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RESEARCH MEMORANDUM

A STUDY OF FUEL-NITRIC ACID REACTIVITY

By Charles E. Feiler and Louis Baker, Jr.

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

April 6, 1956

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RESEARCH MEMORANDUM

A STUDY OF FUEL-NITRIC ACID REACTIVITY

By Charles E. Feiler and Louis Baker, Jr.

SUMMARY

The relative reactivities of six fuels with red fuming nitric acid (19 percent NO_2) were determined in a 40-pound-thrust rocket engine with rapid liquid-phase mixing. The combustion-chamber characteristic length required to obtain 97 percent of maximum experimental characteristic exhaust velocity was used as the measure of reactivity. Hydrazine, trimethyl-trithiophosphite, furfuryl alcohol, unsymmetrical dimethyl-hydrazine, allylamine, and o-toluidine were studied; reactivity decreased in that order.

A swirl-cup-type injector was used. Injector spray pattern and mixing efficiency were determined. The swirl-cup pressure drop depended strongly on the nature of the fuel-acid mixture and was assumed to be a measure of the vigor of the reaction occurring in the cup.

One-inch-diameter chambers of various lengths were used. Two of the fuels were also studied in $1\frac{1}{2}$ - and 2-inch-diameter chambers. Reactivities are shown to be dependent on the acid-fuel ratio. Reactivities, injector-cup pressure drops, and ignition delays are compared and discussed.

INTRODUCTION

The selection of rocket propellants for a specific purpose would be aided if, in addition to thermodynamic and physical data, there were available some index of reaction rate. Such an index would also be of value in the design of the smallest, lightest combustion chambers consistent with efficient combustion.

Several investigations have been made to determine reactivities or conversion rates in rocket combustion chambers. In one, the characteristic exhaust velocity c^* was measured as a function of chamber length for several fuels with liquid oxygen as the oxidizer (ref. 1). (The symbols used in this report are defined in appendix A.) The study was primarily for the purpose of correlating conversion rates with flame speeds and slow oxidation rates. Flame speeds and slow oxidation rates are not

necessarily related to combustion processes that occur in rocket engines; however, qualitative correlations were obtained. Similar data have also been used in the evaluation of injector configurations for the system, white fuming nitric acid (WFNA) and JP-3 fuel (ref. 2).

In another investigation the static-pressure profile along a tubular engine was determined, and from this, reaction rates were inferred (ref. 3). WFNA-ammonia and WFNA-hydrazine systems were studied with a number of injector configurations. Similar data have been interpreted to give a minimum required residence time for the combustion of gaseous methane and oxygen (ref. 4).

This report describes an investigation of the relative reactivities of several fuels with red fuming nitric acid (RFNA) under conditions where the effect of liquid-phase mixing is minimized. The combustion-chamber characteristic length L^* required to obtain 97 percent of the maximum experimental characteristic exhaust velocity c^* was used as the measure of reactivity. A swirl-cup-type injector was used because this type has been shown to produce very rapid liquid-phase mixing (ref. 5). The mixing efficiency and spray pattern of the injector were determined.

Six fuels, representative of several classes, were studied using RFNA (19 percent NO_2) as the oxidizer. The experiments were conducted in a nominal 40-pound-thrust rocket engine. The characteristic length L^* of the combustion chamber was varied by using different lengths of 1-inch-diameter pipe. Two of the fuels were also studied in $1\frac{1}{2}$ - and 2-inch-diameter chambers to determine the effect of diameter on the general level of performance and on the reactivities of the fuels. The ratings of the fuels, based on data for c^* and L^* and cup pressure drop, are compared.

An attempt was made to interpret the results of this study assuming that the conversion of NO to N_2 is an important rate-determining step in the final stages of combustion involving nitric acid (refs. 6 and 7).

APPARATUS AND PROCEDURE

Rocket Engine

A cross-sectional view of the rocket engine and injector is shown in figure 1.

Injectors. - The injectors were of a swirl-cup type similar to that reported in reference 8. Propellants entered the mixing cup tangentially at an inlet angle of 10° . The cross-sectional area of the mixing cup was 4 times the sum of the cross-sectional areas of the inlet orifices. The cup length was chosen for approximately 1 millisecond of residence time based on the calculated velocity of unreacted propellants. Two injectors

with different inlet-orifice diameters were required to permit operation over a wide range of mixture ratios. The injector heads were constructed of stainless steel and contained a pressure tap leading directly to the chamber.

Separate experiments were conducted to determine the mixing efficiencies and spray patterns of the injectors. The details of these experiments are presented in appendix B. The results indicate that mixing was largely excluded as a factor in the present study and that the data represent primarily evaporation and chemical-reaction rates. Studies of the spray patterns indicated an almost uniform distribution with a cone angle of about 37° .

Chambers. - Uncooled chambers were made of extra-heavy seamless steel pipe having 1-, $1\frac{1}{2}$ -, and 2-inch nominal diameters. In addition, transparent chambers of cast acrylic resin were used for a photographic study. These had a wall thickness of $\frac{1}{4}$ inch and inside diameters of 1, $1\frac{1}{2}$, and 2 inches. Figure 1 shows a 1-inch chamber only. Adaptors were used to fit the wider chambers to the injector. When adaptors were used, there was a prechamber space $\frac{2}{3}$ -inch long with a 1-inch diameter. This space had a characteristic length of 6 inches. The 1-, $1\frac{1}{2}$ -, and 2-inch-diameter chambers had characteristic lengths of 8.1, 19.9, and 33.3 inches, respectively, per inch of chamber length.

Nozzles. - Stainless-steel water-cooled nozzles having a convergent section only were used. The nozzles were constructed with steps to accommodate the various chamber diameters. The injector, chamber, and nozzle were bolted together and sealed by copper or aluminum gaskets at both ends of the chamber. The entire assembly was directed downward.

Flow System and Operation

The flow system of the test rig was similar to those used in other experimental rocket setups. The two propellant tanks could be pressurized independently to about 850 pounds per square inch gage. A pneumatically operated firing valve permitted flow of both propellants to begin simultaneously. The initial flow rates were about twice the steady-state values. Because of the high initial flow rates, the ignition process was affected and hard starts were encountered with furfuryl alcohol, allylamine, and o-toluidine. In order to prevent such hard starts, these fuels were preceded by a 3- to 5-cubic-centimeter slug of 82 percent hydrazine, which was fed directly into the firing valve through a short length of vertically mounted tubing. The other fuels showed smooth-starting characteristics over the entire range of acid-fuel ratios.

Without starting fuel the total running time was usually 1 to 2 seconds. When starting fuel was used, the running time was increased to about 3 seconds to ensure the complete removal of the starting fuel. Running time on starting fuel ranged from 0.2 to 0.5 second. Transition from starting fuel to running fuel could sometimes be detected in the flow and chamber-pressure records. All the runs were long enough so that the flow rates and chamber pressure reached constant values.

In order to purge the injector and chamber at the end of each run, high-pressure helium was automatically admitted downstream of the firing valve just as the valve closed.

Instrumentation

Duplicate measurements were made of all primary variables. Propellant flow rates were measured both by rotating-vane flowmeters and by orifices in conjunction with strain-gage differential-pressure transducers. In order to protect the pressure transducer in the acid line from the corrosive action of the acid, a fluorocarbon oil was placed in the lines connecting the orifice and the transducer chamber. The oil (sp. gr., 1.95), being heavier than acid, prevented contact between the acid and the sensitive instrument diaphragms. Although some NO₂ was absorbed by the oil, no corrosion of the metal diaphragm was observed over a period of a year.

The chamber pressure was measured by two strain-gage static-pressure transducers placed 18 and 30 inches from the injector on a single pressure tap line. The pressure tap line was 1/4-inch-diameter stainless-steel tubing and was provided with a slight helium bleed to keep it unblocked and to prevent possible explosions due to propellant entry on starting.

The outputs of all instruments were recorded on a multichannel galvanometer-type oscillograph. The flow rates and pressures used were averages of the duplicate measurements. The deviations between flow rates obtained from the rotating-vane instrument and the orifice-strain-gage combination averaged 0.003 pound per second for the acid and 0.002 pound per second for the fuel. The deviations between chamber-pressure measurements from each of the strain gages averaged 2.2 pounds per square inch.

The nozzle diameter was measured before and after each series of runs, and an average of these two values was used. Propellant temperatures were measured with a mercury thermometer at each loading of the tanks.

Fuels and Acids

The acid used throughout the study was a red fuming nitric acid containing 19 percent NO_2 and 2 percent water. The six fuels used were 92.2 percent hydrazine, commercial-grade trimethyl-trithiophosphite (TMTP), commercial-grade furfuryl alcohol, commercial-grade unsymmetrical dimethylhydrazine (UDMH), commercial-grade allylamine, and chemically pure o-toluidine. In the mixing efficiency tests, 18.8 percent HNO_3 and 18.2 percent NaOH in water were used.

Treatment of Data

The characteristic length L^* was calculated from chamber volume/nozzle throat area; characteristic exhaust velocity c^* was calculated from (chamber pressure)(nozzle throat area)/total flow rate. The L^* corresponding to maximum c^* is difficult to locate accurately because the experimental curves are almost horizontal over a wide range of L^* near the maximum. For this reason the L^* for comparison was chosen as that at which c^* reached 97 percent of its maximum value. At this point L_{97}^* the curves are steep enough to give a well-defined value of L^* .

Values of $\beta (o/f)/(o/f)_{\text{stoichiometric}}$ of 0.55, 0.65, 0.80, 1.0, and 1.25 were selected for comparing the various fuels. The acid-fuel weight ratios o/f corresponding to these β values are shown for each fuel in table I. The choice of these values was limited by the range of the data, which in some cases did not extend to the extreme values. Special significance is attached to β of 0.80 since it corresponds approximately to the o/f of maximum c^* for all the fuels.

Theoretical performance data for the exact acid composition used in this study were not available; however, some applicable data were found. The data for hydrazine and furfuryl alcohol are from reference 9. The data for UDMH are from reference 10. It was necessary to correct the hydrazine data for the effect of about 8 percent water. The correction was based on the data of reference 9 and reduced the c^* values for anhydrous hydrazine by 1.2 percent.

RESULTS

The basic measured and calculated data are shown in table II for each fuel. The flow-rate values are given to three decimal places; however, in some cases four places were used to compute c^* and o/f . Runs in which screaming (high-frequency sound due to combustion oscillations)

was heard are marked. In every case when screaming was heard, the chamber-pressure record was smooth and free from random disturbances otherwise present.

Figure 2 shows typical $c^* - o/f$ curves for each fuel at the L^* giving the highest c^* . These data are for 1-inch-diameter chambers and are representative of data obtained at other L^* values. The experimental points show the reproducibility of the data to be very good. Theoretical c^* curves for three of the fuels are also shown in figure 2.

Combustion Characteristics of the Fuels

Three of the fuels, hydrazine, TMFP, and UDMH, were very smooth in operation giving no hard starts or audible screaming. Furfuryl alcohol screamed consistently in chambers having an L^* of 50 inches and greater over the entire o/f range studied. Some intermittent screaming was observed with allylamine and *o*-toluidine in the longer chambers. This usually occurred near the end of a run, so that it was usually possible to obtain data when there was no screaming. No difference was observed between c^* values for screaming and nonscreaming runs. This is illustrated in figure 2 where data points for both conditions are shown for furfuryl alcohol and *o*-toluidine. TMFP produced hard deposits in the nozzle throat. Both furfuryl alcohol and *o*-toluidine formed copious carbon deposits in the chambers.

Fuel Ratings

In figure 3, c^* is shown as a function of L^* and o/f for each fuel. The curves are for 1-inch-diameter chambers and are taken from smoothed $c^* - o/f$ plots like those in figure 2. The β values at which the fuels are compared later are marked. From figure 3 it can be seen that the o/f giving a maximum c^* generally increases as L^* is increased.

In figure 4, the fuels are compared at a β of 0.80; L_{97}^* points are shown. These curves are similar in form to those obtained at the other values of β . The characteristic exhaust velocities c^* for allylamine and *o*-toluidine did not reach a maximum even at an L^* of 100 inches. As an approximation, maximum c^* was taken as that at an L^* of 100 inches; therefore the L_{97}^* values are a minimum for these two fuels. The results of the evaluation of L_{97}^* are given in table III as a function of β for the six fuels. The maximum c^* values are listed in table IV.

The fuels in order of increasing L_{97}^* and hence decreasing reactivity are hydrazine, TMFP, furfuryl alcohol, UDMH, allylamine, and *o*-toluidine.

It is apparent from table III that the reactivity decreases as the stoichiometric o/f increases. On the fuel rich side, the L_{97}^* values generally increase for a given fuel as β increases. The dependence on the relative amounts of acid and fuel present is shown in figure 5 in which all of the L_{97}^* values in table III are plotted against the corresponding o/f . The data fall into two groups with allylamine and o -toluidine separated from the remaining four fuels.

Pressure in the Mixing Cup

The flow rates observed during live runs were much lower than those expected from cold-flow tests. This effect was apparently due to a large pressure drop in the injector mixing cup resulting from liquid-phase reaction. Cup pressure drop is a measure of the amount of liquid-phase reaction in the cup, since only a negligible pressure drop would have resulted from fluid friction alone. The cup pressure drop was calculated using the equation for flow through an orifice. Details of the calculation are given in appendix C. Calculated values of the cup pressure drop are shown in figure 6 as a function of o/f . The values are corrected to a uniform flow rate of 0.2 pound per second (see appendix C). The pressure drops tend toward a common value independent of the fuel as o/f is increased.

Effect of Chamber Diameter

The effect of chamber diameter on the general level of performance and on the reactivities of the fuels was investigated. Two fuels, hydrazine and UDMH, showing widely different reactivities in the 1-inch-diameter chambers were studied in $1\frac{1}{2}$ - and 2-inch-diameter chambers. Characteristic exhaust velocity c^* for each diameter is shown as a function of L^* in figure 7(a) and as a function of chamber length in figure 7(b). Data for β equal to 0.80 only are shown as they are typical of the data for all β values. From figure 7(a), the L^* corresponding to maximum c^* increased with diameter for both fuels. From figure 7(b) the chamber length corresponding to maximum c^* decreased with diameter for UDMH, while no trend was observed for hydrazine. The maximum c^* increased slightly with diameter for UDMH, while no trend was observed for hydrazine.

