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RESEARCH MEMORANDUM

EFFECT OF FUELS ON SCREAMING IN 200-POUND-THRUST LIQUID-OXYGEN - FUEL ROCKET ENGINE

By Isaac Pass and Adelbert O. Tischler

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

The tendencies of 14 different fuels and three fuel blends to produce high-frequency oscillatory combustion (screaming) were measured in a 200-pound-thrust, water-cooled, liquid-oxygen - fuel rocket engine. In this apparatus, the fuels, in order of increasing screaming tendency, were (1) hydrazines (these did not scream at all); (2) branched-chain paraffins, aromatics, and amines; and (3) straight-chain paraffins. This same trend of increasing screaming tendency also correlated with increasing fuel evaporation rate. The choice of fuels did not permit a clear distinction to be made as to the relative importance of fuel type and evaporation rate.

Examination of two idealized modes of heat release indicated that combustion for which flame propagation through a gaseous mixture is rate controlling is more sensitive to pressure changes than is combustion for which fuel-droplet burning is rate controlling. This observation is discussed as an explanation of the trend of screaming tendency with evaporation rate.

There was a minimum oxidant-fuel ratio for screaming; for normal heptane, this ratio was 2.3. Screaming amplitudes varied from 0.1 to 0.5 of the operating pressure, but there were no significant differences among fuels with regard to oscillation amplitude. A slight trend of decreasing amplitude with increasing oxidant-fuel ratio was noted at oxidant-fuel ratios larger than that required for peak experimental performance.

INTRODUCTION

Combustion oscillations have long been a problem in rocket-engine development. In general, these oscillations can be classified into two broad categories, namely, low-frequency oscillations, known in the industry as chugging (refs. 1 to 3), and high-frequency oscillations, called screaming (ref. 4). There is also evidence of a group of combustion-driven oscillations of intermediate frequency (refs. 5 and 6). These, however, have not been as clearly identified as the others.

The high-frequency or screaming oscillations are strong pressure waves which are usually accompanied by greatly increased heat-transfer rates to the combustion-chamber surfaces (refs. 7 to 10). As a result, burnouts often occur, and measures are being sought experimentally to limit and control such oscillations.

The driving energy for these strong waves apparently comes from the combustion reaction, which reinforces the pressure waves by releasing heat (and thus generating new pressure waves) at a propitious time in the oscillation cycle, in accordance with the Rayleigh criterion (ref. 11). The driving of the combustion wave depends on both the rate and the pressure sensitivity of the rate of the over-all combustion mechanism. The over-all combustion mechanism comprises two kinds of processes. These are physical processes, which affect the preparation and distribution of the fuel-oxidant mixture, and chemical processes, which are subsequent and/or concurrent reactions of the fuel-oxidant mixture. This division is arbitrary since the two processes undoubtedly occur simultaneously with undetermined amounts of interaction. That physical processes can have a pronounced effect on screaming tendency is demonstrated in reference 12, in which a single oxidant-fuel combination was used with a series of injectors. Fuel additives have been used to attenuate screaming in nitric acid - fuel rocket engines (ref. 13). In this case it is not clear whether the change in the chemical nature of the fuel or the change in the physical processes affected by the fuel additive was instrumental in attenuating screaming.

This report presents the results of a study of the screaming properties of several fuels in a 200-pound-thrust liquid-oxygen - fuel rocket engine. In order to minimize variations in physical factors, an engine of fixed geometry and the same oxidant were used throughout the study. Fourteen fuels and three fuel blends were chosen as representatives of various chemical types. The relative tendency of each fuel-oxygen combination to sustain screaming oscillations was evaluated by comparing the percentage of total runs that screamed. In addition, the amplitude of the screaming oscillation for each propellant combination was measured.

APPARATUS

Engine Configuration

The engine used in this investigation was a 200-pound-thrust water-cooled rocket using liquid oxygen and various fuels as propellants (fig. 1). The internal diameter of the combustion chamber was 2 inches; the characteristic length was 50 inches.

A photograph of the injector is shown in figure 2; the injector design and water spray patterns are shown in figure 3. The fuel issues from the center orifice and impinges upon the deflection cylinder, thus forming a hollow-cone spray. The oxidant flow, from the outer orifices, consists of two jets parallel to the chamber axis. This injector was chosen because it had demonstrated a marked proclivity to cause screaming in a similar engine configuration during an earlier investigation (ref. 12). With heptane fuel and this injector, about 90 percent of the theoretical characteristic velocity (based on equilibrium expansion) was obtained for screaming operation and about 80 percent of theoretical characteristic velocity, for smooth-combustion operation. The water-cooled convergent nozzle had a 30° convergence half-angle and a throat diameter of 0.80 inch.

The propellants were forced into the combustion chamber by high-pressure helium. Ignition was accomplished either by a spark plug mounted in the injector head or by a gaseous oxygen-propane torch mounted in the chamber wall 2 inches from the injector face. Check valves shut off the gas supply to the torch when the combustion-chamber pressure built up.

Instrumentation

Instantaneous chamber pressure was measured by a high-fidelity pressure transducer having a natural frequency greater than 20,000 cps. This transducer was a water-cooled, double-catenary diaphragm type with a bonded strain-gage sensing element. The transducer was flush-mounted in the chamber wall at a station 2 inches downstream of the injector. The output of this transducer was fed into an oscilloscope and recorded on a moving film camera. The accuracy of the instantaneous chamber pressure measurements was within ±5 percent. Because pressure amplitudes varied considerably between runs, no attempt was made to get more accurate measurements.

As a check of the high-fidelity pressure transducer, steady-state combustion-chamber pressure was measured by both a recording Bourdon type gage (accuracy, ±2 percent) and an unbonded strain-gage pressure senser (accuracy, ±1 percent).

Propellant flow rates were measured with turbine-type flowmeters (accuracy, ±1 percent). The accuracy of the characteristic-velocity performance measurements, therefore, was within ±3 percent.

Fuels

The fuels used in this program are as follows:

Straight chain paraffins:

- n-Heptane
- n-Octane
- n-Hexadecane

Branched-chain paraffins:

- Triptane (2,2,3-trimethylbutane)
- Isooctane (2,2,4-trimethylpentane)

Unsaturated hydrocarbon:

- Triptene (2,2,3-trimethyl-1-butene)

Alicyclic hydrocarbon:

- Turpentine

Aromatics:

- Benzene
- Toluene

Amines:

- Triethylamine
- o-Toluidine

Hydrazines:

- Hydrazine
- Unsymmetrical dimethylhydrazine (hereinafter called UDMH)

Alcohol:

- Ethanol

In addition, the following blends (by volume) were used: 20 percent UDMH, 80 percent n-heptane; 20 percent turpentine, 80 percent n-heptane; 20 percent acetone, 80 percent n-heptane. Some properties of these fuels are summarized in table I.

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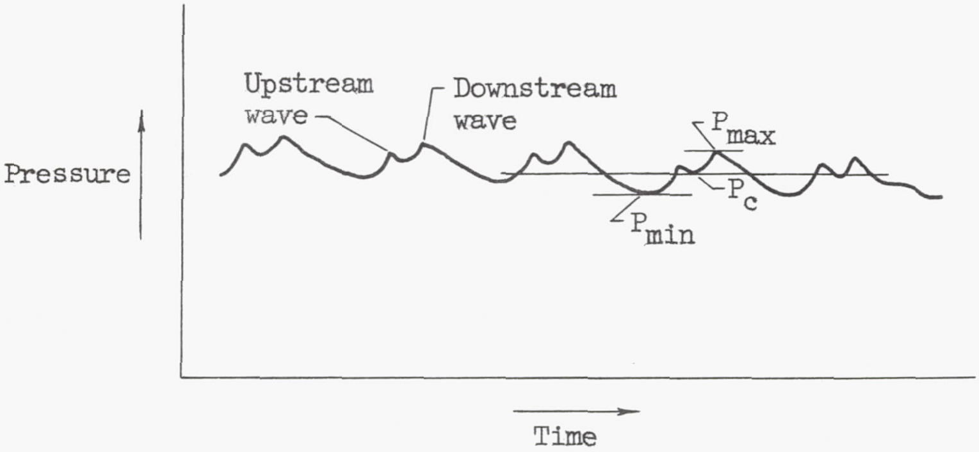
PROCEDURE

In firing the rocket, the spark plug (or torch) was turned on first. Next, the liquid propellants were introduced into the chamber. When successful ignition was accomplished, the ignition source was shut down. The run duration was about 2 seconds, which was sufficient for reliable flow and pressure measurements. Longer runs would probably have resulted in a greater proportion of screaming runs; it is likely that the order of screaming tendency would not have changed materially, however.

