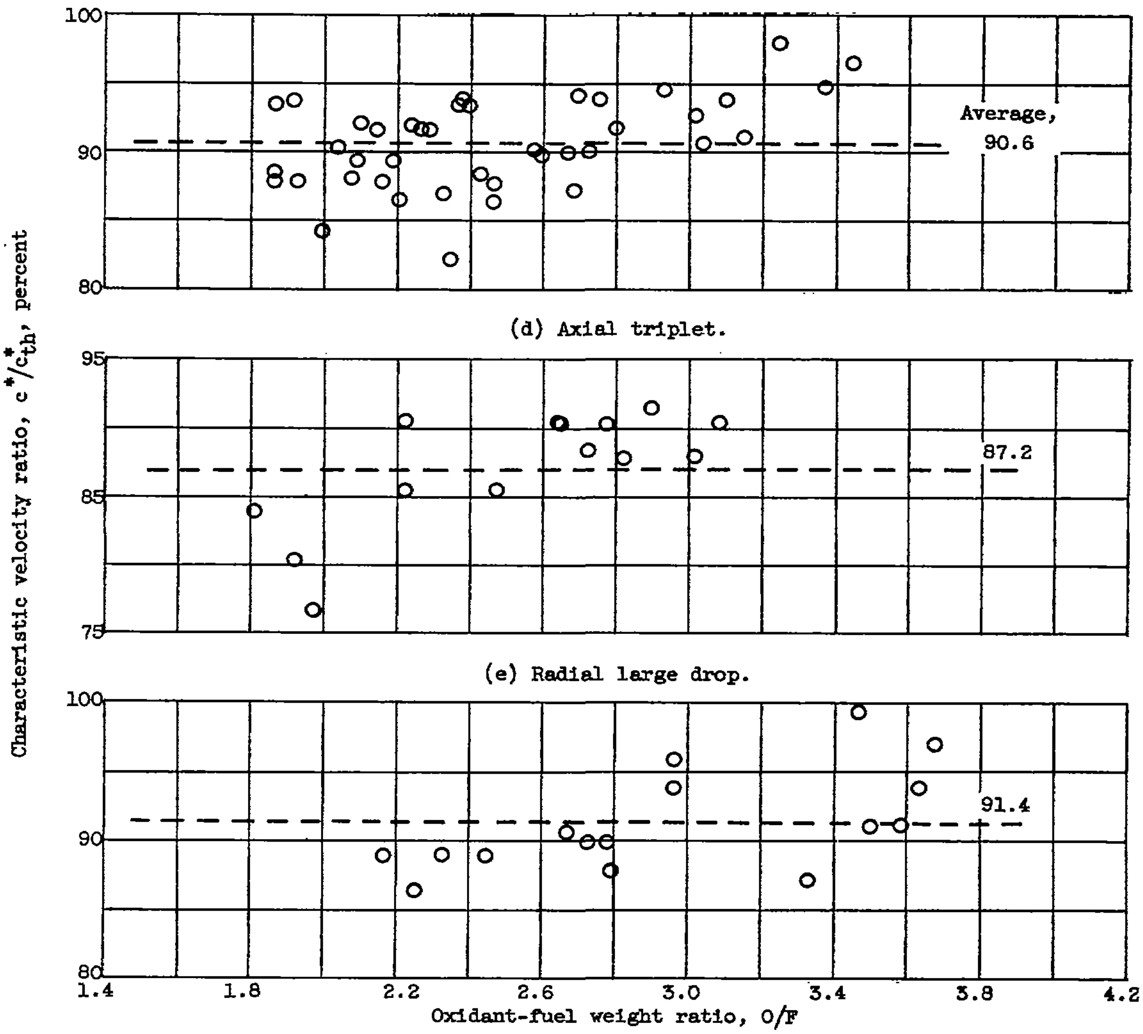

(f) Radial like-on-like.

Figure 6. - Concluded. Injector performance.