L_{97}^* values are shown in table V as functions of diameter for hydrazine and UDMH. L_{97}^* increases with both diameter and β .

DISCUSSION

Effect of Chamber Diameter

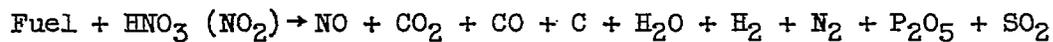
An analysis of the data of table V showed that an essentially constant difference exists between the L_{97}^* values of each of the larger chambers and the 1-inch chambers. The average differences in L_{97}^* values, shown in table VI, are 19.1 inches between the $1\frac{1}{2}$ - and 1-inch diameters and 42.9 inches between the 2- and 1-inch diameters. As discussed in appendix B, the injectors produced a conical spray pattern. It was assumed that the chamber volume outside the spray cone did not contribute to the effective combustion volume. This ineffective combustion volume was calculated from the cone angle and chamber geometry. The ineffective volume was converted to an equivalent L^* for each of the chamber diameters. The difference in L^* values thus obtained for the various chamber diameters were of the same order of magnitude as those observed experimentally. The differences may be applied as a correction to the L_{97}^* values obtained with the larger-diameter chambers resulting in approximately the same L_{97}^* values for all diameters. This result indicates that in the range of diameters studied there is little effect of chamber diameter on the observed reactivities.

Correlation of Reactivity with Initial NO Concentration

From the relation between L_{97}^* and o/f shown in figure 5, it appears that, in a very general way, the reactivity of a combination containing unit mass of fuel depends on the amount of acid present; that is, even on the fuel rich side, the reactivity decreases as the acid concentration is increased. For some of the fuels the differences in reactivity between fuels were less than those produced by changes in the acid-fuel ratio. It seems reasonable therefore to relate reactivity to some function of acid concentration in the reactant mixture.

It has been postulated that in oxidation reactions involving nitric acid or NO_2 , where NO is an intermediate, the steps involving NO are slow and rate-determining. It has been found that the measured flame speeds of NO-hydrocarbon mixtures were about 1/10 those of oxygen-hydrocarbon mixtures with hydrocarbons such as ethane, ethylene, and acetylene (ref. 11). Other evidence indicates that higher temperatures are required to propagate NO supported flames than flames supported by O_2 or NO_2 (ref. 12). Also, analysis of the primary cone of a premixed gaseous nitric acid-hydrocarbon flame showed that nearly all the nitrogen is recovered as NO (ref. 13).

An attempt was therefore made to correlate the experimental data with some function of NO concentration. It was assumed that the following reaction occurs very rapidly to form intermediates and products as shown:



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All the nitrogen in the acid has been assumed to form NO. The other species are formed, where applicable, from the fuel. For each mixture ratio, the initial mole fraction of NO (moles NO/total moles) was calculated. Whether CO₂, CO, or C and H₂O or H₂ is formed is not known but has no effect on the total number of moles. It was necessary, however, to assume that the amounts of O₂, OH, H, CH, and so forth present after the initial reaction are negligible. Using experimental chamber pressures each mole fraction was converted to a partial pressure of NO. The initial partial pressure of NO represents the amount of NO that must react to carry the reaction to completion. These pressures are plotted as a function of L_{97}^*/c_{97}^* for each fuel in figure 8. The ratio L_{97}^*/c_{97}^* has the dimensions of time and is shown in appendix D to be roughly proportional to the residence time of the propellants from injection to the point of 97 percent maximum c^* .

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The shapes of the curves for the individual fuels in figure 8, with the possible exception of hydrazine, are inconsistent with any rate law based on a single reaction. If, at the final state (97 percent maximum c^*), the partial pressure of NO is the same value for all mixtures, and if the disappearance of NO followed a first, second, or higher order dependence, the curves would be concave to the pressure axis.

The curves for furfuryl alcohol, UDMH, and allylamine approach a common limiting line at higher initial NO concentrations. The slope of the limiting line is small and may represent the thermal decomposition of NO. At lower initial NO concentrations the slopes are higher suggesting that NO is reacting with fuel fragments. Thus the shape of the curves may be explained on the basis of two competing reactions, one, the thermal decomposition of NO, which is slower, and the other, the reaction of NO with fuel fragments, which is faster. The curve for hydrazine does not suggest such a mechanism; however, the initial partial pressures of NO in all runs with hydrazine were quite low. The TMIP and o-toluidine curves are not consistent with such a conclusion.

The slope of the limiting line in figure 8 was found to be 3.9×10^3 pounds per square inch per second. The calculation of the slope includes a correction of the time base of figure 8 as shown in appendix D. The rate of thermal decomposition of NO, calculated from experimental data, increased from 6.5×10^3 to 4.6×10^4 pounds per square inch per second as the temperature was increased from 3500° to 4100° R (ref. 6). Thus the slope of the limiting line is of the same order of magnitude as the calculated rate of thermal decomposition of NO.

The validity of this correlation is, of course, limited by the uncertainty of the final concentration of NO and the assumptions regarding the fate of the fuel atoms.

Comparison of Cup Pressure-Drop, L_{97}^* , and Ignition-Delay Values

The values of the steady-state pressure drop in the mixing cup were shown in figure 6 as a function of o/f for each fuel. The propellants are in the mixing cup for about 1 millisecond so that a high cup pressure drop indicates appreciable early reaction. From figure 6 it is apparent that the pressure drop is fuel dependent for fuel-rich mixtures. Cup-pressure-drop values and L_{97}^* values are compared at a β of 0.65 in table VII. With the exception of furfuryl alcohol, cup-pressure-drop ratings follow the same trend as L_{97}^* ratings.

The ignition-delay values of the fuels also shown in table VII were not all obtained under comparable conditions; however in general, the fuels are divided into two groups according to their ignition delays. Fuels having short ignition delays, hydrazine, TMTP, and UDMH, have the highest cup-pressure-drop values. Fuels having long ignition delays have the lowest cup-pressure-drop values.

It is to be expected that cup pressure drops and ignition delays should correlate because both characterize the initial processes in the combustion reaction. However, L_{97}^* is a measure of the over-all conversion rate and characterizes the entire combustion process. Moreover, the correlation with initial NO concentration suggests that L_{97}^* may be largely determined by the final stages of the combustion process. The observation that L_{97}^* ratings and cup-pressure-drop ratings follow the same trend indicates that generally a combustion reaction which is vigorous in its early stages also will have a high over-all conversion rate.

As shown in figure 6, the cup-pressure-drop values for all the fuels seem to approach a common value of about 80 pounds per square inch at high o/f ratios. This value is considerably higher than would be expected from fluid friction alone. It may be due to thermal decomposition of the acid, with the necessary heat being supplied by transfer upstream from the combustion process. If it were caused entirely by reaction of fuel and acid in the cup, it would be expected that different values would be obtained for the various fuels such as were obtained at lower o/f ratios.

Over-All Combustion Efficiency

Theoretical performance curves for three of the fuels were shown in figure 2. The following table shows the percent of theoretical c^* obtained at the o/f of experimental peak c^* .

Fuel	L*	Percent of theoretical c*	
		Frozen expansion	Equilibrium expansion
Hydrazine	40	92.4	----
Furfuryl alcohol	50	94.3	90.5
UDMH	75	----	90.6

As discussed previously, the acid composition used in the calculation of theoretical c^* did not correspond exactly to that used in the experimental study. Within this limitation the experimental efficiency is about the same for all three fuels. The experimental data are uncorrected for heat lost to the walls. An estimate of such heat loss showed that it could vary from about 3 percent in an L^* of 30 inches to about 8 percent in an L^* of 100 inches for the 1-inch-diameter chambers. It appears therefore that the relatively low efficiency can be largely accounted for by heat transfer to the chamber walls.

CONCLUDING REMARKS

The concept of a volume required to complete a reaction has been used to classify six fuels with respect to their reactivities. The importance of data of this kind can be illustrated by the results of some performance measurements on a 5000-pound-thrust NH_3 -RFNA engine having an L^* of 17.5 inches (ref. 14). In spite of the small L^* , high specific impulse was obtained indicating that NH_3 has a high reactivity. The effect of adding UDMH to the NH_3 was then studied. Although UDMH has a higher theoretical performance than NH_3 , the addition of 30 percent UDMH to the NH_3 lowered the specific impulse 13 percent. This is not surprising in the light of the present research since an L^* of about 75 inches was required to obtain maximum performance with UDMH.

It is possible that finer discrimination between fuel-oxidant systems could be obtained by using a continuously variable L^* engine. This would improve the internal consistency of the data by eliminating cross plots. It would also allow the entire L^* range to be scanned.

SUMMARY OF RESULTS

Using the chamber characteristic length L^* required to obtain 97 percent of maximum experimental characteristic exhaust velocity c^* as an index, the relative reactivities of six fuels with RFNA were determined. The experiments were conducted in a 40-pound-thrust rocket engine using a swirl-cup injector which gave about 70-percent-complete liquid-phase mixing. The results of the investigation may be summarized as follows:

1. The reactivities of the fuels were found to decrease in the following order: Hydrazine, trimethyl-trithiophosphite, furfuryl alcohol, unsymmetrical dimethylhydrazine, allylamine, and o-toluidine. The latter two fuels had considerably lower reactivities than the remaining four fuels.

2. As acid-fuel ratio o/f was increased, the reactivities of the fuels generally decreased.

3. From an analysis of the effect of stoichiometry, it appears that for at least three of the fuels two reactions involving NO may be important. The reaction of NO with fuel fragments is the faster reaction; the thermal decomposition of NO is slower.

4. The pressure drop through the mixing cup appeared to be a measure of the extent of liquid-phase reaction. This pressure drop followed the same general trend as ignition delay.

5. The chamber diameter had no effect on the relative ratings of two fuels studied as functions of diameter.

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

APPENDIX A

The following symbols are used in this report:

- A area, sq in.
- C_d discharge coefficient
- c^* characteristic exhaust velocity, $p_c A_t g / w_t$, ft/sec
- g gravitational constant, 32.2 ft/sec²
- h ratio of average value of RT/M to value at nozzle entrance
- K flow constant, $C_d^2 A^2 2g_0 / 144$, (lb)(sq in.)/sec²
- L^* characteristic length, V_c / A_t , in.
- M molecular weight of combustion gases
- o/f acid-fuel ratio, w_o / w_f
- p pressure, lb/sq in.
- R universal gas constant, ft-lb/lb-mole °R
- T combustion-chamber temperature, °R
- t residence time of combustion gases in chamber, sec
- V_c combustion-chamber volume, cu in.
- V_g average specific volume of gases in combustion chamber, cu ft/lb
- w flow rate, lb/sec
- w_T total flow rate, $w_o + w_f$, lb/sec
- β weight fraction of stoichiometric o/f , $\frac{o/f}{(o/f)_{\text{stoichiometric}}}$
- Γ $\gamma \sqrt{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$
- γ specific-heat ratio
- ρ density, lb/cu ft

Subscripts:

av average
c combustion chamber
cup injector mixing cup
f fuel
i nozzle inlet
o acid
p propellant tank
t nozzle throat

APPENDIX B

INJECTOR CHARACTERISTICS

The injector was characterized by studies of its mixing efficiency and spray pattern.

Mixer

A separate apparatus (fig. 9) was used to study the mixing efficiency of the injector. The flow arrangement was identical to that in the injector except that the mixing cup was extended to a length of 6 inches with tubing having a 0.020-inch wall thickness. Iron-constantan thermocouples were spot-welded to the mixing tube at various stations. The entire mixer was enclosed by a heater so that the initial temperature of the block, which is the greatest heat sink, could be adjusted to minimize heat transfer. The extended tube was carefully insulated from the heater to avoid heat transfer from the heater to the mixing tube during a run.

Efficiency of Mixing

The mixing efficiency of the injector was studied with dilute nitric acid and sodium hydroxide. Inasmuch as the reaction between a strong base and a strong acid is instantaneous and dependent only on the rate of mixing (ref. 5), the heat evolved by such a reaction can be used as an index of the completeness of mixing under adiabatic conditions. By following the temperature rise as a function of distance along the mixing tube, mixing efficiency can be determined (ref. 5). The temperature corresponding to complete mixing is calculable from thermodynamic data.

Smoothed data with three initial block temperatures are shown in figure 10. The upper curve corresponds to a high initial block temperature, which caused heat to be added to the stream resulting in a final temperature well above theoretical. The lower curve corresponds to a low initial block temperature for which the final temperature is below theoretical. The middle curve closely approximates the adiabatic case since the final temperature does reach theoretical. This is substantiated by the fact that the initial block temperature seems to be a reasonable average of the stream temperature in the region of the large block. From this curve it can be deduced that it requires 2.2 inches to achieve 97-percent-complete mixing. The extent of mixing at the distance corresponding to the end of the mixing cup in the rocket injector was found to be 70 percent. Whether the efficiency measured in the test mixer can be applied to mixing in the injector, under conditions where large amounts of heat and gas are evolved, may be somewhat questionable. A similar mixer,

under these conditions, gave an essentially complete reaction as fast as the reactants emerged from the mixer (ref. 15). It is thus concluded that mixing is largely excluded as a factor in the present study and that the data represent primarily evaporation and chemical-conversion rates.

Studies of Spray Pattern

Experiments were conducted with plastic chambers of three diameters to determine how the reactants leaving the injector entered the chamber. Erosion patterns of the chambers using hydrazine as the fuel are shown in figure 11. The diameter measurements shown are averages of those made at a given station for two radial positions at right angles. The data for both positions are shown for the 2-inch chamber. Erosion was nearly symmetric about the circumference of the chamber indicating an almost uniform spray distribution.

The point of maximum erosion moved away from the injector as the diameter was increased. It was assumed that the point of maximum erosion represents the point of impingement of the burning spray from the injector on the chamber walls. These points are shown on a sketch of the chambers in figure 11. It can be seen that a straight line connecting them can be extended to the vicinity of the injector cup. This indicates that the injector spray under operating conditions is a cone having an included angle of about 37° . High-speed motion pictures, made with a framing camera, of the steady-state combustion showed that the chambers were not filled by luminous flame and that the cone angle was of the order of 40° . High-speed streak photographs showed considerable recirculation in the vicinity of the injector. Cold-flow tests using water gave a hollow-cone spray with an included angle of about 60° .

These results indicate that at least a part of the chamber volume upstream of the cone of burning may not contribute to the effective combustion volume.