A series of test runs was made with each propellant combination over a range of oxidant-fuel weight ratios. The pressure-time records were examined, and the occurrence or absence of screaming was noted. After some experience had been obtained with each propellant combination, further runs were designed to make the engine scream as often as possible. For screaming operation, the frequency of oscillation was determined by comparison with a 400-cps timing trace which was also printed on the film. The amplitude of the timing trace was adjusted to equal a known pressure with the base at zero pressure. The oscillation amplitude $\frac{(P_{max} - P_{min})}{P_c}$ was determined by averaging the amplitudes of a number of randomly selected cycles. (Symbols defined in following sketch.) Figure 4 contains samples of the pressure-time records obtained. Shown are typical records for smooth-combustion operation, for the start of screaming, and for fully developed screaming.

The pressure-time records for screaming operation had the following general shape:



The apparent double peaks correspond to the upstream wave and the downstream wave passing the diaphragm of the pressure transducer. The mean chamber pressure P_c was determined by averaging the pressure (by eye) over a short time interval in the immediate vicinity of the particular cycle being examined. The computed value of the amplitude parameter was relatively insensitive to small changes in P_c, thus making more accurate determination of P_c unnecessary.

RESULTS AND DISCUSSION

For all the fuels tested, the screaming frequencies were in the range of 2300±200 cps. This range corresponds to the fundamental longitudinal (closed-closed-end organ pipe) mode of the combustion chamber at the theoretical combustion gas temperature.

The onset of screaming (see fig. 4(b)) was, in all cases, accompanied by a low-frequency oscillation (about 100 cps) which was rapidly attenuated, usually within 2 cycles. As the pressure level rose and fell because of this oscillation, so did the screaming amplitude.

The average chamber pressure was higher during screaming operation than during normal combustion. The characteristic velocity, based on average chamber pressure, also was higher for screaming than for smooth-combustion portions of a run.

Screaming Tendency

There was an oxidant-fuel ratio below which each of the fuels would not support screaming. With n-heptane, for which this limit was most accurately determined, the oxidant-fuel ratio was 2.3.

The percentage of screaming runs encountered with each fuel-oxygen combination is shown in figure 5. Also shown is the total number of runs made with each fuel. The runs do not represent a random sampling over the oxidant-fuel range studied, because the operating conditions were deliberately selected to make the engine scream as often as possible. The data do, however, show differences among the fuels with respect to their tendencies to scream. The fuels, in order of increasing screaming tendency, are

(1) Hydrazines (these did not scream at all)

(2) Branched-chain paraffins, aromatics, and amines

(3) Straight-chain paraffins

In order to check the possibility that the nonscreaming fuels might release their heat at a different station in the combustion chamber than the fuels which did scream, streak photographs were taken in Lucite chambers, and gas velocity profiles were determined. Figure 6 is a plot of the percentage of final chamber gas velocity against distance from the injector for n-heptane and for hydrazine. The figure shows that the velocity profiles and, hence, the heat-release patterns are very similar for the two fuels. Since the heat-release patterns for heptane and for hydrazine are essentially the same, and since the same injector and engine configuration was used in both cases, the difference in their abilities to sustain screaming oscillations cannot be due to different effective driving positions for the combustion reactions but is apparently due to different pressure sensitivities of their over-all combustion mechanisms.

Screaming Amplitude

In this program n-heptane was used as a reference fuel because of the previous experience obtained with it in the work of reference 12. Figure 7 shows portions of pressure-time records for two runs with n-heptane. The oxidant-fuel ratio for both these runs was 3.3. In one case, the average screaming amplitude was 0.28 and in the other, 0.12. These data indicate a two-fold magnitude of scatter for otherwise identical runs. Similar scatter in screaming amplitude occurred with the other fuels.

Screaming amplitudes are plotted against oxidant-fuel weight ratio in figure 8. For convenience of viewing, these data are separated into several groups, with the data for n-heptane being repeated in each group. The amplitude values ranged from about 0.1 to 0.5. Each fuel showed considerable variation in amplitude, the variations for one fuel being as great as the differences among the fuels. In view of this, it is questionable whether the somewhat lower amplitudes for the amines (fig. 8(c)) and the somewhat higher amplitudes for turpentine and the 20 percent UDMH - 80 percent heptane blend (fig. 8(d)) are significant. In general, no meaningful differences in screaming amplitude were ascribed to the various fuels.

A composite of the amplitude - oxidant-fuel data for all the fuels tested is shown in figure 9. There appears to be a slight trend of decreasing amplitude with increasing oxidant-fuel weight ratio. Since most of the data were taken at conditions more oxidant-rich than the oxidant-fuel ratio for peak experimental performance, such a decrease is to be expected. A possible reason is that experimental performance decreases with increasing oxidant-fuel ratio in this region; thus, the energy available for driving a pressure wave is correspondingly reduced.

The data of figures 7 and 8 indicate that it is possible for a given fuel to scream over a range of amplitudes even at the same oxidant-fuel conditions. This implies that amplitude of pressure oscillation is not a good parameter for correlating the screaming tendencies of fuels. The lack of reproducibility is evidence of uncontrolled variables in the apparatus or operational procedure. No significant differences are reported in reference 14 in either frequency or amplitude of the first longitudinal mode in a liquid-oxygen rocket engine using different fuels.

ANALYSIS OF RESULTS

The screaming tendencies of the fuels tested show an apparent correlation with the chemical type of the fuel. However, it is almost impossible to vary the chemical type of the fuels without simultaneously varying associated physical properties. Therefore, a number of attempts were made to correlate the observed screaming tendencies with fuel properties. Those properties examined were spontaneous ignition temperature, flame speed, octane-number rating, and evaporation rate. Of these, only the evaporation-rate data gave any trend; namely, the screaming tendency increased with increasing evaporation rate. Evaporation rates were calculated from the equation of reference 15, namely,

$$\frac{dD^2}{d\theta} = \frac{4k_g \ \Delta t}{\rho_L H_v} \ Nu$$

where D is the drop diameter, θ is time, k_g is the thermal conductivity of the gas, Δt is the temperature difference between the drop and the surrounding gas, ρ_L is the drop liquid density, H_v is the heat of vaporization of the drop liquid, and Nu is the heat-transfer Nusselt number based on the drop diameter. It was assumed that the time required for the oxygen to evaporate was negligible and that the combustion-gas conductivity and temperature, the temperature difference between the drop and the gas, and the Nusselt number were the same for all fuels. Also, it was considered that the drop-size distribution was not a function of the fuel. The relative evaporation rate (rate of change in area of a drop) is then inversely proportional to the product of the density and the heat of vaporization of the drop liquid. The trend of screaming tendency with relative evaporation rate is shown in figure 10.

The limited number of fuels tested in this preliminary research unfortunately makes is impossible to determine whether the observed screaming tendency it an effect of fuel type or an effect of fuel evaporation rate. Obviously, further research is required to evaluate the relative importance of these possibilities.