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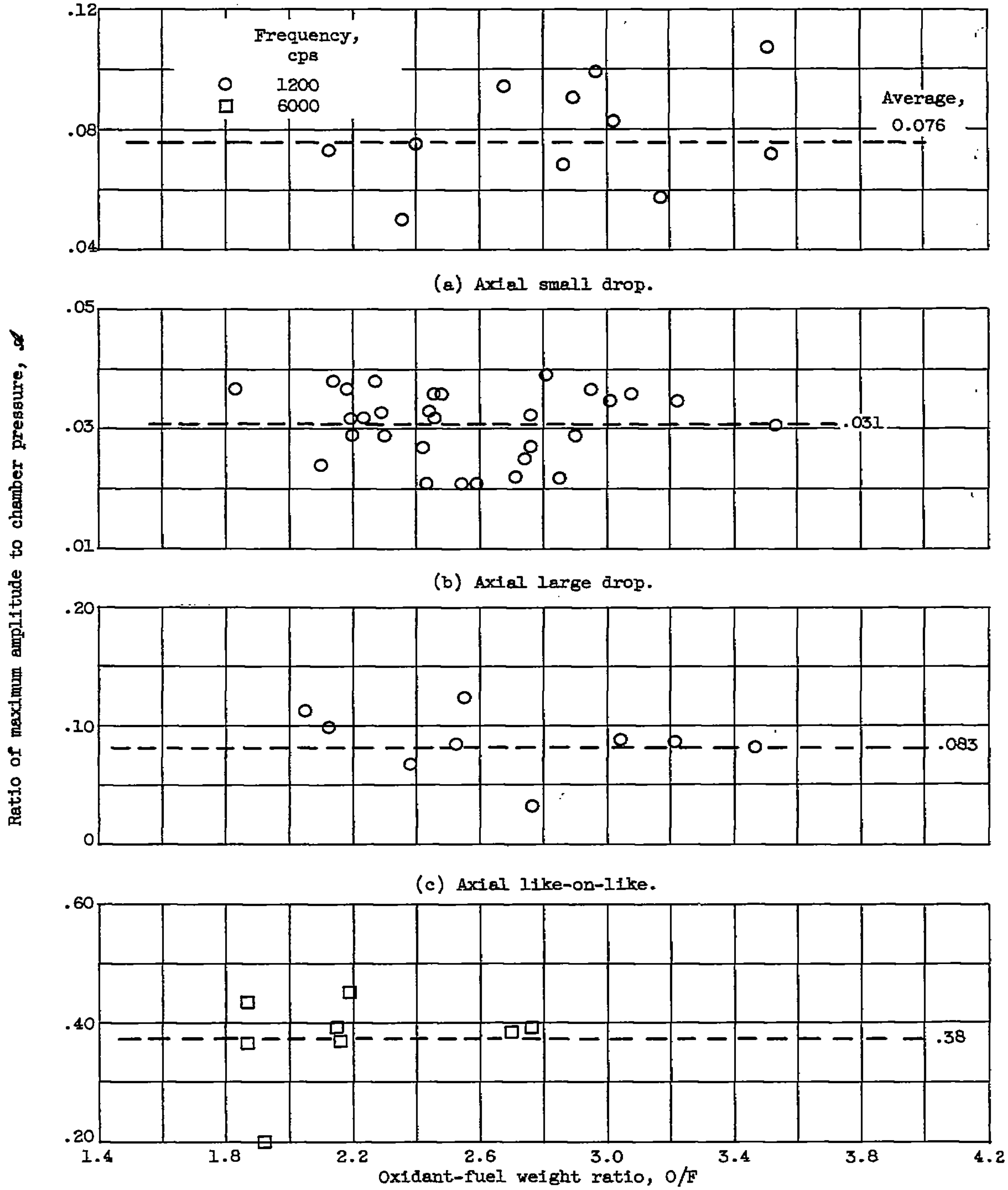


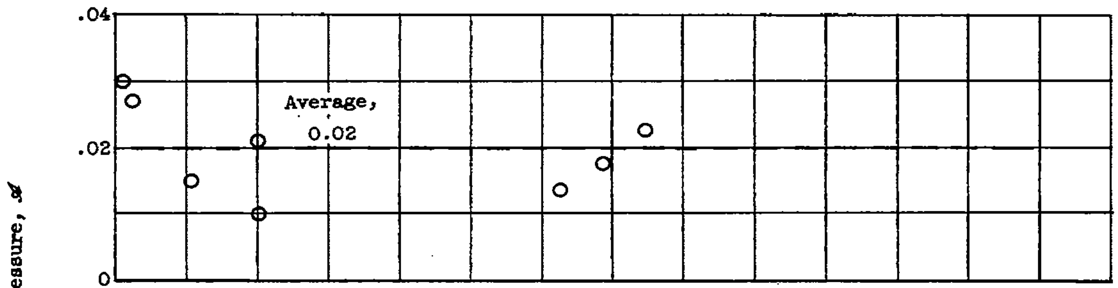
(a) Axial small drop.

(b) Axial large drop.