APPENDIX C

CALCULATION OF PRESSURE DROP IN THE MIXING CUP

The calculation of cup pressure drop is possible because the mixing cup is the first point common to both the fuel and the acid flow lines. The calculation is based on the equation for orifice flow

$$w = C_d A \sqrt{\frac{2g\Delta p}{144}} \quad (C1)$$

If the friction factor is assumed constant, equation (C1) may be applied to the entire flow line. Equation (C1) may be squared and written both for the fuel line and the oxidant line as follows:

$$w_f^2 = K_f (p_{f,p} - p_{cup}) \quad (C2)$$

$$w_o^2 = K_o (p_{o,p} - p_{cup}) \quad (C3)$$

where $p_{f,p}$ and $p_{o,p}$ are the fuel and oxidant tank pressures, respectively. Eliminating p_{cup} from equation (C2) and (C3),

$$\frac{w_o^2}{K_o} - \frac{w_f^2}{K_f} = p_{o,p} - p_{f,p} \quad (C4)$$

Dividing by w_f^2 and rearranging give

$$\frac{p_{o,p} - p_{f,p}}{w_f^2} = \frac{(o/f)^2}{K_o} - \frac{1}{K_f} \quad (C5)$$

When $(p_{o,p} - p_{f,p})/w_f^2$ is plotted against $(o/f)^2$, equation (C5) is a straight line of slope $1/K_o$ and intercept $-1/K_f$.

The experimental program was conducted at a number, usually eight, of tank pressure settings for each fuel at each of the characteristic lengths studied. The experimental values of w_o , w_f , and p_c obtained with the various characteristic lengths at given tank pressure settings were averaged. The tank pressure settings and the average of each of the observed flow rates were then used to plot equation (C5). Such a plot for hydrazine is shown in figure 12. The corresponding plots for the other fuels also gave straight lines. From the measured slope and intercept, values of K_o and K_f were determined. K_o , K_f , $p_{f,p}$, $p_{o,p}$, w_f ,

and w_0 being known, P_{cup} was calculated from equations (C2) and (C3). The two values of P_{cup} agreed very closely, and their average was used to calculate the pressure drop by subtracting the chamber pressure from it;

$$\Delta P_{cup} = P_{cup} - P_c \quad (C6)$$

Since the average total flow rate w_T was not the same for each fuel, the cup-pressure-drop values were corrected to a common flow rate of 0.2 pound per second. In the absence of data on the flow of reacting mixtures the cup-pressure-drop values were assumed proportional to the total flow rate and adjusted to the reference value as follows:

$$\Delta P_{cup,0.2} = \frac{0.2}{w_T} \Delta P_{cup,w_T} \quad (C7)$$

This constituted a relatively minor correction except in the case of hydrazine where the total flow rates were relatively low. The application of equation (C7) did not, however, change the relative order of the results.

APPENDIX D

RESIDENCE TIME IN CHAMBER

The residence time is given by equation (6-4) of reference 16

$$t = \frac{V_c}{w_T V_g} \quad (D1)$$

V_g may be eliminated from equation (D1) by using the perfect gas law $V_g = (RT/M)_{av}/p_c$ to give

$$t = \frac{p_c V_c}{w_T (RT/M)_{av}} \quad (D2)$$

Since $c^* = p_c A_t g / w_T$ and $L^* = V_c / A_t$,

$$t = L^* c^* \frac{1}{g (RT/M)_{av}} \quad (D3)$$

The $(RT/M)_{av}$ term is an average value for the entire chamber. It may be eliminated from equation (D3) by making use of an alternate expression for c^* , equation (3-32) of reference 16,

$$c^* = \frac{\sqrt{g \gamma (RT/M)_i}}{\Gamma} \quad (D4)$$

The $(RT/M)_i$ in equation (D4) refers to conditions at the nozzle entrance. The c^* and L^* values involved in figure 8 refer to 97 percent maximum c^* . Because of the general similarity between the $c^* - L^*$ curves for different fuels, it is reasonable to assume that $(RT/M)_{av}$ is equal to the same fraction of $(RT/M)_i$ for all cases since the nozzle conditions in all cases are comparable. Hence

$$(RT/M)_{av} = h (RT/M)_i \quad (D5)$$

where h is a constant.

Combining equations (D3), (D4), and (D5) yields

$$t = \frac{L^*}{c^*} \frac{\gamma}{h \Gamma^2}$$

The value of γ/Γ^2 is rather insensitive to the value of γ chosen. For γ values between 1.10 and 1.60, γ/Γ^2 varies from 2.53 to 1.95. A value of 2.3 for γ/Γ^2 was used. A value of unity was chosen for h . A value of h as low as 0.5 is unlikely; however, such a value would halve the rate obtained from the limiting line in figure 8.

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TABLE I. - ACID-FUEL RATIOS CORRESPONDING
TO VARIOUS β VALUES

Fuel	Acid-fuel ratio o/f for β^a of -				
	0.55	0.65	0.80	1.00	1.25
Hydrazine	----	0.96	1.18	1.48	1.85
TMIP	----	1.82	2.24	2.80	3.50
Furfuryl alcohol	----	1.85	2.28	2.85	3.56
UDMH	1.86	2.20	2.70	3.38	----
Allylamine	2.33	2.75	3.38	4.23	----
<u>o</u> -Toluidine	2.41	2.85	3.50	4.38	----

$$^a \left[\frac{(o/f)}{(o/f)_{\text{stoichiometric}}} \right]$$

TABLE II. - BASIC EXPERIMENTAL DATA

[1-in. diam. chamber used except where noted]

Chamber pressure, P_c , lb/sq in. abs	Acid flow, W_o , lb/sec	Fuel flow, W_f , lb/sec	Acid-fuel weight ratio, o/f	Characteristic exhaust velocity, o^* , ft/sec	Chamber pressure, P_c , lb/sq in. abs	Acid flow, W_o , lb/sec	Fuel flow, W_f , lb/sec	Acid-fuel weight ratio, o/f	Characteristic exhaust velocity, o^* , ft/sec	Chamber pressure, P_c , lb/sq in. abs	Acid flow, W_o , lb/sec	Fuel flow, W_f , lb/sec	Acid-fuel weight ratio, o/f	Characteristic exhaust velocity, o^* , ft/sec
Hydrazine; $A_t = 0.0882$ sq in.														
L*, 10 in.					L*, 20 in.					L*, 50 in.				
201	0.085	0.072	0.77	4510	190	0.046	0.072	0.64	4550	182	0.049	0.071	0.69	4560
205	.083	.068	.82	4480	204	.058	.087	.83	4720	207	.057	.088	.87	4770
207	.089	.064	1.08	4410	219	.085	.083	1.02	4880	227	.087	.084	1.04	4950
233	.090	.064	1.41	4320	249	.083	.083	1.33	4810	248	.080	.081	1.32	4870
254	.109	.064	1.88	4170	271	.102	.081	1.87	4710	286	.084	.081	1.85	4885
267	.121	.068	1.85	4065	282	.114	.081	1.89	4570	278	.106	.060	1.76	4780
261	.126	.081	2.07	3985	279	.122	.087	2.13	4410	276	.113	.087	1.89	4610
247	.130	.055	2.35	3790	271	.130	.084	2.43	4200	288	.120	.054	2.24	4350
L*, 40 in.					L*, 60 in.					L*, 75 in.				
218	0.088	0.074	0.78	4695	244	0.088	0.075	0.90	4880	258	0.088	0.077	0.85	4730
228	.084	.068	.84	4880	250	.073	.071	1.02	4940	204	.058	.089	.85	4870
256	.080	.087	1.18	4950	283	.078	.088	1.11	5000	241	.072	.069	1.05	4855
270	.088	.064	1.37	5020	275	.089	.087	1.33	4990	283	.088	.086	1.29	4940
270	.084	.062	1.53	4820	286	.100	.088	1.63	4890	288	.083	.083	1.47	4870
282	.108	.090	1.81	4745	283	.109	.083	1.73	4840	287	.108	.083	1.69	4820
277	.118	.057	2.04	4540	279	.114	.059	1.92	4580	290	.119	.081	1.94	4580
262	.121	.082	2.33	4310	275	.119	.058	2.13	4480	272	.119	.057	2.11	4380
L*, 100 in.														
237	0.088	0.078	0.90	4665										
233	.070	.072	.88	4890										
248	.078	.070	1.11	4770										
267	.088	.067	1.30	4770										
253	.088	.063	1.42	4720										
268	.100	.062	1.63	4700										
283	.118	.062	1.92	4470										
278	.128	.058	2.17	4280										
Trimethyl-trithiophosphate; $A_t = 0.0881$ sq in.														
L*, 20 in.					L*, 30 in.					L*, 40 in.				
235	0.105	0.075	1.44	3750	242	0.104	0.073	1.42	3880	244	0.104	0.073	1.42	3910
248	.112	.070	1.60	3885	259	.116	.072	1.62	3930	255	.113	.072	1.59	3900
288	.128	.088	1.85	3875	271	.126	.068	1.82	3990	278	.128	.088	1.85	4020
288	.130	.084	2.03	3928	275	.129	.063	2.05	4030	281	.131	.063	2.08	4110
273	.134	.087	2.35	4050	274	.134	.057	2.35	4075	275	.132	.057	2.32	4150
271	.141	.080	2.81	4030	274	.139	.051	2.73	4090	275	.137	.052	2.83	4150
253	.145	.044	3.30	3800	288	.143	.043	3.32	3970	261	.143	.043	3.31	4010
257	.158	.043	3.87	3820	285	.153	.041	3.73	3880	287	.154	.042	3.88	3870
L*, 50 in.					L*, 75 in.					L*, 100 in.				
237	0.102	0.073	1.40	3840	234	0.103	0.074	1.40	3780	238	0.106	0.073	1.43	3770
261	.114	.072	1.58	3980	257	.117	.071	1.85	3880	255	.118	.071	1.88	3880
276	.128	.089	1.82	4040	268	.126	.088	1.84	3940	271	.128	.088	1.89	3940
277	.129	.084	2.01	4080	278	.131	.083	2.07	4000	277	.133	.083	2.10	4010
279	.132	.087	2.31	4210	274	.130	.058	2.25	4130	272	.134	.057	2.34	4080
272	.138	.050	2.72	4140	271	.135	.051	2.84	4180	271	.138	.050	2.78	4090
282	.142	.043	3.30	4010	283	.144	.042	3.42	4010	282	.142	.043	3.30	4030
270	.154	.041	3.78	3920	271	.153	.040	3.59	3975	271	.154	.041	3.78	3945

TABLE II. - Continued. BASIC EXPERIMENTAL DATA

[1-in. diam. chamber used except where noted]

Series of runs	Chamber pressure, P_o , lb/sq in. abs	Acid flow, w_o , lb/sec	Fuel flow, w_f , lb/sec	Acid-fuel weight ratio, o/f	Characteristic exhaust velocity, c^* , ft/sec	Chamber pressure, P_o , lb/sq in. abs	Acid flow, w_o , lb/sec	Fuel flow, w_f , lb/sec	Acid-fuel weight ratio, o/f	Characteristic exhaust velocity, c^* , ft/sec	Chamber pressure, P_o , lb/sq in. abs	Acid flow, w_o , lb/sec	Fuel flow, w_f , lb/sec	Acid-fuel weight ratio, o/f	Characteristic exhaust velocity, c^* , ft/sec
Furfuryl alcohol; $A_t = .00881$ and $P_o = 0.0913$ sq in.															
1	$L^*, 20$ in.					$L^*, 30$ in.					$L^*, 40$ in.				
	285	0.122	0.078	1.57	4060	286	0.118	0.078	1.50	4290	298	0.115	0.078	1.47	4390
	294	.129	.074	1.76	4120	310	.125	.075	1.67	4400	311	.124	.074	1.68	4470
	313	.138	.073	1.89	4210	330	.136	.073	1.87	4490	332	.133	.073	1.83	4590
	302	.142	.088	2.09	4080	312	.134	.085	2.06	4430	321	.134	.086	2.04	4560
	289	.142	.059	2.41	4080	303	.140	.080	2.34	4300	299	.130	.056	2.32	4580
	289	.148	.055	2.69	3760	286	.148	.053	2.76	4080	293	.136	.051	2.69	4450
	246	.157	.049	3.20	3390	280	.150	.047	3.17	3740	255	.156	.040	3.92	3700
246	.165	.049	3.37	3260	271	.160	.046	3.46	3720	272	.161	.044	3.63	3760	
2	288	.129	.091	1.42	3850	302	.124	.090	1.38	4150	294	.130	.084	1.54	4040
	308	.140	.092	1.52	3900	325	.133	.088	1.51	4320	321	.133	.079	1.69	^c 4450
	320	.150	.087	1.72	3970	342	.142	.084	1.69	4450	339	.142	.077	1.84	^c 4550
	294	.158	.083	1.90	3590	341	.144	.078	1.89	4560	332	.147	.070	2.10	4500
	275	.163	.078	2.40	3355	331	.148	.069	2.14	4585	327	.150	.063	2.38	4510
	299	.157	.064	2.45	3990	315	.151	.081	2.48	4370	324	.152	.059	2.58	4510
	270	.162	.059	2.74	3590	306	.153	.055	2.78	4325	314	.153	.054	2.83	4460
	274	.179	.054	3.31	3460	287	.175	.051	3.43	3730	302	.172	.050	3.44	4000
1	$L^*, 50$ in.					$L^*, 75$ in.					$L^*, 100$ in.				
	258	0.098	0.084	1.15	^c 4080	302	0.119	0.073	1.63	^c 4430	289	0.117	0.075	1.58	^c 4270
	275	.104	.079	1.32	^c 4280	310	.126	.070	1.80	^c 4490	304	.126	.071	1.77	^c 4400
	321	.130	.074	1.76	^c 4480	328	.131	.067	1.98	^c 4700	313	.131	.067	1.86	^c 4490
	312	.129	.063	2.05	^c 4600	328	.135	.060	2.28	^c 4770	307	.134	.060	2.23	^c 4490
	306	.133	.057	2.34	^c 4560	309	.137	.054	2.53	^c 4590	313	.141	.054	2.62	^c 4555
	303	.136	.051	2.67	^c 4600	307	.145	.049	2.95	4490	309	.142	.049	2.91	^c 4590
	285	.142	.041	3.44	^c 4410	289	.146	.041	3.57	4390	285	.149	.041	3.63	^c 4260
287	.154	.040	3.89	^c 4215	280	.159	.039	4.09	4010	283	.158	.040	3.95	^c 4060	
2	302	.123	.082	1.51	^c 4330	288	.121	.089	1.78	^c 4460	288	.119	.077	1.54	^c 4320
	322	.133	.080	1.67	^c 4440	314	.135	.085	2.08	^c 4620	308	.131	.073	1.79	^c 4410
	344	.141	.076	1.85	4660	323	.144	.064	2.26	^c 4585	326	.142	.071	1.99	^c 4500
	336	.145	.069	2.11	4620	324	.147	.080	2.44	^c 4600	322	.143	.065	2.21	^c 4550
	326	.147	.062	2.36	4590	319	.149	.056	2.68	^c 4575	308	.145	.058	2.61	^c 4505
	315	.151	.054	2.80	4520	308	.152	.048	3.14	^c 4530	305	.149	.050	3.01	^c 4510
	298	.159	.047	3.39	4250	302	.156	.045	3.50	^c 4420	285	.156	.041	3.78	^c 4250
	305	.170	.043	3.94	^c 4210	313	.174	.044	4.00	^c 4220	268	.178	.039	4.61	^c 3630

^aFirst series of runs.^bSecond series of runs.^cAudible scream.