Assuming that the evaporation rate governs screaming tendency, and assuming further that it does so by affecting the proportion of fuel consumed by droplet burning, the trend suggests that, when the percentage of heat release which occurs by droplet-burning increases, the fuel exhibits less tendency to scream. As mentioned previously, the difference in screaming tendency of the fuels was due to different pressure sensitivities of their over-all combustion mechanisms. Accordingly, the manner in which heat-release rates vary when a pressure change occurs was calculated for two idealized modes of heat release. The modes and their variation with pressure in an isentropic wave are (1) liquid-droplet burning, for which the mass burning rate is proportional to pressure$^{0.5}$ ($M_b \propto P^{0.5}$), and (2) flame in a gaseous mixture, for which $M_b \propto P^{1.3}$. The calculations are outlined in the appendix. The results indicate that combustion in which fuel-droplet burning predominates would be less likely to drive screaming oscillations than would combustion controlled by flame propagation through a gaseous fuel-oxidant mixture. This is in agreement with the observed trend of decreased screaming tendency with decreasing evaporation rate. The hypothesis is further substantiated by the implications of reference 12, where an increase of screaming tendency with increasing fuel atomization (hence, decreasing amounts of droplet burning) was observed.

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SUMMARY OF RESULTS

The screaming tendencies of 14 fuels and three fuel blends were studied in a 200-pound-thrust, liquid-oxygen - fuel rocket. Only the fundamental longitudinal mode was observed. The results of this study may be summarized as follows:

1. In the range of oxidant-fuel ratios where screaming was most likely to occur, there were large differences among fuels with regard to the percentage of runs which screamed.

2. The fuels, in order of increasing screaming tendency, were (1) hydrazines (these did not scream at all); (2) branched-chain paraffins, aromatics, and amines; and (3) straight-chain paraffins.

3. This same trend of increasing screaming tendency correlated with increasing evaporation rate.

4. A hypothesis to explain the trend of increasing screaming tendency with increased evaporation rate was based on the observation that, when flame propagation through a gas mixture is rate controlling, the heat-release rate is more sensitive to pressure changes than when fuel droplet burning is rate controlling.

5. There was a minimum oxidant-fuel weight ratio for screaming. For example, n-heptane did not scream at oxidant-fuel ratios below 2.3.

6. Screaming amplitude varied from 0.1 to 0.5. There was considerable variation in pressure amplitude for each fuel. This variation was as large for one fuel as it was among the fuels. Hence, no differences in screaming amplitude due to the fuel were discernible.

7. Generally, screaming amplitude decreased slightly with increasing oxidant-fuel weight ratio at oxidant-fuel ratios larger than that required for peak experimental performance.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 19, 1956

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APPENDIX - PRESSURE SENSITIVITIES OF TWO COMBUSTION MECHANISMS

Due to the present lack of data at rocket combustion conditions, the following estimates of the pressure sensitivities of combustion reactions during screaming performance must, of necessity, be based on extrapolation from low-pressure combustion data.

Combustion Limited by Flame Propagation

Reference 16 reports that pressure dependence of laminar flame speed is a function of the absolute value of the flame speed. For low flame speeds (less than 50 cm/sec) the flame speed is proportional to P^n, where n has a negative value. For flame speeds greater than about 100 centimeters per second, the exponent n has a positive value. Most of the data are for fuel-oxygen-nitrogen mixtures. The limited amount of data for fuel-oxygen mixtures indicates that these mixtures are in the region where flame speed U is roughly proportional to $P^{0.25}$.

Flame speed has also been shown to be roughly proportional to temperature$^{1.2}$ (ref. 17). Flame speed, then, is given by the following equation:

$$U \propto P^{0.25}T^{1.2}$$

In order to convert this equation to mass burning rate M_b, multiply it by the density term P/T. Thus,

$$M_b \propto P/TP^{0.25}T^{1.2}$$

or

$$M_b \propto P^{1.25}T^{0.2}$$

Assuming that these expressions are applicable to rocket combustion and that in a screaming wave front the pressure and temperature are raised by isentropic compression, $T = P^{\gamma-1/\gamma}$, using the ratio of specific heats γ equal to 1.25, and $T = P^{0.2}$, then

$$M_b \propto P^{1.25}(P^{0.2})^{0.2}$$

or

$$M_b \propto P^{1.3}$$

Combustion Limited by Liquid-Droplet Burning

The mass burning rate of a liquid droplet is approximately proportional to $P^{0.25}$ (ref. 18). The data in figure 11 of reference 19 indicate that the burning rate of droplets is also roughly proportional to gas temperature. Thus,

$$M_b \propto P^{0.25}T$$

If adiabatic compression is assumed and $\gamma = 1.25$, the burning rate is

$$M_b \propto P^{0.25}P^{0.2}$$

or, roughly,

$$M_b \propto P^{0.5}$$

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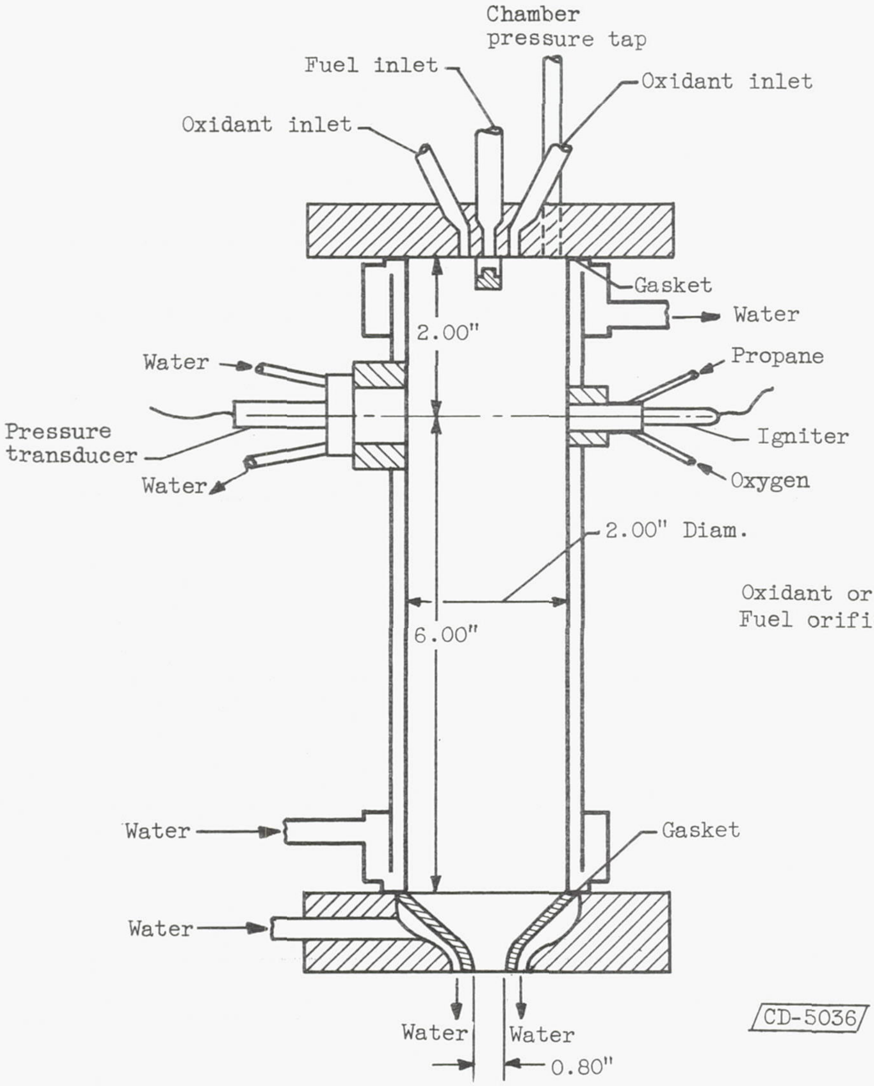
TABLE I. - SUMMARY OF FUEL PROPERTIES[a]