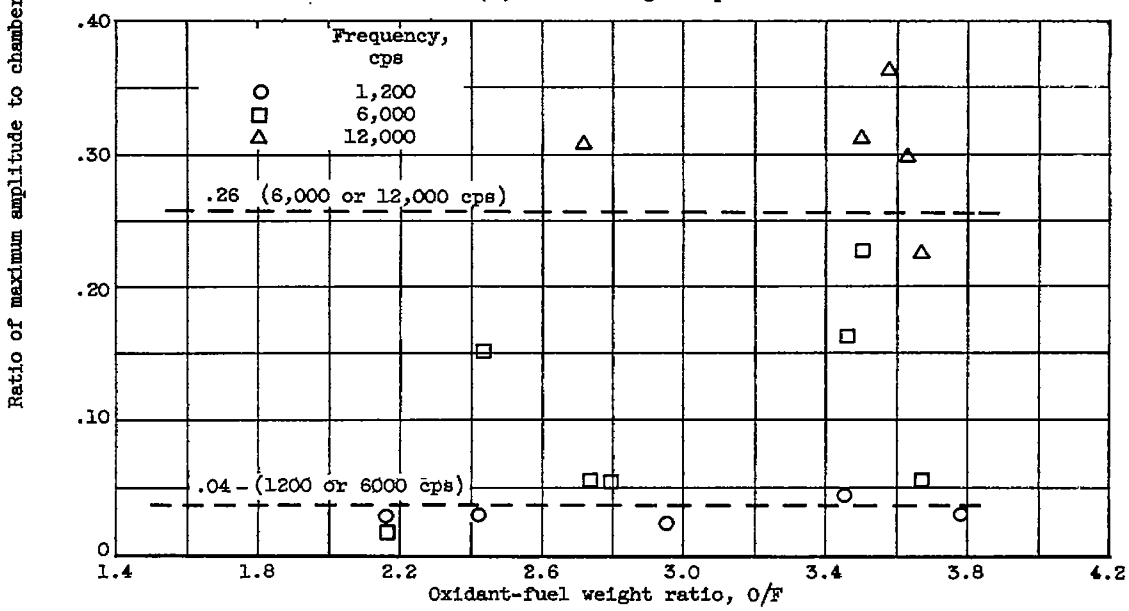
(c) Axial like-on-like.

(d) Axial triplet.

Figure 7. - Variation of screaming amplitude with oxidant-fuel ratio for each injector.

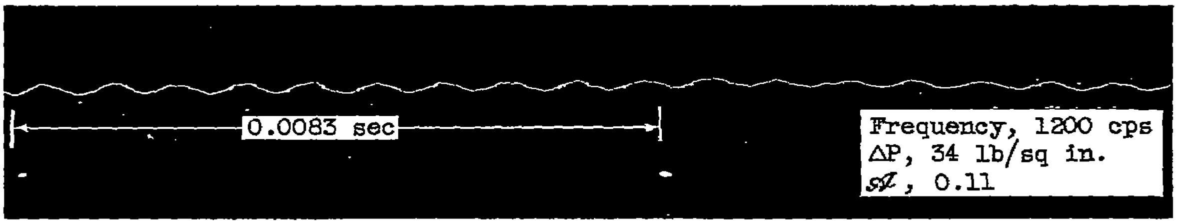


(e) Radial large drop.

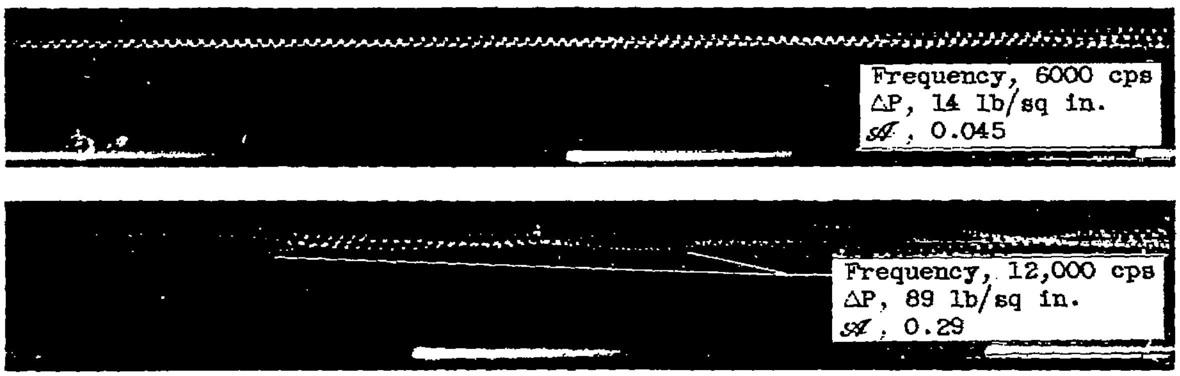


(f) Radial like-on-like.

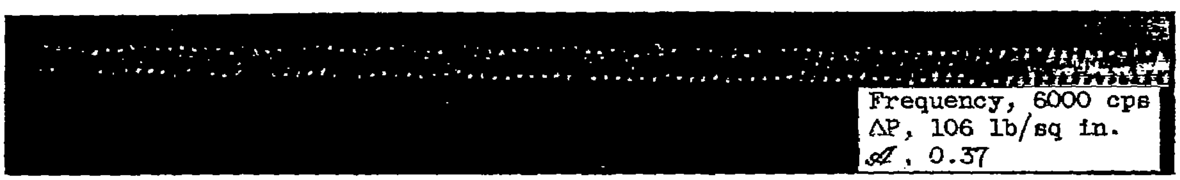
Figure 7. - Concluded. Variation of screaming amplitude with oxidant-fuel ratio for each injector.



(a) Axial small-drop injector.



(b) Radial like-on-like injector.



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(c) Axial triplet injector.

Figure 8. - Oscilloscope records of typical chamber-pressure oscillations.

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