TABLE II. - Continued. BASIC EXPERIMENTAL DATA

[1-in. diam. chamber used except where noted]

Series of runs	Chamber pressure, P_0 , lb/sq in. abs	Acid flow, W_0 , lb/sec	Fuel flow, W_f , lb/sec	Acid-fuel weight ratio, q/f	Characteristic exhaust velocity, c^* , ft/sec	Chamber pressure, P_0 , lb/sq in. abs	Acid flow, W_0 , lb/sec	Fuel flow, W_f , lb/sec	Acid-fuel weight ratio, q/f	Characteristic exhaust velocity, c^* , ft/sec	Chamber pressure, P_0 , lb/sq in. abs	Acid flow, W_0 , lb/sec	Fuel flow, W_f , lb/sec	Acid-fuel weight ratio, q/f	Characteristic exhaust velocity, c^* , ft/sec	
Unsymmetrical dimethylhydrazine; $A_t = 0.0822$ and 0.0888 sq in.																
1	$L^*, 20$ in.					$L^*, 30$ in.					$L^*, 40$ in.					
	260	0.101	0.085	1.55	4800	252	0.097	0.085	1.49	4840	283	0.098	0.085	1.48	4890	
	275	.109	.081	1.79	4845	281	.108	.081	1.79	4750	278	.105	.081	1.72	4810	
	282	.118	.081	1.95	4685	298	.117	.080	1.95	4800	306	.122	.081	2.00	4850	
	309	.135	.080	2.22	4800	318	.128	.087	2.21	4940	358	.136	.081	2.25	4840	
	309	.141	.088	2.52	4800	390	.158	.086	2.43	4710	350	.138	.085	2.81	4910	
	305	.145	.081	2.84	4470	318	.144	.080	2.88	4710	394	.141	.080	2.89	4870	
	300	.142	.048	3.24	4480	308	.148	.045	3.24	4830	314	.146	.044	3.32	4750	
	294	.155	.040	3.88	4350	303	.152	.038	3.90	4840	305	.158	.038	4.00	4610	
	1	$L^*, 50$ in.					$L^*, 75$ in.					$L^*, 100$ in.				
281		0.088	0.064	1.50	4880	266	0.099	0.068	1.52	4880	289	0.099	0.066	1.50	4510	
283		.107	.082	1.73	4810	282	.108	.082	1.74	4780	295	.115	.064	1.80	4730	
313		.125	.082	2.00	4880	324	.128	.082	2.06	4800	314	.127	.061	2.08	4800	
326		.130	.089	2.80	4880	340	.137	.089	2.32	4980	325	.132	.089	2.94	4860	
322		.134	.055	2.48	4890	328	.135	.053	2.56	4890	336	.141	.064	2.81	4980	
329		.141	.050	2.88	4970	358	.142	.049	2.90	5040	350	.140	.048	2.86	5010	
318		.145	.044	3.30	4830	324	.146	.043	3.40	4920	323	.145	.043	3.37	4930	
324		.150	.043	3.48	4820	318	.153	.038	4.03	4780	314	.153	.037	4.14	4750	
2																
						282	.106	.082	1.68	4710	284	.109	.064	1.69	4800	
						321	.122	.082	1.87	4880	299	.117	.060	1.95	4710	
						298	.115	.055	2.09	4885	321	.128	.089	2.14	4855	
						325	.128	.054	2.33	5000	327	.130	.087	2.28	4870	
						359	.136	.052	2.85	4970	359	.139	.082	2.87	4945	
						332	.141	.046	3.07	4950	329	.140	.048	3.04	4850	
						318	.148	.038	3.69	4730	314	.150	.038	3.85	4858	
						318	.156	.035	4.74	4410	316	.165	.035	4.68	4450	
	Allylamine; $A_t = 0.0905$, 0.0864 , and 0.0872 sq in.															
1	$L^*, 20$ in.					$L^*, 30$ in.					$L^*, 40$ in.					
	385	0.185	0.085	1.94	4880	373	0.164	0.087	1.90	4330	379	0.163	0.084	1.95	4480	
	359	.171	.078	2.21	4210	369	.170	.078	2.24	4370	378	.168	.075	2.21	4800	
	349	.175	.069	2.55	4175	358	.178	.066	2.80	4300	364	.171	.087	2.65	4480	
	307	.190	.088	3.42	3840	347	.183	.080	3.07	4180	358	.178	.058	3.07	4420	
	295	.193	.084	3.57	3480	320	.182	.083	3.22	3805	353	.184	.062	3.51	4040	
	275	.200	.049	4.08	3220	309	.183	.080	3.86	3700	321	.188	.049	3.88	3995	
						287	.200	.048	4.35	3600	300	.198	.044	4.80	3610	
	2	$L^*, 50$ in.					$L^*, 75$ in.					$L^*, 100$ in.				
		387	0.181	0.085	1.95	4535	394	0.189	0.078	2.05	4630	402	0.180	0.081	1.98	4640
387		.168	.072	2.19	4875	381	.180	.070	2.28	4730	386	.180	.073	2.21	4740	
378		.185	.083	2.62	4610	385	.185	.080	2.78	4750	387	.182	.080	2.70	4850	
368		.172	.053	3.24	4820	378	.189	.053	3.21	4780	378	.188	.048	3.43	4850	
348		.184	.048	3.87	4180	382	.181	.045	4.02	4480	368	.180	.042	4.30	4800	
334		.192	.042	4.57	3970	344	.189	.040	4.73	4180	356	.182	.040	4.81	4810	
316		.196	.039	5.03	3770	339	.184	.038	4.84	4280	340	.189	.036	5.22	4285	
3																
		374	.167	.083	2.85	4580										
	363	.179	.058	3.07	4530											
					368	.167	.048	3.80	4350							
					317	.185	.040	4.86	3780							

^aFirst series of runs for UDMH.
^bSecond series of runs for UDMH.
^cFirst series of runs for allylamine.
^dSecond series of runs for allylamine.
^eThird series of runs for allylamine.

TABLE II. - Continued. BASIC EXPERIMENTAL DATA

[1-in. diam. chamber used except where noted]

Chamber pressure, P_c , lb/sq in. abs	Acid flow, W_o , lb/sec	Fuel flow, W_f , lb/sec	Acid-fuel weight ratio, o/f	Characteristic exhaust velocity, c^* , ft/sec	Chamber pressure, P_c , lb/sq in. abs	Acid flow, W_o , lb/sec	Fuel flow, W_f , lb/sec	Acid-fuel weight ratio, o/f	Characteristic exhaust velocity, c^* , ft/sec	Chamber pressure, P_c , lb/sq in. abs	Acid flow, W_o , lb/sec	Fuel flow, W_f , lb/sec	Acid-fuel weight ratio, o/f	Characteristic exhaust velocity, c^* , ft/sec
p-Toluidine; $A_t = 0.0920$ sq in.														
L*, 30 in.				L*, 40 in.					L*, 50 in.					
337	0.162	0.085	1.78	3920	350	0.159	0.091	1.74	4180	350	0.155	0.086	1.80	4300
336	.166	.083	2.00	4000	345	.164	.080	2.05	4190	357	.160	.078	2.05	4440
350	.171	.072	2.39	4030	354	.167	.072	2.32	4140	345	.167	.069	2.42	4350
324	.176	.062	2.83	4040.	333	.174	.062	2.82	4175	312	.177	.049	3.61	4090
311	.182	.053	3.43	3920	316	.180	.053	3.43	4030	300	.211	.039	5.41	3550
311	.196	.052	3.77	3720	314	.190	.049	3.88	3890	348	.157	.081	1.73	4150
304	.203	.047	4.32	3600	313	.206	.046	4.48	3690	345	.162	.080	2.03	4225
L*, 75 in.				L*, 100 in.					L*, 100 in.					
556	0.157	0.088	1.78	4310	354	0.158	0.088	1.80	4265	342	.167	.071	2.35	4280
319	.159	.090	1.54	4130	364	.163	.079	2.06	4460	331	.172	.060	2.87	4250
339	.155	.074	2.09	4390	349	.163	.066	2.47	4520	324	.177	.052	3.40	4180
349	.171	.059	2.90	4500	360	.169	.057	2.96	4720	324	.190	.047	4.04	4050
340	.176	.049	3.63	4480	348	.175	.048	3.80	4540	317	.209	.044	4.75	3710
344	.187	.044	4.25	4410	358	.188	.044	4.27	4370					
343	.205	.038	5.39	4180	345	.211	.033	6.39	4190					
Hydrazine; 1.5-in.-diam. chambers; $A_t = 0.0848$ sq in.														
L*, 33 in.				L*, 50 in.					L*, 75 in.					
245	0.062	0.078	0.82	4860	234	0.058	0.075	0.77	4780	225	0.058	0.075	0.77	4830
240	.066	.070	.94	4810	253	.068	.070	.86	5010	241	.065	.070	.92	4890
239	.074	.062	1.19	4810	250	.068	.066	1.03	5060	247	.069	.067	1.03	4940
257	.081	.065	1.25	4810	261	.079	.062	1.27	5050	270	.083	.064	1.31	5015
260	.092	.061	1.50	4630	274	.092	.061	1.50	4860	306	.101	.066	1.52	5000
276	.104	.061	1.71	4565	284	.102	.061	1.68	4770	312	.113	.064	1.77	4850
269	.113	.057	1.98	4340	300	.121	.060	2.02	4520	316	.125	.061	2.04	4620
282	.127	.055	2.28	4225	297	.130	.057	2.27	4325	308	.132	.057	2.31	4400
L*, 100 in.				L*, 144 in.					L*, 144 in.					
241	0.063	0.076	0.83	4750	250	0.060	0.074	0.80	4710					
231	.062	.070	.90	4770	229	.065	.069	.94	4680					
231	.067	.065	1.01	4780	232	.069	.065	1.06	4700					
250	.077	.062	1.26	4910	264	.084	.065	1.30	4860					
279	.091	.062	1.46	4990	273	.092	.062	1.50	4850					
317	.119	.064	1.86	4720	300	.110	.063	1.75	4760					
286	.120	.057	2.11	4410	274	.114	.056	2.05	4410					
285	.130	.055	2.36	4210	290	.126	.057	2.21	4320					
Hydrazine; 2-in.-diam. chambers; $A_t = 0.0848$ sq in.														
L*, 50 in.				L*, 75 in.					L*, 100 in.					
238	0.064	0.074	0.86	4700	237	0.060	0.074	0.82	4820	255	0.086	0.076	0.87	4820
233	.067	.069	.97	4680	236	.062	.071	.87	4840	244	.065	.072	.90	4830
234	.068	.065	1.05	4810	255	.072	.068	1.06	4850	261	.074	.069	1.08	4860
257	.068	.064	1.38	4815	273	.085	.066	1.29	4900	270	.081	.067	1.22	4970
269	.103	.062	1.66	4440	262	.087	.061	1.42	4820	296	.098	.066	1.50	4940
272	.109	.060	1.92	4390	263	.095	.061	1.54	4695	308	.109	.065	1.69	4850
291	.128	.060	2.13	4220	299	.117	.061	1.92	4570	289	.110	.059	1.84	4680
285	.132	.056	2.36	4140	295	.126	.057	2.20	4390	297	.120	.058	2.09	4560
L*, 171 in.				L*, 300 in.					L*, 300 in.					
242	0.064	0.078	0.83	4715	244	0.066	0.077	0.85	4640					
241	.065	.071	.91	4835	242	.067	.073	.92	4715					
256	.073	.069	1.06	4890	251	.073	.068	1.07	4840					
252	.078	.064	1.21	4825	276	.089	.066	1.35	4860					
269	.092	.060	1.53	4810	286	.096	.064	1.50	4880					
313	.113	.065	1.75	4800	278	.105	.059	1.80	4630					
288	.118	.060	1.97	4430	297	.118	.061	1.92	4540					
288	.124	.057	2.17	4330	284	.126	.056	2.25	4250					

*Audible scream.