Fuel	Boiling point, °C	Specific gravity at 60/60° F	Viscosity at 20° C and 1 atm, centipoise	Maximum relative flame speed with air at 77° F and 1 atm	Spontaneous ignition temperature in oxygen at 1 atm, °F	Relative evaporation rate[b]
Straight-chain paraffins						
n-Heptane	98.5	0.687	0.42	100	477	1
n-Octane	125.8	.709	.56	---	446	1
n-Hexadecane	287.5	.777	3.65	96	464	1.20
Branched-chain paraffins						
Triptane (2,2,3-trimethylbutane)	80.9	.681	.60	93	----	.95
Isooctane (2,2,4-trimethylpentane)	99.3	.695	.50	90	837	1.10
Unsaturated hydrocarbon						
Triptene (2,3,3-trimethyl-1-butene)	77.9	.709	.48	107	----	----
Alicyclic hydrocarbon						
Turpentine	154.0	.852	1.49	---	486	.89
Aromatics						
Benzene	80.1	.884	.67	105	1097	.61
Toluene	110.8	.870	.60	91	1054	.67
Amines						
o-Toluidine	199.8	1.080	4.39	---	900	.50
Triethylamine	89.5	.730	.38	---	----	----
Hydrazines						
Hydrazine	115.0	1.010	.97	---	518	.15
Unsymmetrical dimethylhydrazine (UDMH)	62.7	.790	.53	---	----	.49
Alcohol						
Ethanol	78.5	.790	1.50	---	738	.33

[a] Data for this table were taken from refs. 20 to 27.

[b] Calculated by method of ref. 15, assuming no acceleration of droplet.



Oxidant orifices, 0.111" diam.
Fuel orifice, 0.116" diam.

CD-5036

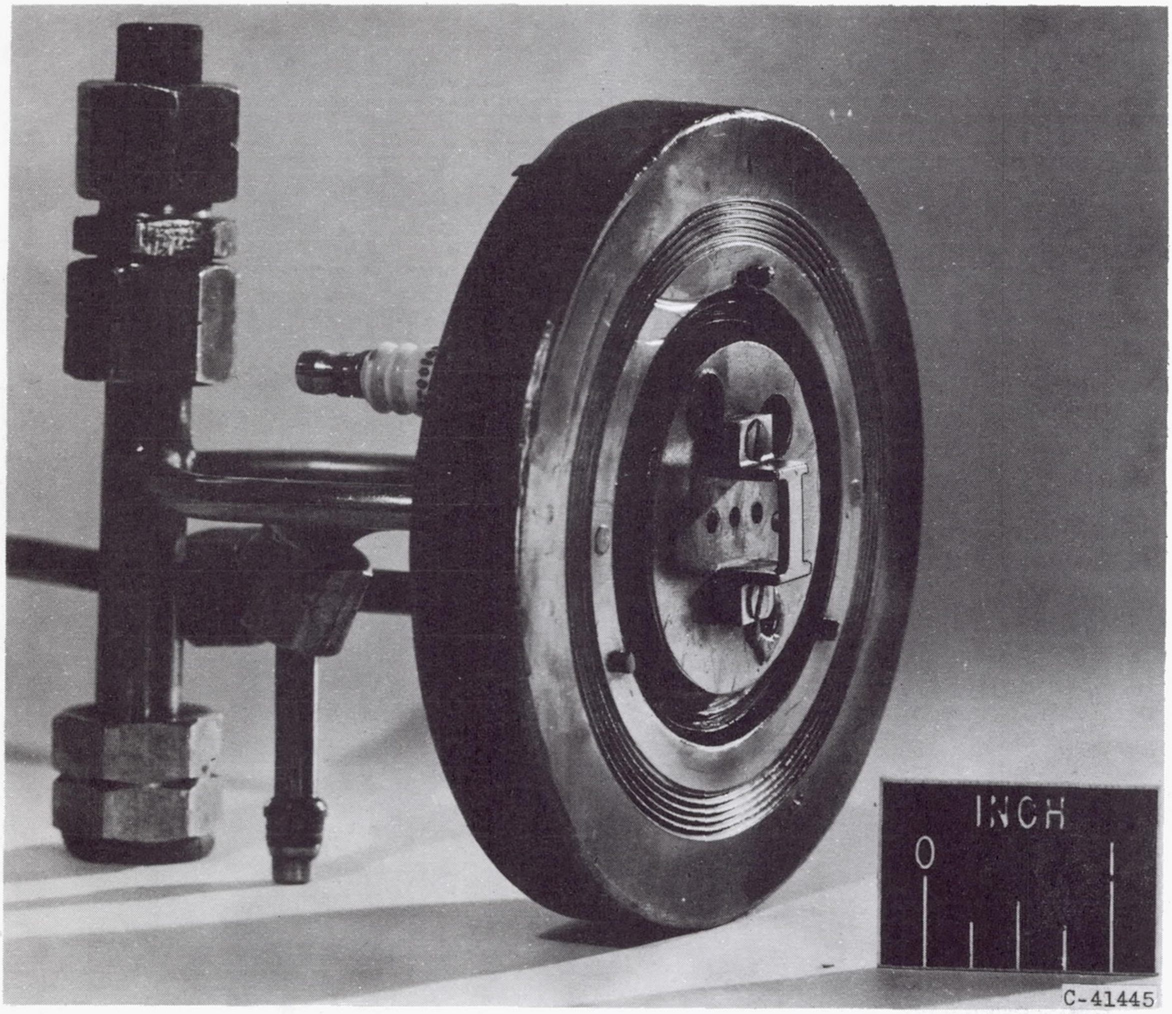
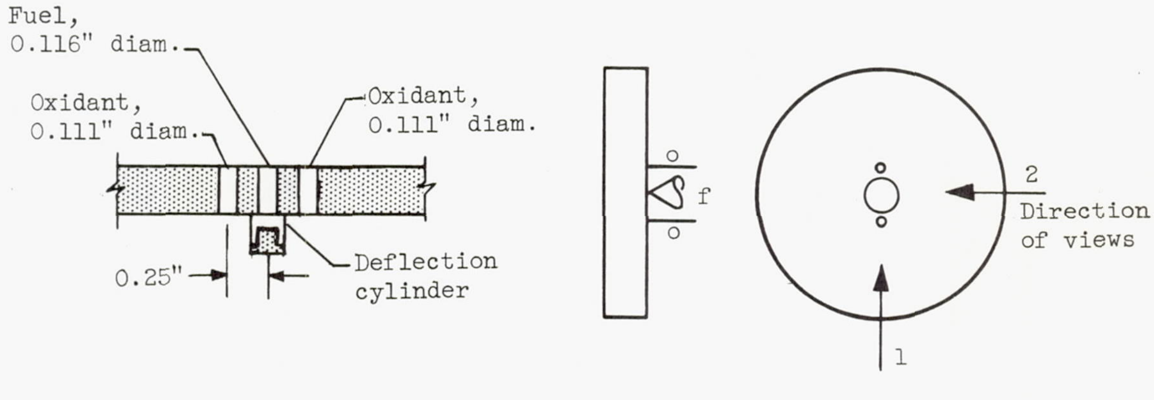
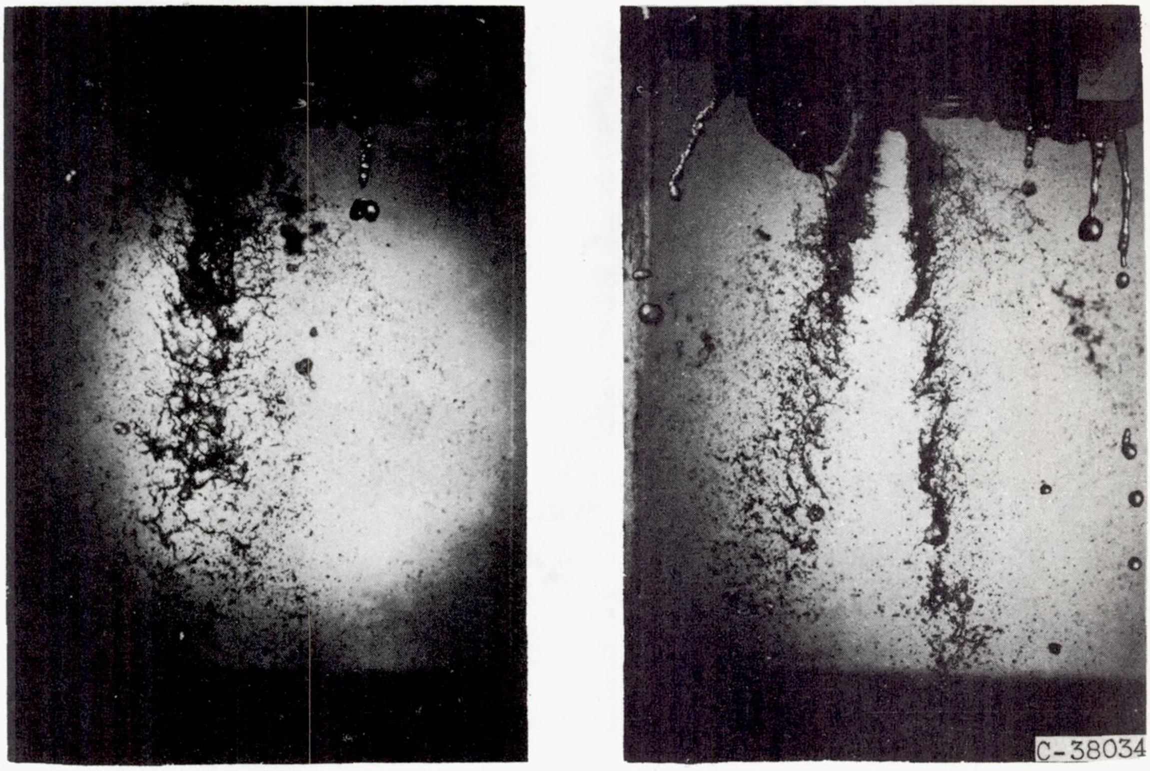