TABLE II. - Concluded. BASIC EXPERIMENTAL DATA

[1-in. diam. chamber used except where noted]

Chamber pressure, P_c , lb/sq in. abs	Acid flow, W_o , lb/sec	Fuel flow, W_f , lb/sec	Acid-fuel weight ratio, o/f	Characteristic exhaust velocity c^* , ft/sec	Chamber pressure, P_c , lb/sq in. abs	Acid flow, W_o , lb/sec	Fuel flow, W_f , lb/sec	Acid-fuel weight ratio, o/f	Characteristic exhaust velocity, c^* , ft/sec	Chamber pressure, P_c , lb/sq in. abs	Acid flow, W_o , lb/sec	Fuel flow, W_f , lb/sec	Acid-fuel weight ratio, o/f	Characteristic exhaust velocity, c^* , ft/sec
Unsymmetrical dimethylhydrazine; 1.5-in.-diam. chambers; $A_t = 0.0850$ sq in.														
L*, 55 in.					L*, 50 in.					L*, 75 in.				
282	0.084	0.066	1.42	4480	289	0.095	0.084	1.48	4850	274	0.094	0.066	1.43	4690
283	.107	.062	1.75	4580	286	.103	.062	1.66	4740	301	.107	.062	1.75	4880
297	.117	.061	1.92	4570	308	.114	.060	1.90	4840	333	.123	.062	1.98	4930
330	.136	.061	2.23	4580	331	.127	.059	2.15	4870	359	.156	.060	2.26	5010
328	.138	.056	2.48	4800	337	.134	.055	2.44	4880	348	.154	.055	2.44	5050
324	.142	.051	2.78	4590	332	.138	.050	2.78	4830	342	.158	.049	2.82	5010
314	.146	.046	3.17	4480	326	.142	.045	3.16	4760	333	.141	.043	3.28	4950
308	.183	.039	3.92	4390	316	.150	.037	4.05	4610	323	.150	.037	4.08	4730
					255	.081	.068	1.19	4320					
					261	.091	.065	1.40	4580					
					279	.099	.063	1.87	4710					
					311	.115	.061	1.89	4840					
					337	.135	.055	2.46	4865					
					333	.139	.050	2.78	4820					
					326	.144	.044	3.27	4730					
					316	.153	.038	4.03	4530					
L*, 100 in.					L*, 144 in.									
270	0.098	0.065	1.48	4590	270	0.098	0.068	1.45	4580					
311	.112	.064	1.75	4840	294	.107	.063	1.70	4730					
318	.116	.060	1.93	4910	314	.117	.061	1.92	4830					
329	.123	.058	2.12	4975	336	.128	.060	2.13	4890					
347	.133	.055	2.42	5060	346	.133	.055	2.42	5020					
346	.138	.049	2.82	5050	343	.138	.049	2.78	5075					
336	.145	.045	3.32	4940	334	.141	.043	3.28	4970					
326	.161	.037	4.08	4730	326	.149	.037	4.03	4780					
Unsymmetrical dimethylhydrazine; 2-in.-diam. chambers; $A_t = 0.0850$ sq in.														
L*, 50 in.					L*, 75 in.					L*, 100 in.				
257	0.097	0.067	1.45	4290	261	0.091	0.065	1.40	4580	265	0.090	0.064	1.41	4710
280	.109	.064	1.70	4430	294	.107	.062	1.73	4760	296	.105	.061	1.72	4880
309	.126	.063	2.00	4475	312	.117	.061	1.92	4800	328	.119	.060	1.98	4980
329	.138	.063	2.16	4525	329	.128	.059	2.14	4870	359	.134	.060	2.23	5080
322	.139	.058	2.48	4520	340	.135	.055	2.45	4900	342	.130	.053	2.45	5115
318	.141	.051	2.76	4505	338	.137	.050	2.74	4950	346	.138	.048	2.88	5120
307	.145	.046	3.15	4400	328	.141	.044	3.20	4850	340	.143	.041	3.49	5060
303	.152	.040	3.80	4320	315	.150	.038	3.95	4690	328	.152	.036	4.22	4775
L*, 171 in.					L*, 300 in.									
268	0.097	0.064	1.52	4430	259	0.097	0.065	1.49	4375					
280	.104	.062	1.68	4620	287	.110	.062	1.77	4570					
322	.119	.062	1.92	4870	305	.119	.060	1.98	4660					
347	.131	.060	2.18	4970	349	.138	.061	2.23	4845					
351	.135	.054	2.50	5080	344	.138	.054	2.52	4935					
346	.139	.048	2.90	5050	341	.140	.049	2.86	4940					
337	.142	.043	3.30	4985	332	.144	.043	3.35	4880					
324	.152	.037	4.11	4690	318	.152	.037	4.11	4605					

TABLE III. - FUEL RATINGS; CHARACTERISTIC LENGTH

 L_{97}^* AS FUNCTION OF β

Fuel	Stoichiometric o/f ratio	L_{97}^* for β of -				
		0.55	0.65	0.80	1.00	1.25
Hydrazine	1:48	----	16.0	19.0	19.5	19.5
TMIP	2.80	----	24.0	27.5	21.5	25.0
Furfuryl alcohol	2.85	----	25.0	31.0	40.0	48.0
UDMH	3.38	24.5	28.5	37.0	42.5	----
Allylamine ^a	4.23	54.0	60.0	75.0	84.0	----
<u>o</u> -Toluidine ^a	4.38	75.0	80.0	83.0	76.0	----

^aMinimum values based on c^* at an L^* of 100 in.

TABLE IV. - MAXIMUM EXPERIMENTAL VALUES FOR

CHARACTERISTIC EXHAUST VELOCITY c^*

Fuel	c^* for β of -				
	0.55	0.65	0.80	1.00	1.25
Hydrazine	----	4900	5010	4940	4720
TMIP	----	4050	4190	4160	3990
Furfuryl alcohol	----	4530	4600	4570	4400
UDMH	4870	4960	5010	4940	----
Allylamine ^a	4790	4860	4860	4650	----
<u>o</u> -Toluidine ^a	4590	4680	4700	4550	----

^aValues at an L^* of 100 in.TABLE V. - CHARACTERISTIC LENGTH L_{97}^*

AS FUNCTION OF CHAMBER DIAMETER

Fuel	Diameter, in.	L_{97}^* for β of -		
		0.65	0.80	1.00
Hydrazine	1.0	16.0	19.0	19.5
	1.5	36.5	36.0	39.0
	2.0	50.0	56.5	76.0
UDMH	1.0	28.5	37.0	42.5
	1.5	49.5	56.0	60.0
	2.0	78.0	75.0	84.0

TABLE VI. - CORRELATION OF CHARACTERISTIC LENGTH

 L_{97}^* FOR VARIOUS CHAMBER DIAMETERS

Fuel	$L_{97}^*(1.5\text{-in. diam}) - L_{97}^*(1.0\text{-in. diam})$			
	β			Average difference
	0.65	0.80	1.00	
Hydrazine	20.5	17.0	19.5	19.0
UDMH	21.0	19.0	17.5	19.2
	$L_{97}^*(2\text{-in. diam}) - L_{97}^*(1.0\text{-in. diam})$			
Hydrazine	34.0	37.5	56.5	42.7
UDMH	49.5	38.0	41.5	43.0

TABLE VII. - COMPARISON OF CHARACTERISTIC LENGTH L_{97}^* ,

CUP PRESSURE DROP, AND IGNITION DELAY VALUES

Fuel	L_{97}^* , in.	Cup pressure drop, ^a lb/sq in.	Ignition delay, millisec
Hydrazine	16	305	^b 6
TMIP	24	129	^c 7.6
Furfuryl alcohol	25	81	^d 25
UDMH	28.5	124	^e 2
Allylamine	^f 60	100	^d 310
<u>o</u> -Toluidine	^f 80	88	^d 350

^aTaken at β of 0.65.^bWith WFNA, 70° F, ref. 17.^cWith RFNA (18 percent NO₂), -40° F, ref. 18.^dWith WFNA, 70° F, ref. 19.^eWith RFNA, -65° to 70° F, ref. 10.^fMinimum values based on c^* at an L^* of 100 in.

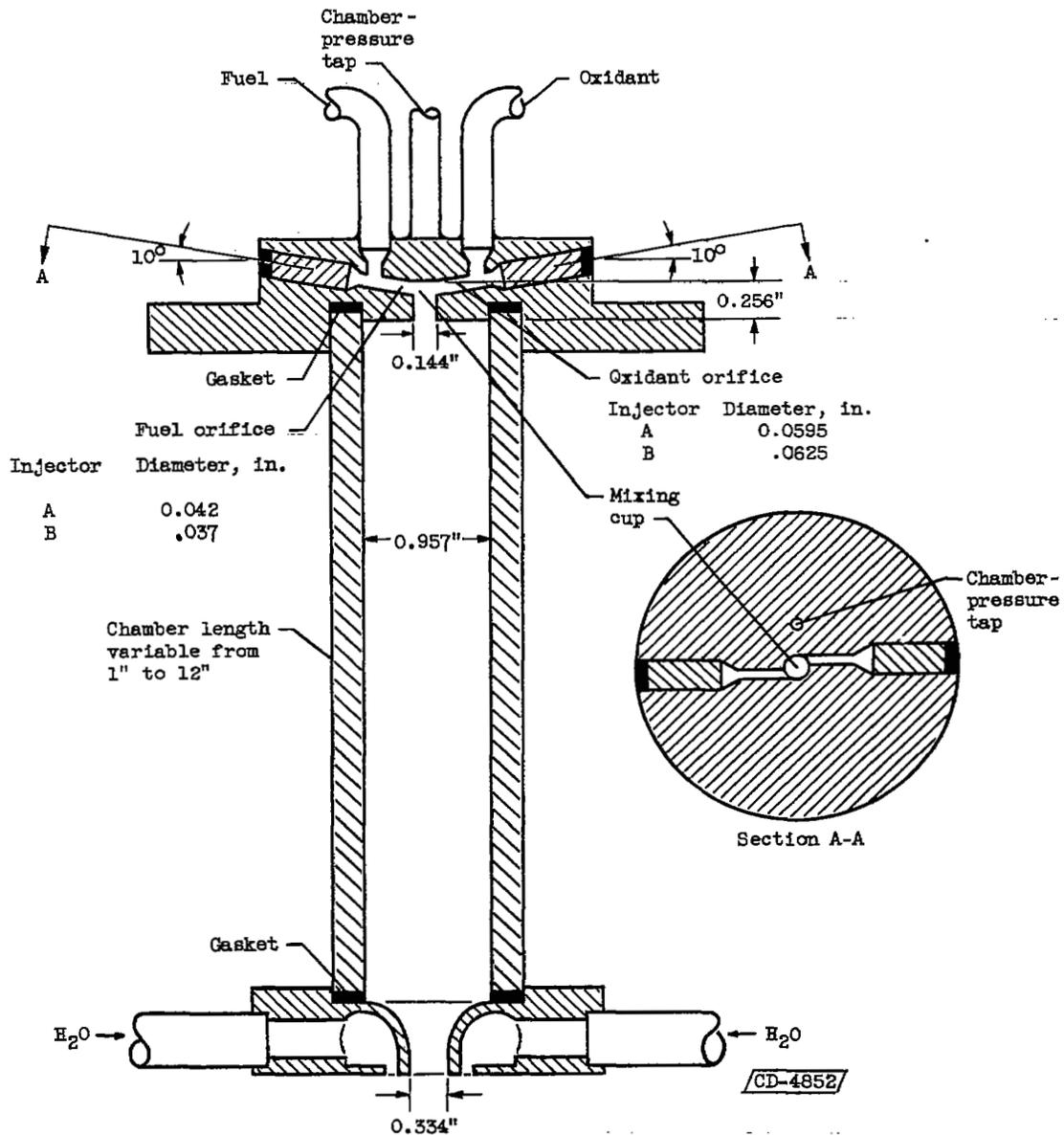


Figure 1. - Cross section of rocket-engine assembly.

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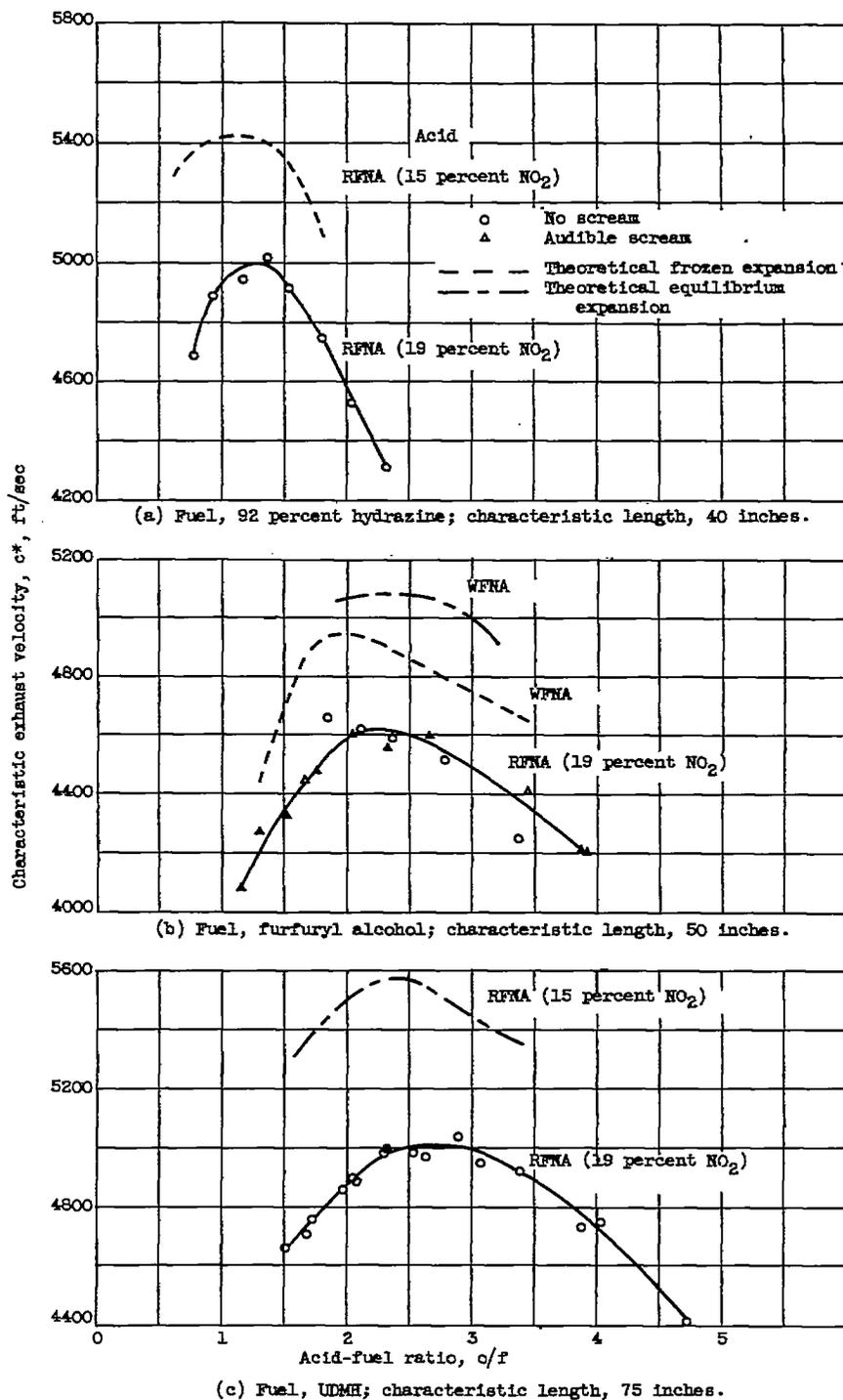


Figure 2. - Characteristic exhaust velocity as function of acid-fuel ratio at characteristic length of maximum experimental characteristic exhaust velocity.

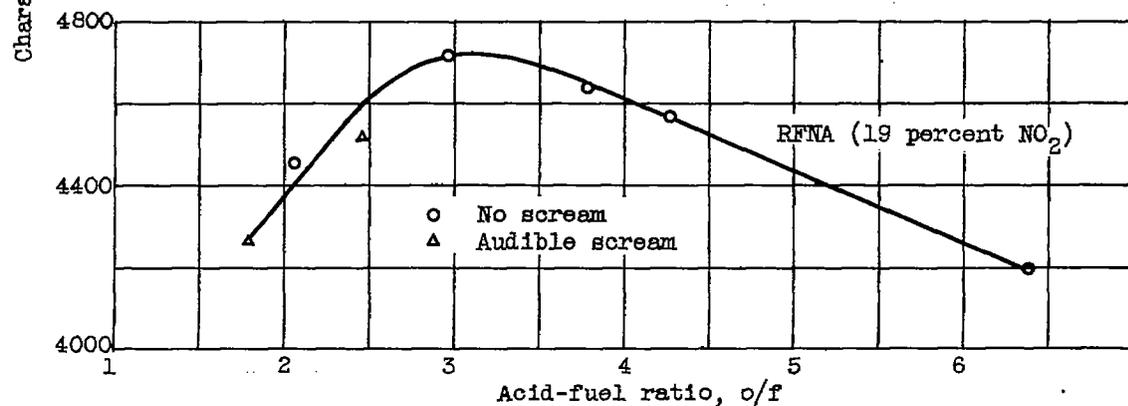
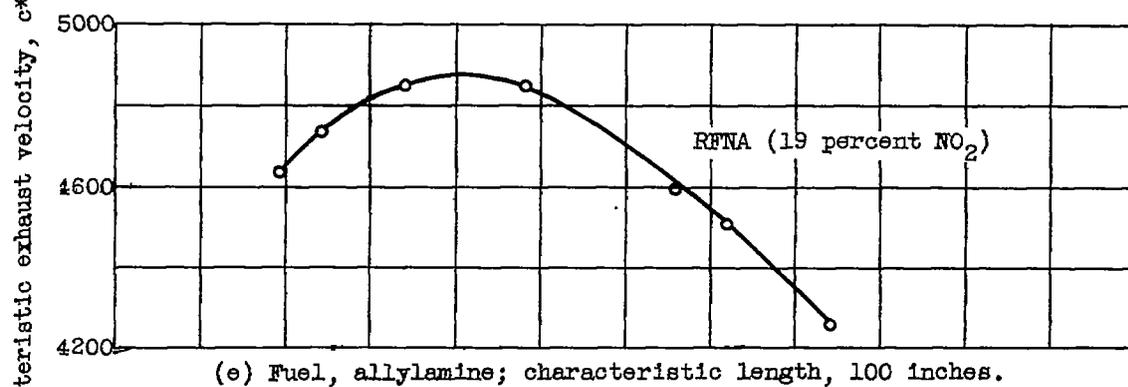
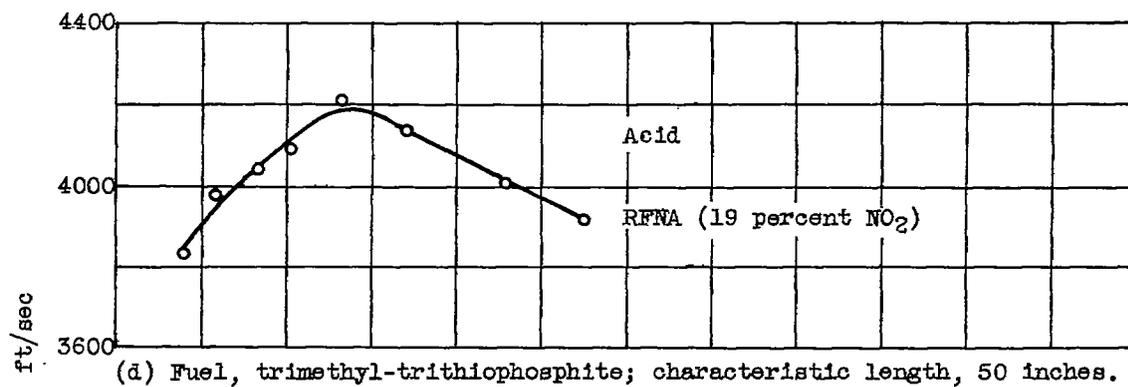
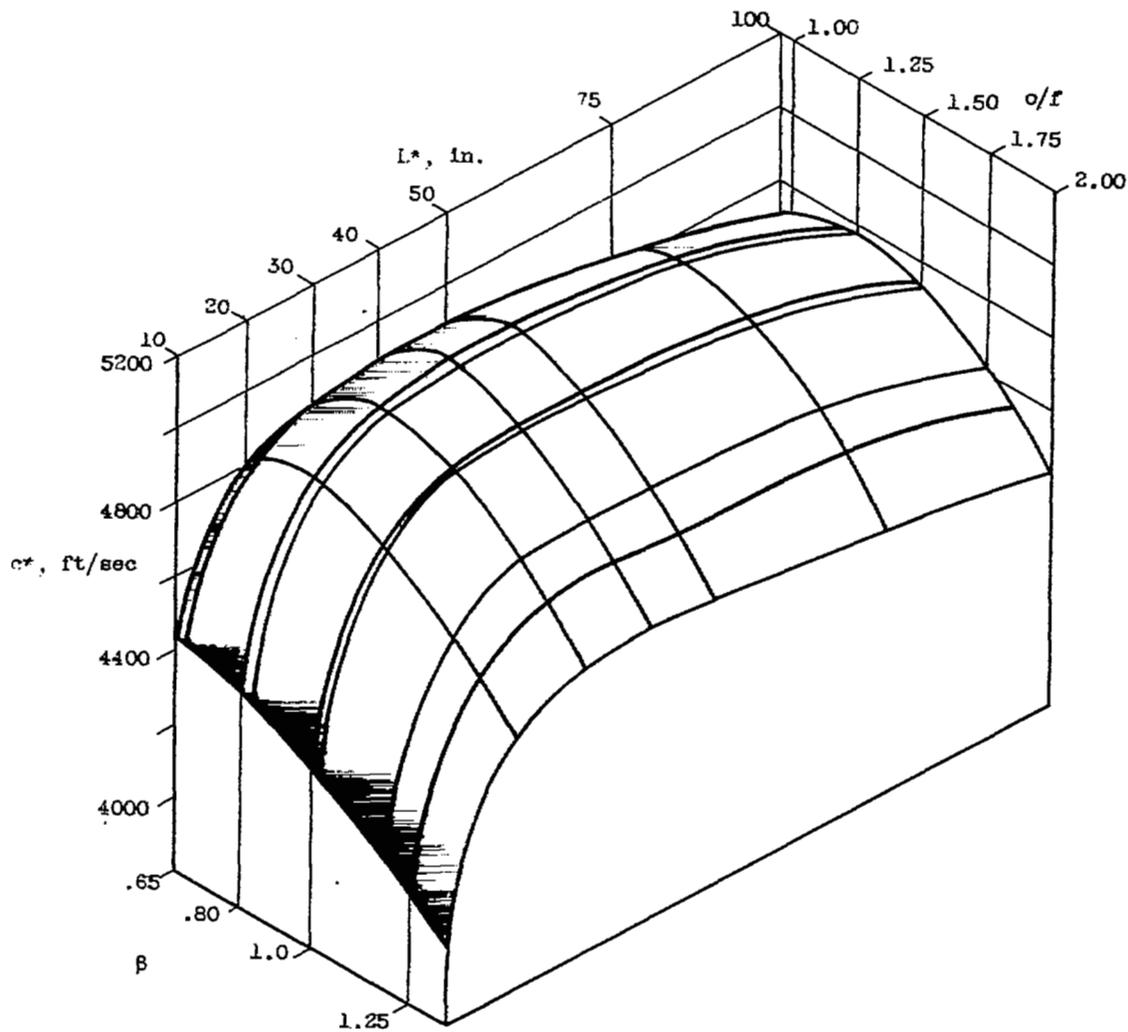
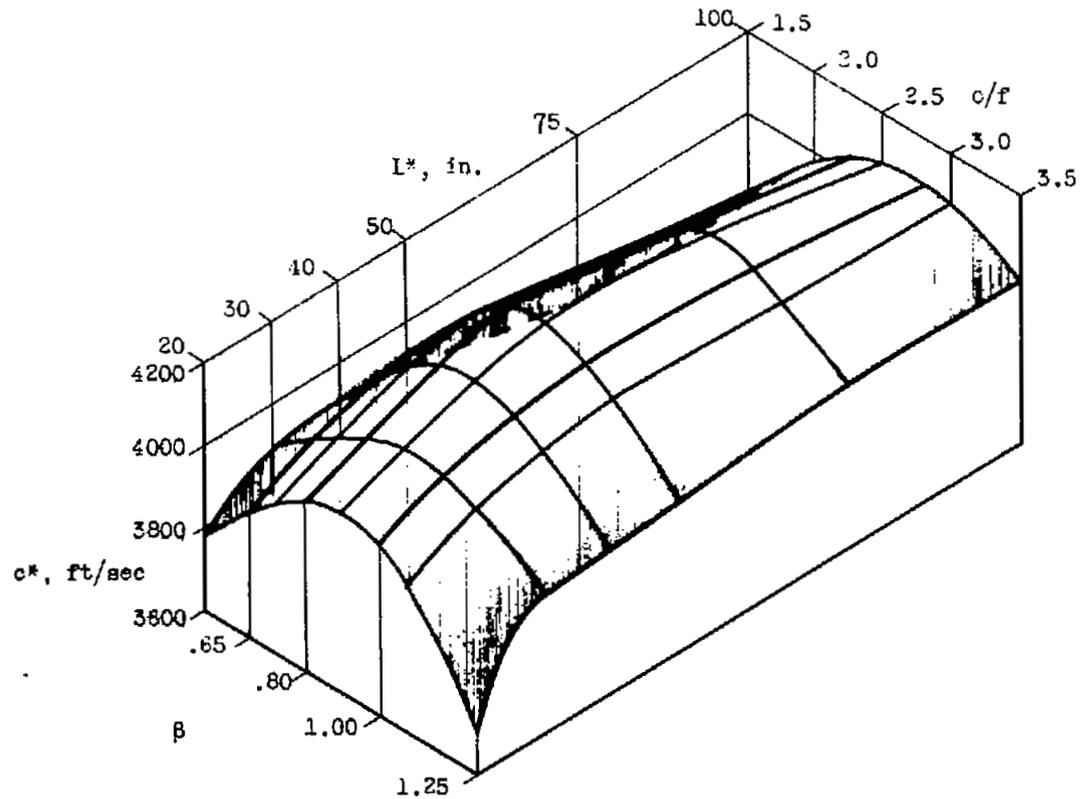


Figure 2. - Concluded. Characteristic exhaust velocity as function of acid-fuel ratio at characteristic length of maximum experimental characteristic exhaust velocity.



(a) Hydrazine.

Figure 3. - Characteristic exhaust velocity c^* as function of characteristic length l^* and acid-fuel ratio o/f in 1-inch-diameter chambers.

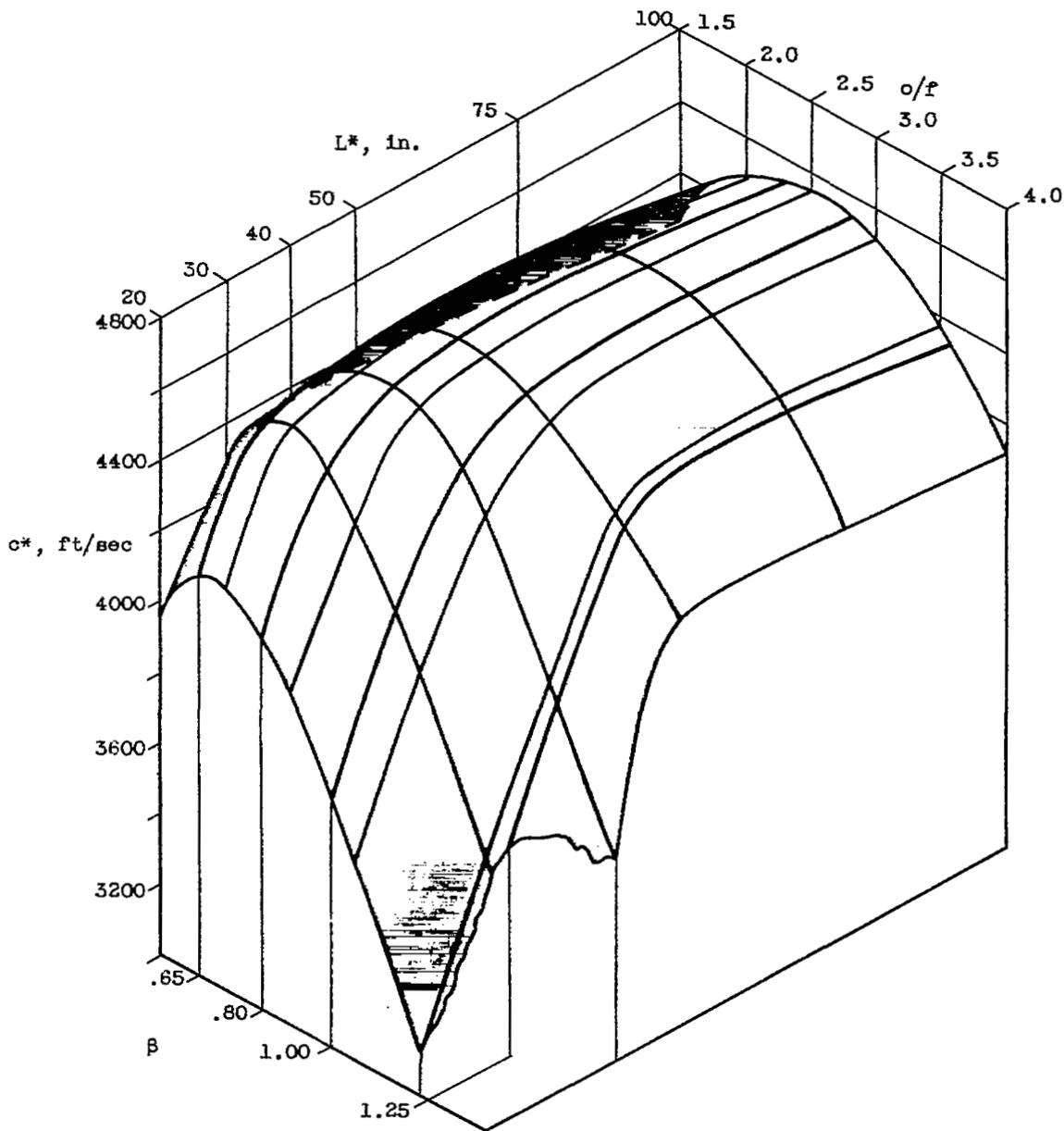


(b) Trimethyl-trithiophosphate.