Figure 2. - Fuel-cone - parallel-oxidant-jets injector.



Injection method

Injection pattern

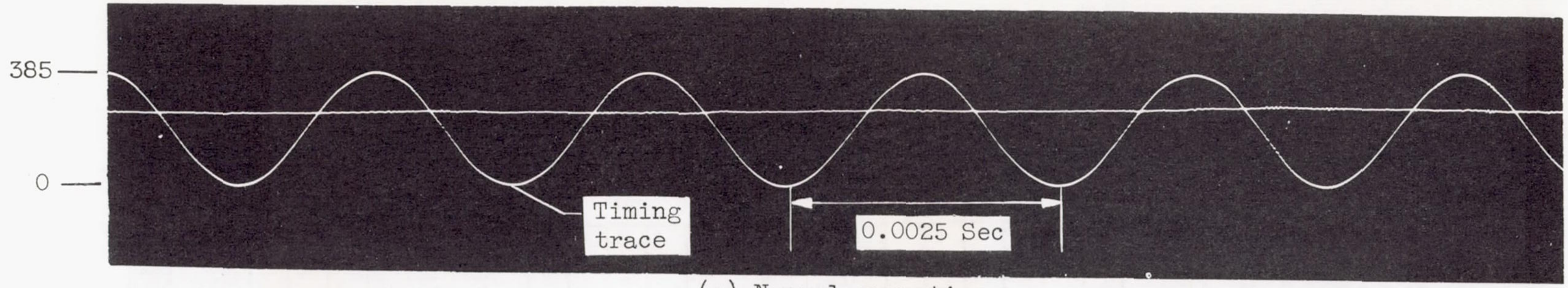


View 1

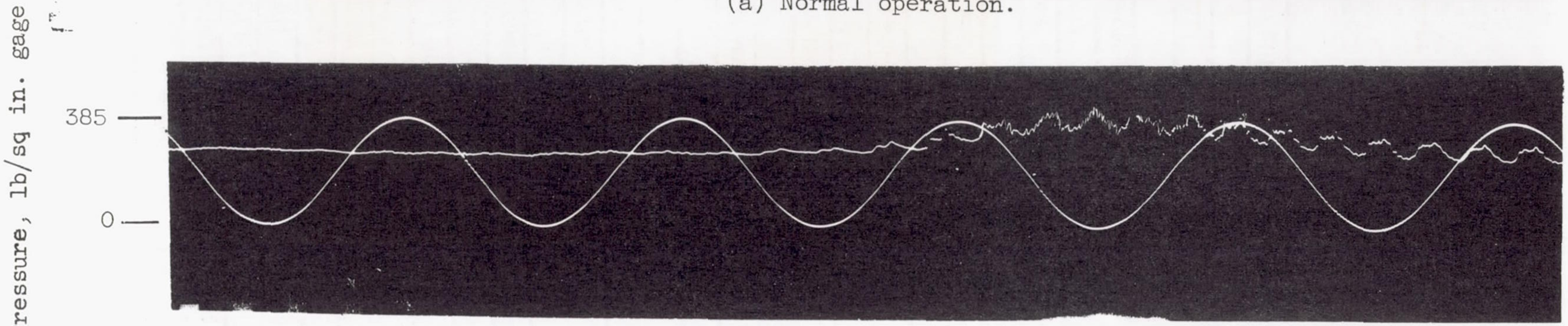
View 2

Spray photographs

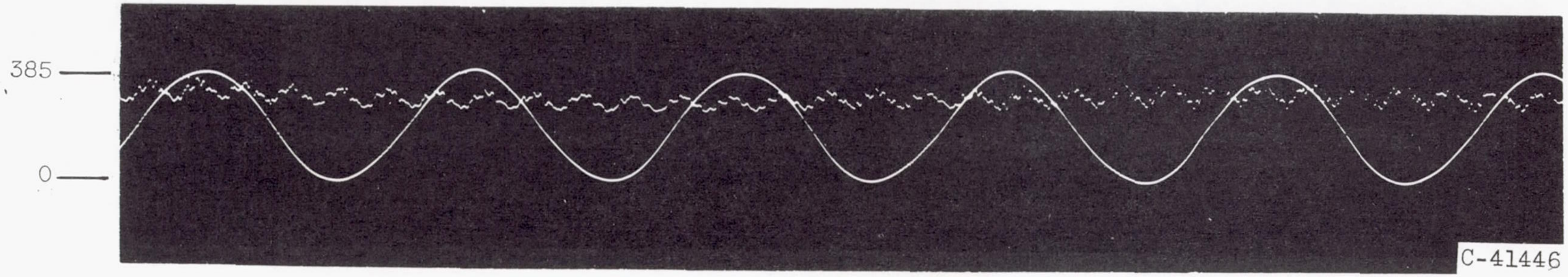
Figure 3. - Design of fuel-cone - parallel-oxidant-jets injector and water-spray photographs (fig. 6(a), ref. 12).



(a) Normal operation.



(b) Start of longitudinal scream.



(c) Fully developed longitudinal scream.

Figure 4. - Samples of pressure-time records used to determine screaming frequencies and amplitudes.

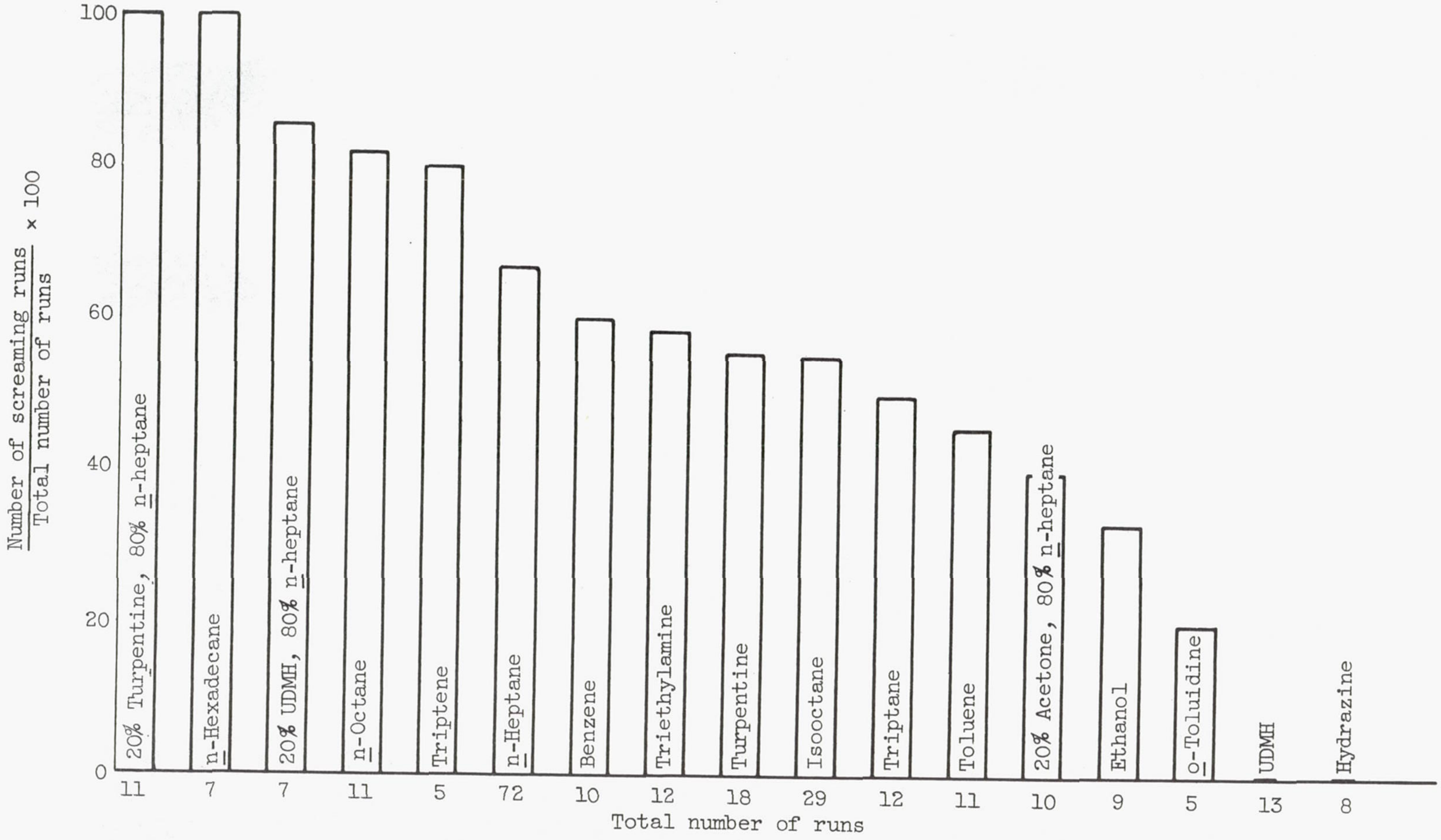


Figure 5. - Percentage of screaming runs with each fuel.

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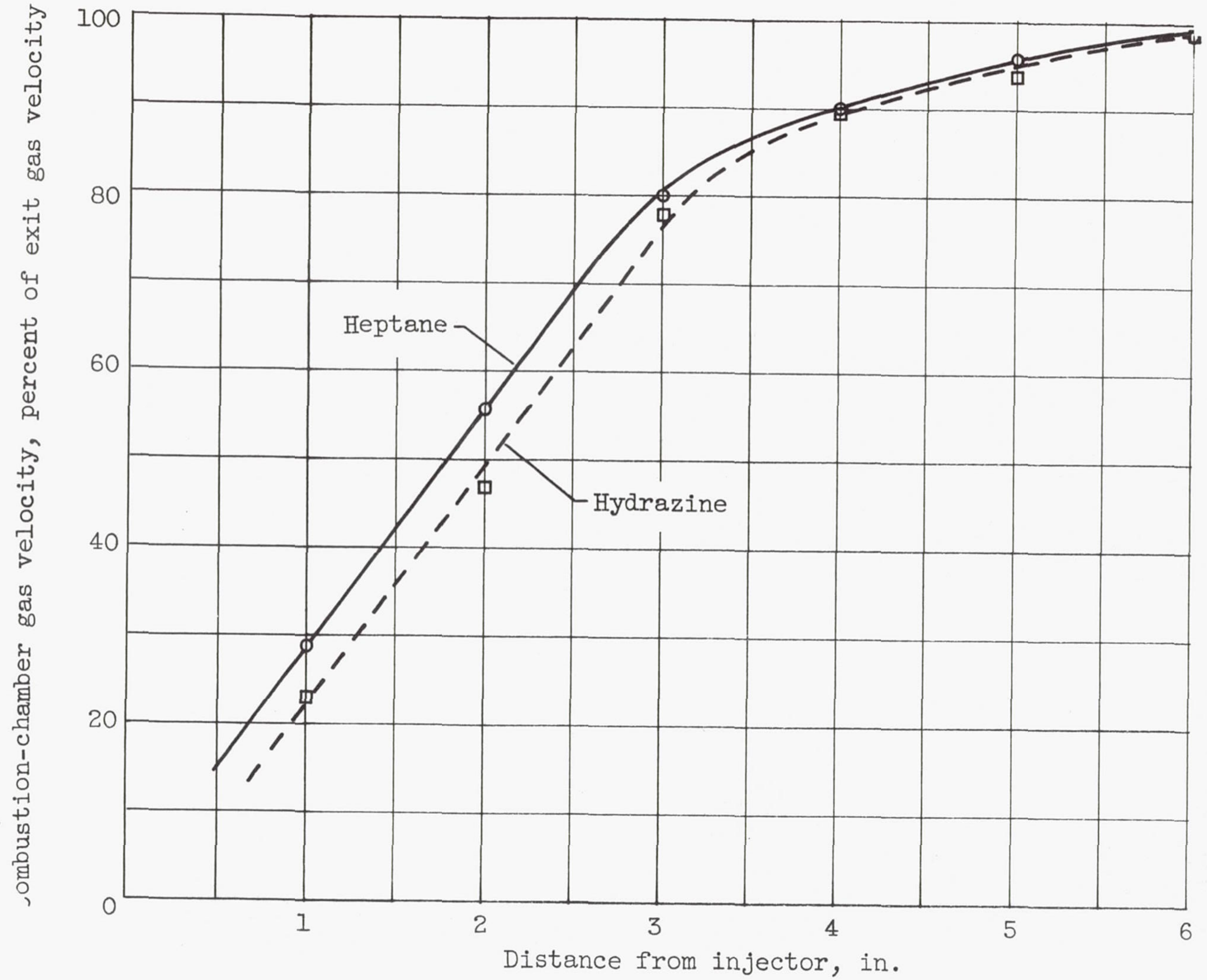
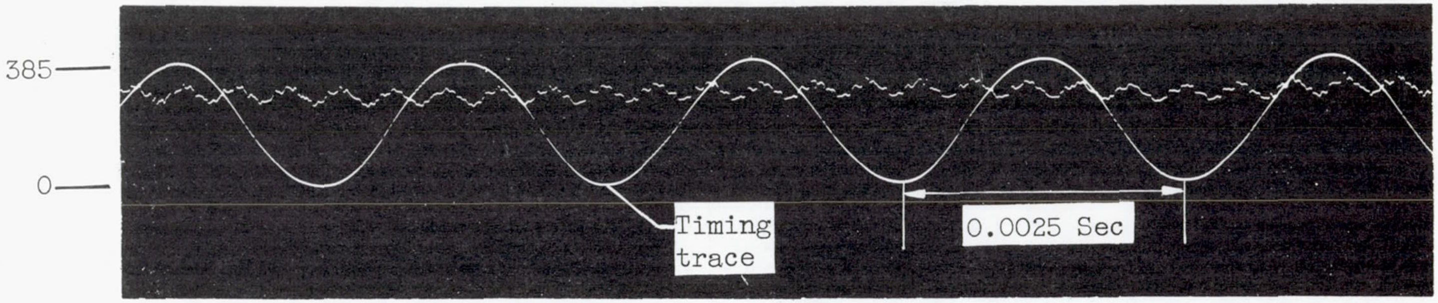
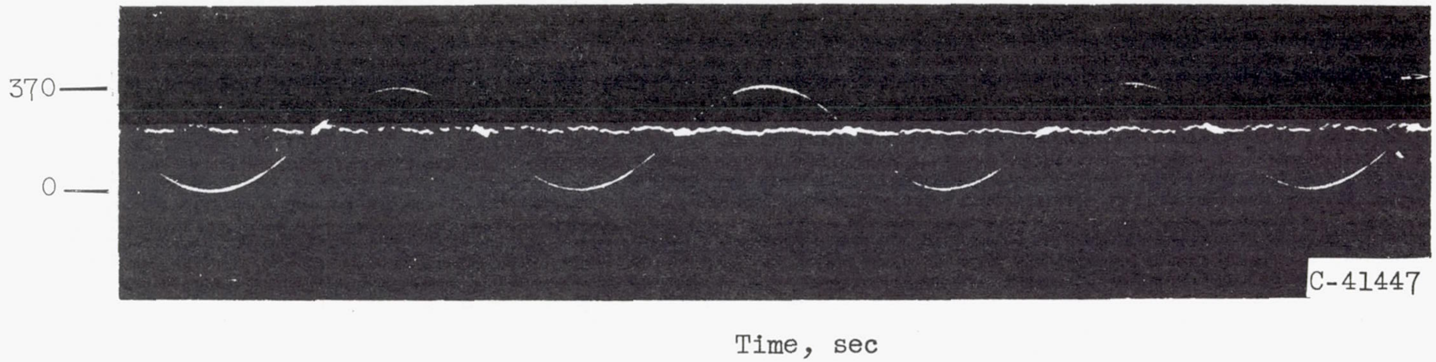