Figure 3. - Continued. Characteristic exhaust velocity c^* as function of characteristic length L^* and acid-fuel ratio o/f in 1-inch-diameter chambers.

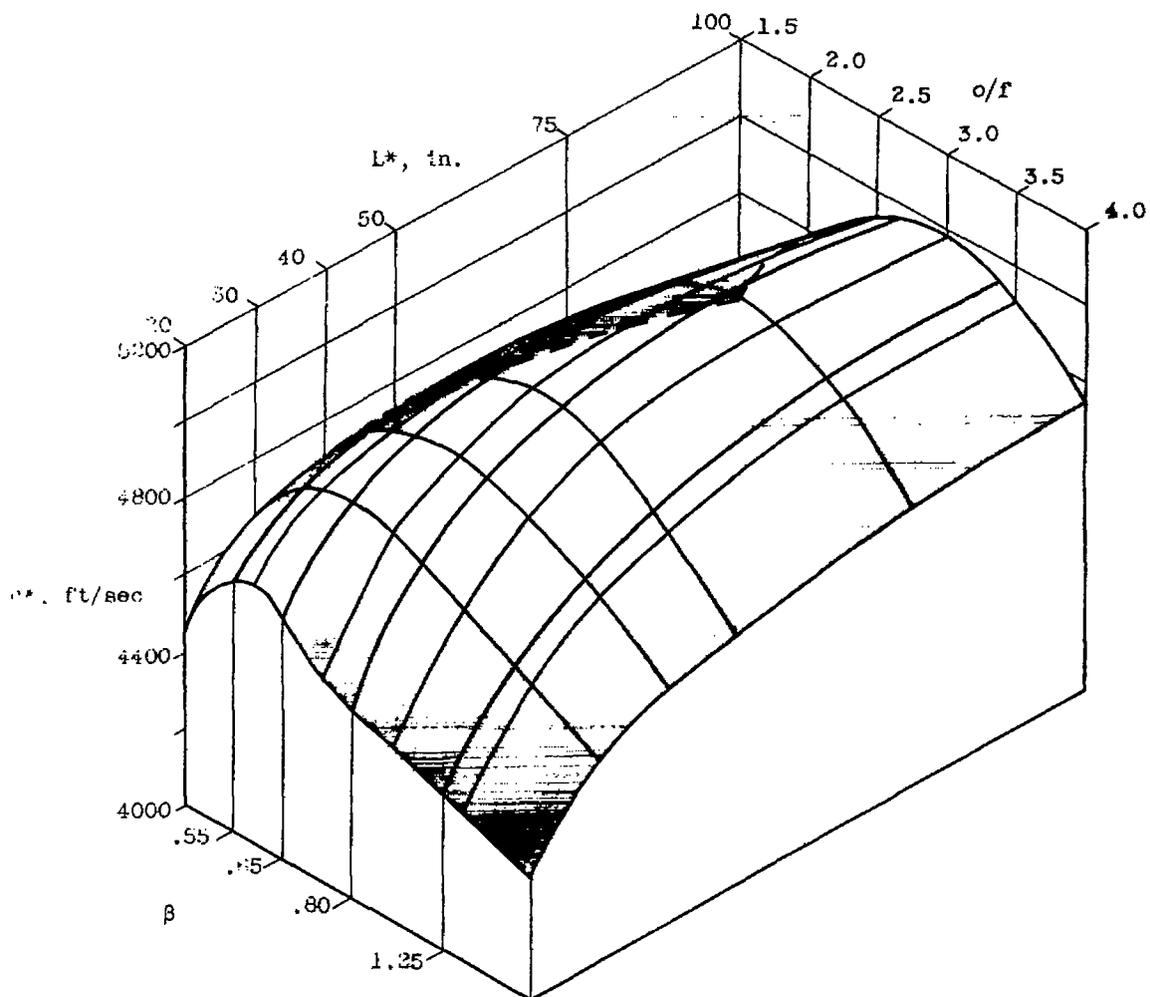
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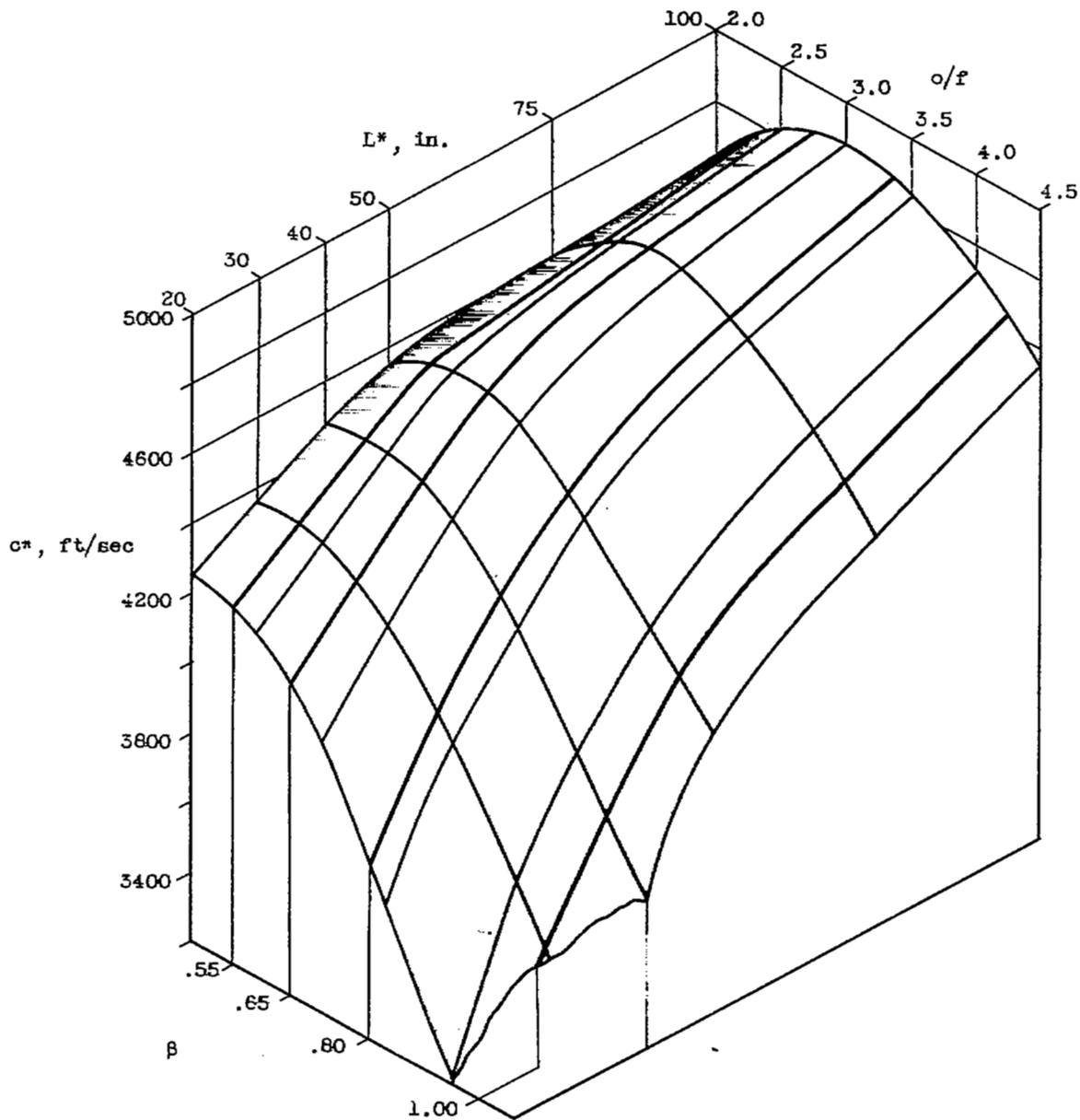
(c) Furfuryl alcohol.

Figure 3. - Continued. Characteristic exhaust velocity c^* as function of characteristic length L^* and acid-fuel ratio o/f in 1-inch-diameter chambers.



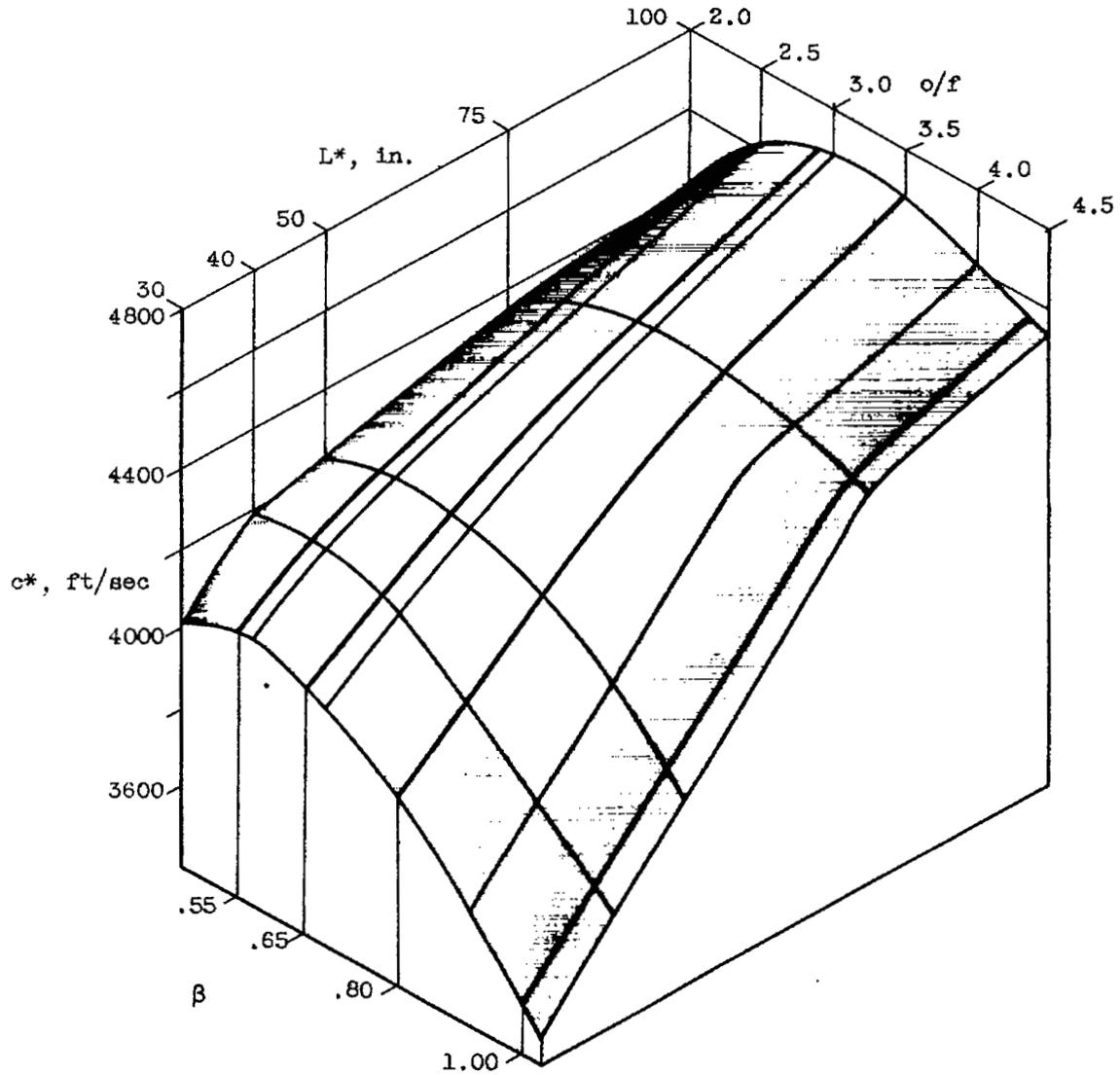
(d) Unsymmetrical dimethylhydrazine.

Figure 3. - Continued. Characteristic exhaust velocity c^* as function of characteristic length L^* and acid-fuel ratio o/f in 1-inch-diameter chambers.



(e) Allylamine.

Figure 3. - Continued. Characteristic exhaust velocity c^* as function of characteristic length L^* and acid-fuel ratio o/f in 1-inch-diameter chambers.



(f) o-Toluidine.

Figure 3. - Concluded. Characteristic exhaust velocity c^* as function of characteristic length L^* and acid-fuel ratio o/f in 1-inch-diameter chambers.