Figure 6. - Plot of combustion-chamber gas velocity against distance from injector for smooth runs with heptane and hydrazine.

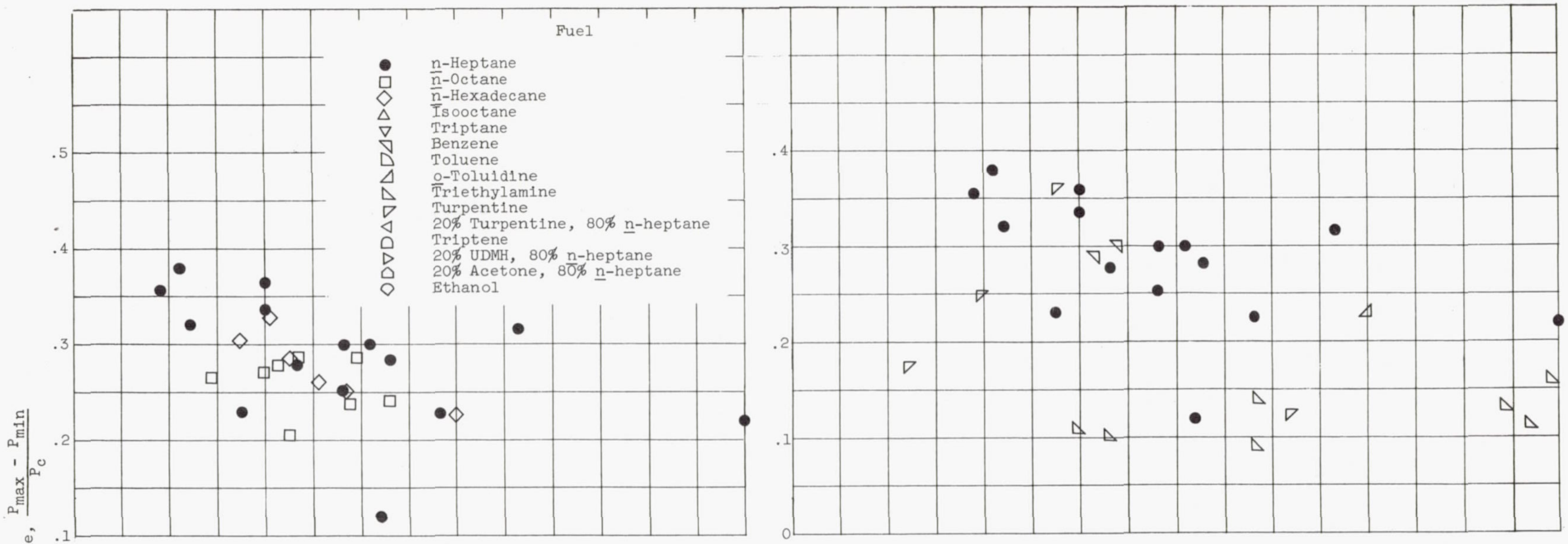


(a) Screaming amplitude, 0.28; screaming frequency, 2300 cps.



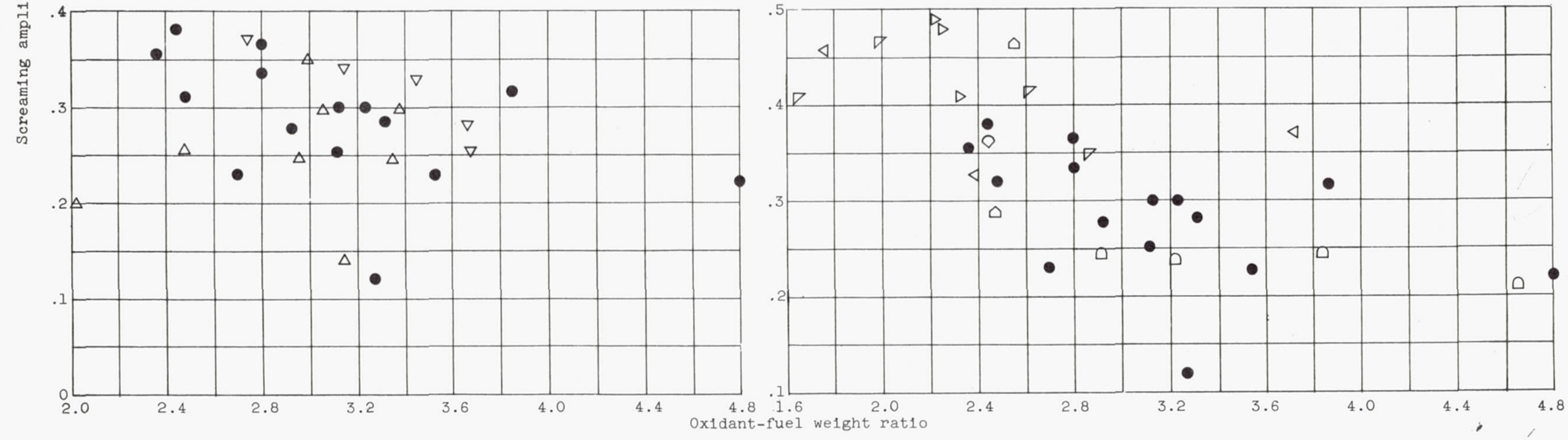
(b) Screaming amplitude, 0.12; screaming frequency, 2250 cps.

Figure 7. - Sample pressure-time records from two runs with different screaming amplitudes. Fuel, n-heptane; oxidant-fuel ratio, 3.3.



(a) Straight-chain paraffins.

(c) n-Heptane, aromatics, and amines.



(b) n-Heptane and branched-chain paraffins.

(d) n-Heptane and remaining fuels.

Figure 8. - Screaming amplitude against oxidant-fuel weight ratio for several fuels.

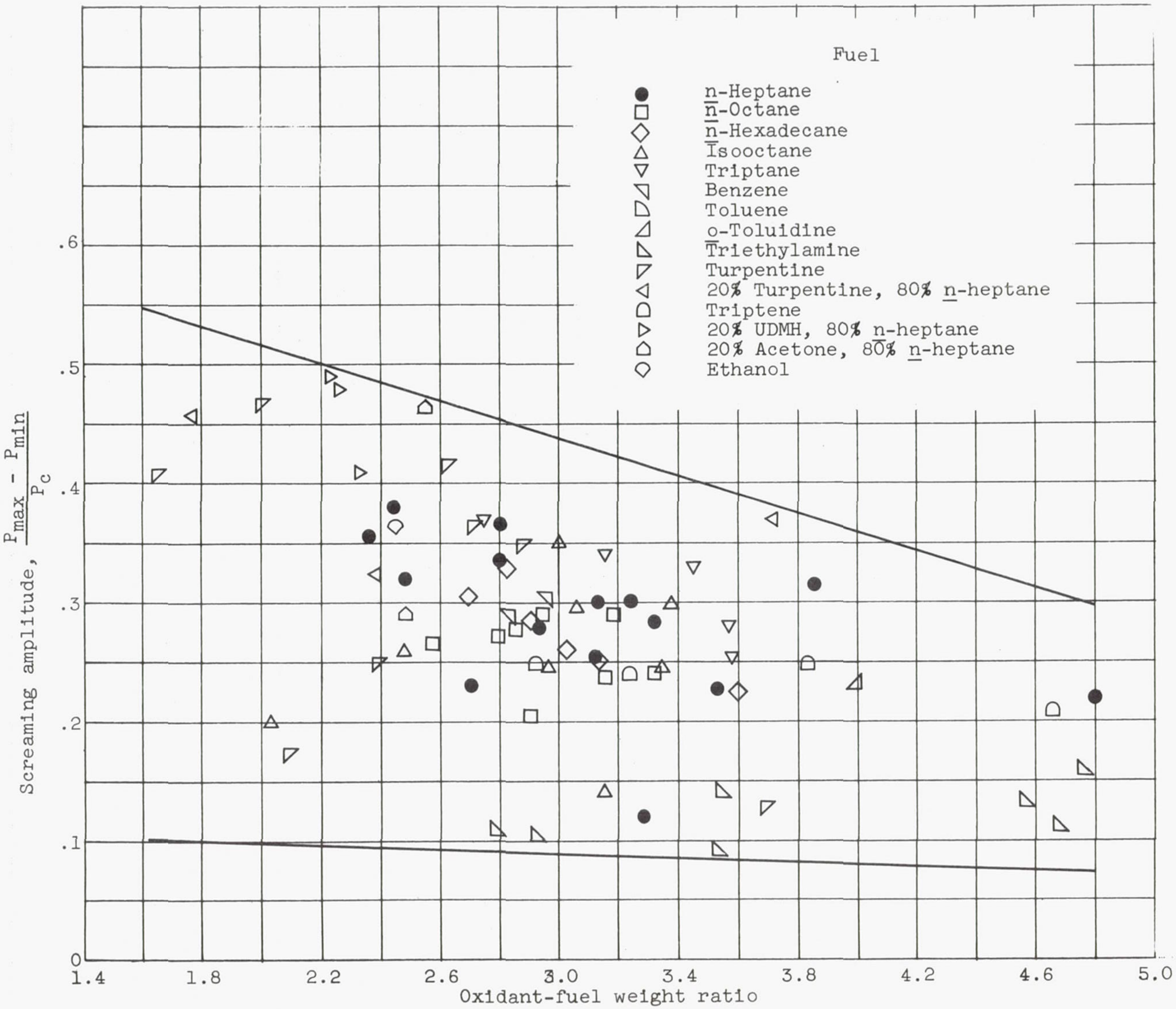


Figure 9. - Composite of screaming amplitude against oxidant-fuel weight ratio for all fuels tested.

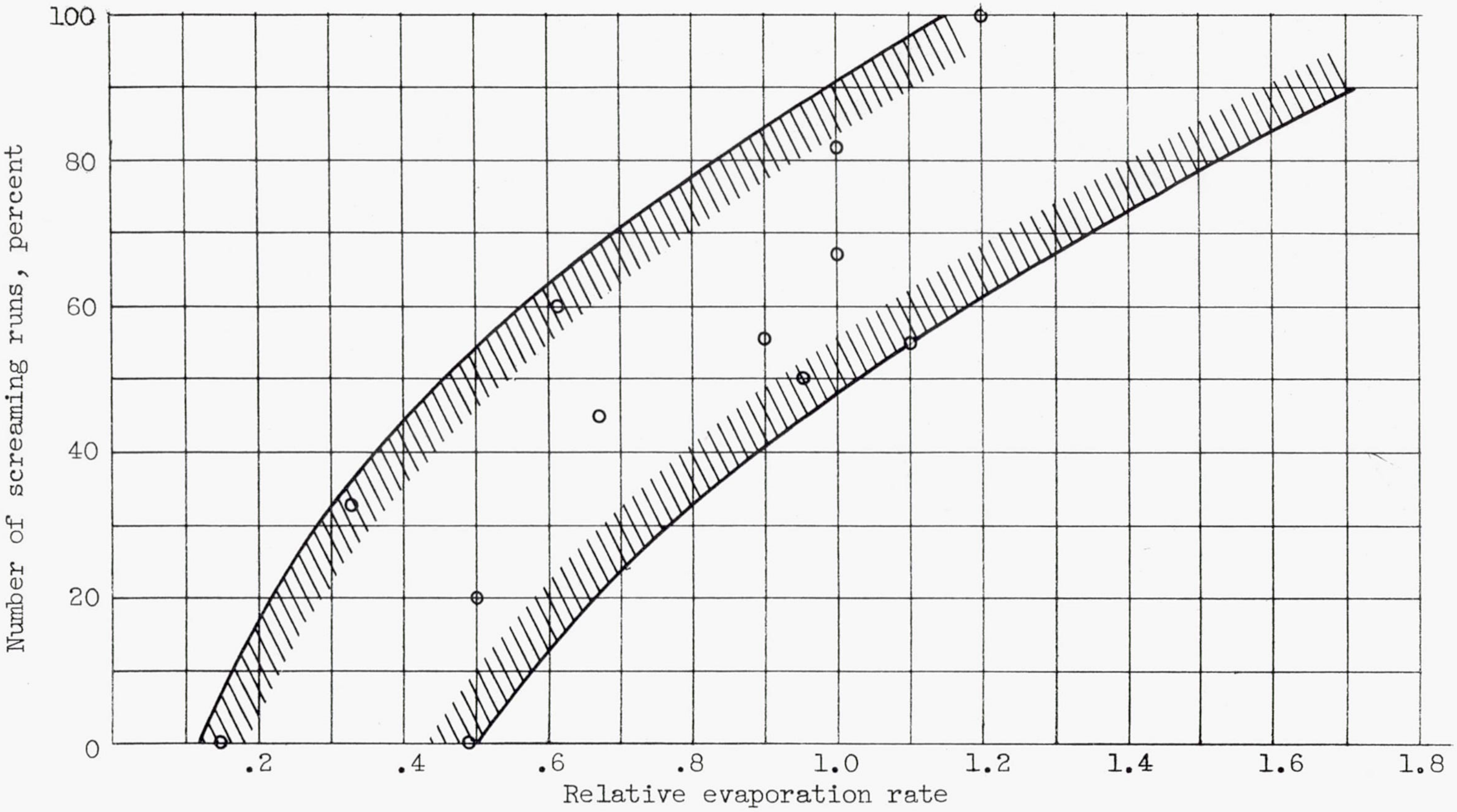


Figure 10. - Plot of screaming tendency against relative evaporation rate.