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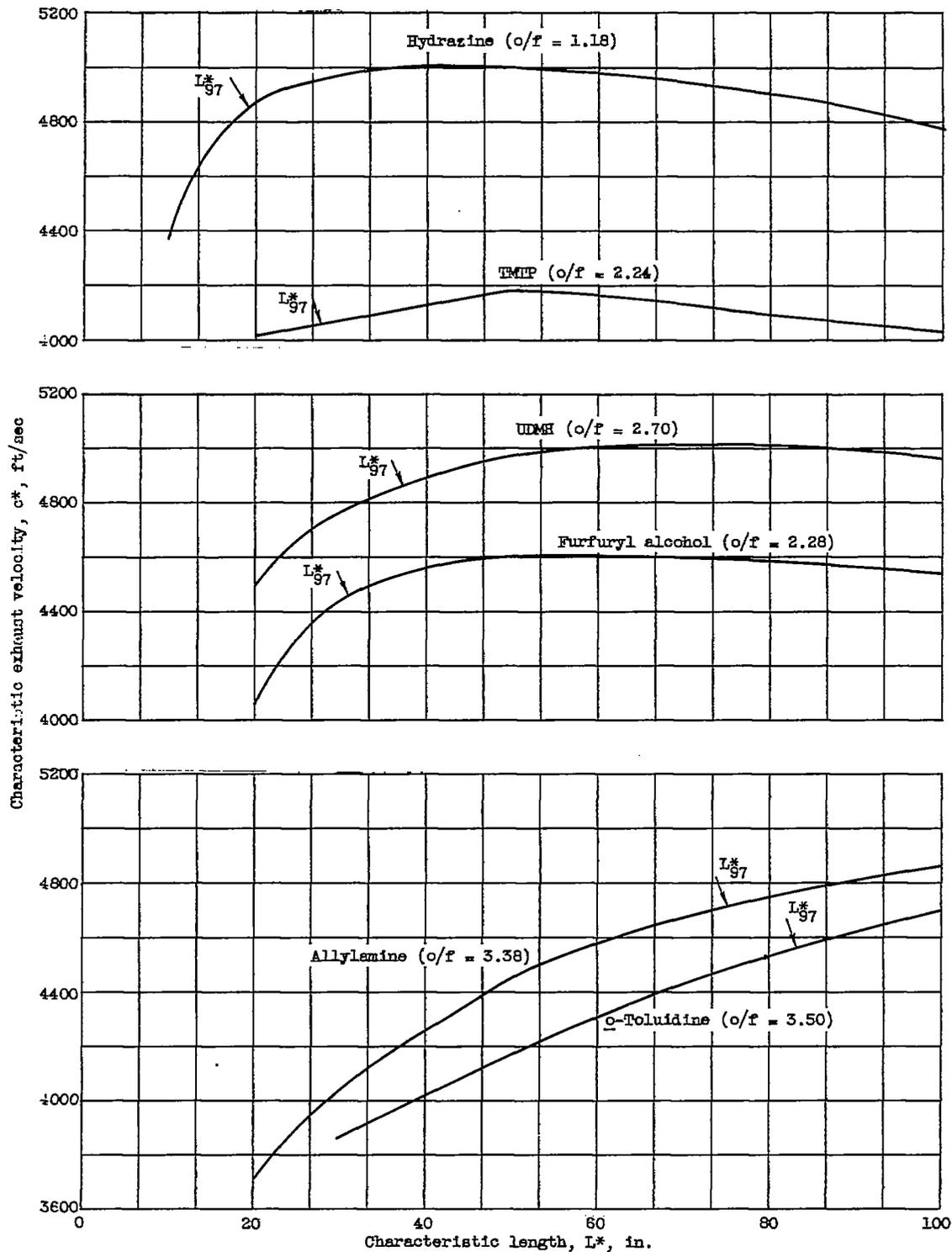


Figure 4. - Comparison of fuels at a β of 0.80.

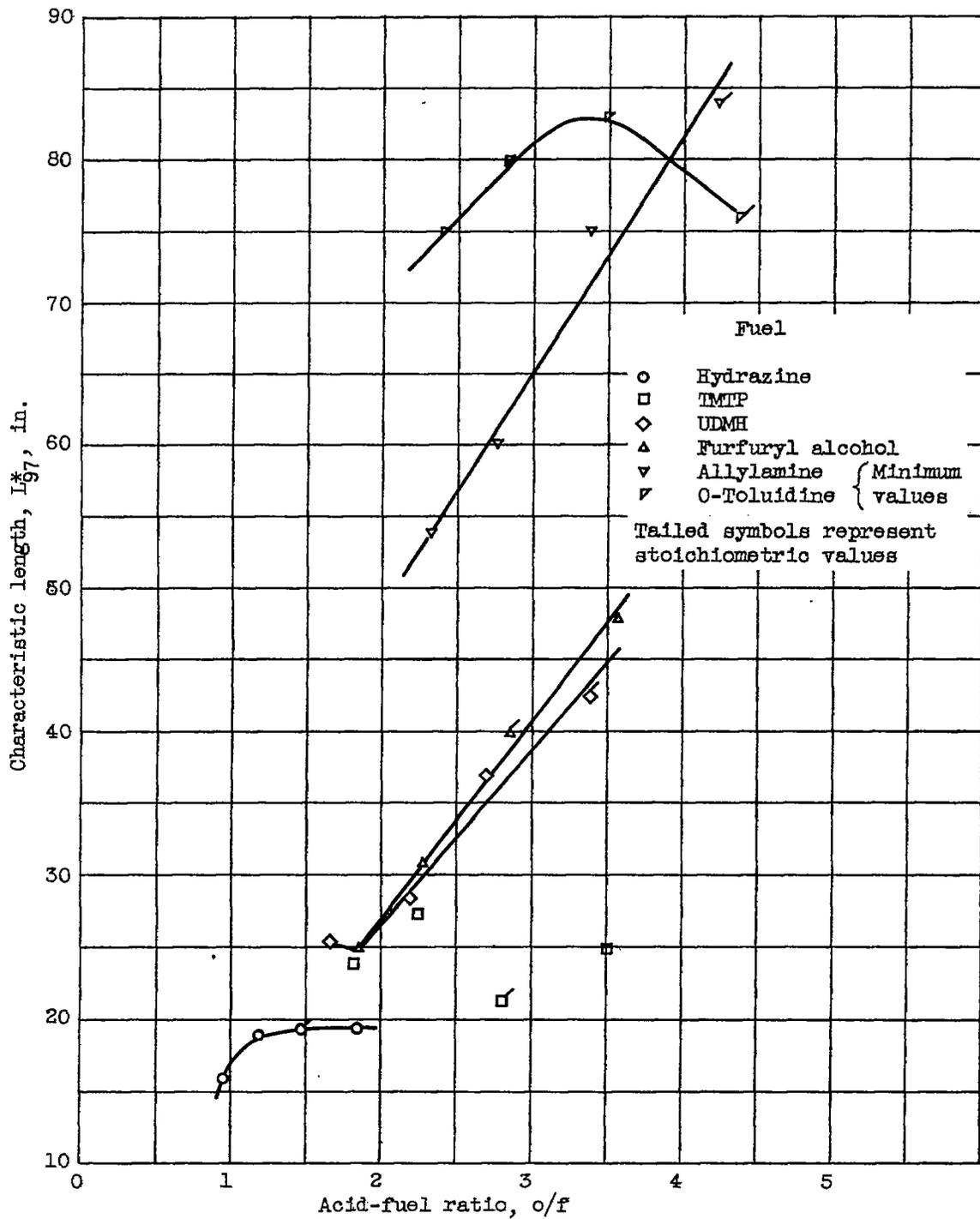


Figure 5. - Effect of stoichiometry; L^*_{97} as function of acid-fuel ratio.

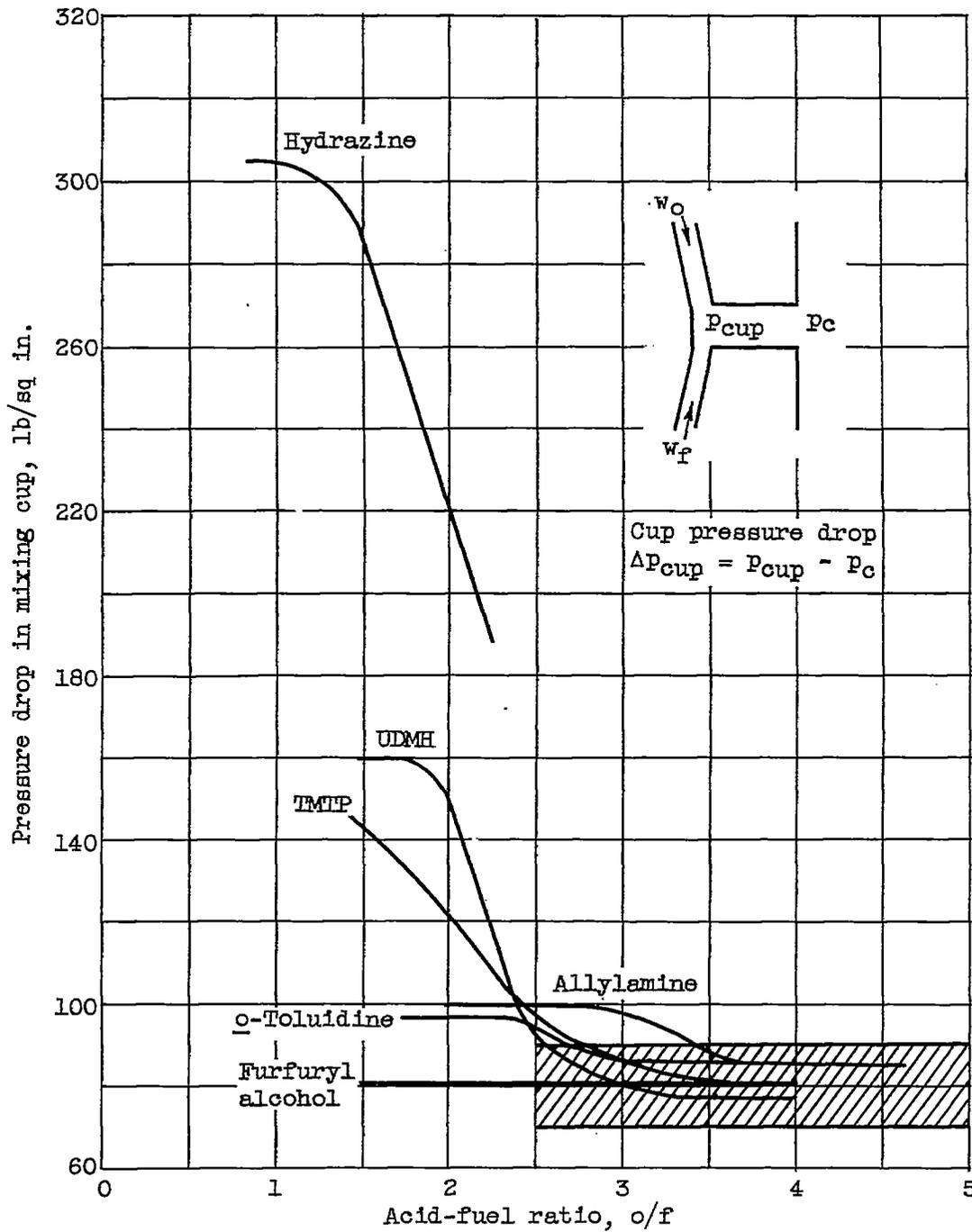
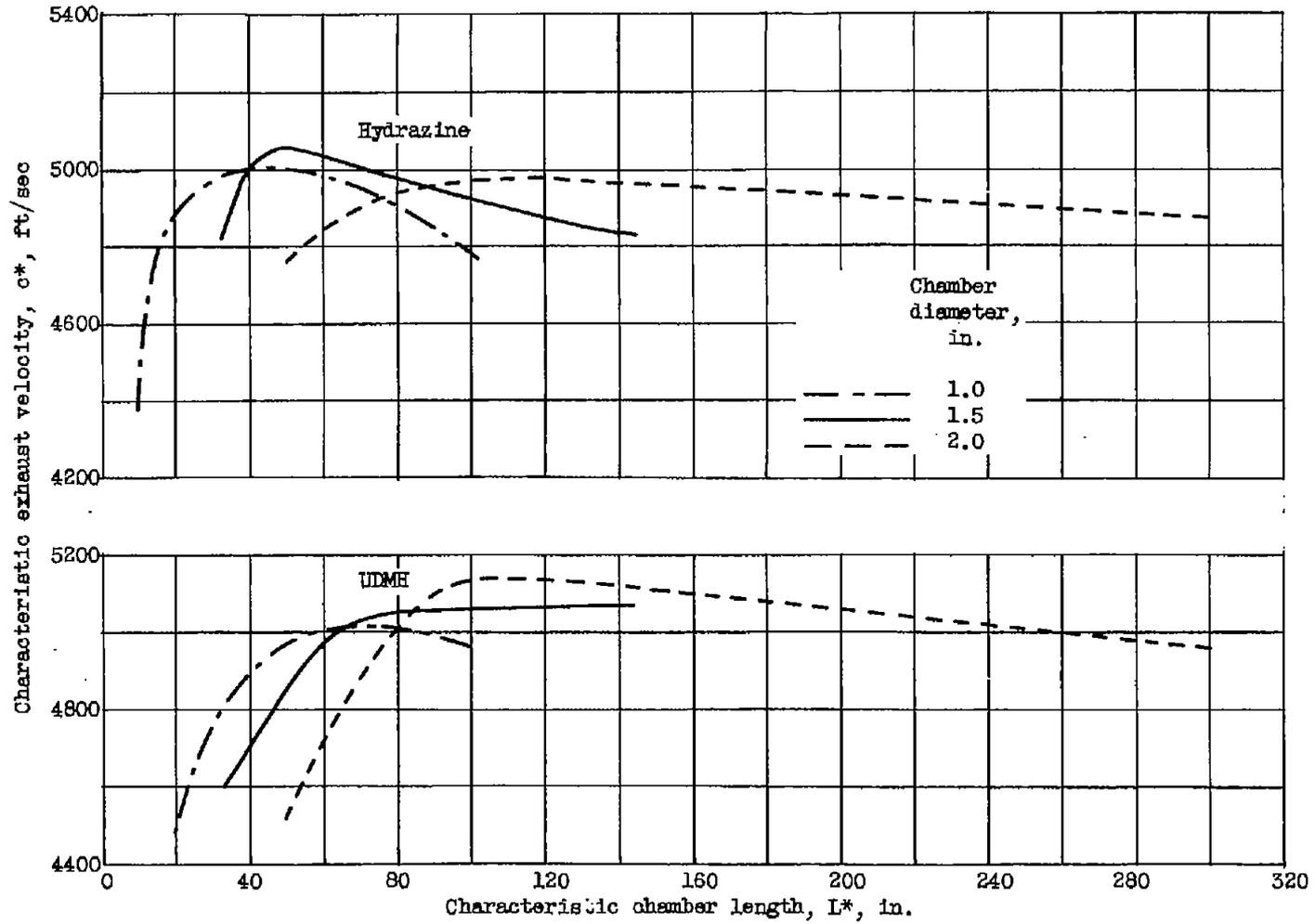


Figure 6. - Cup pressure drop reduced to uniform flow rate ($w_T = 0.2$ lb/sec) as function of acid-fuel ratio.

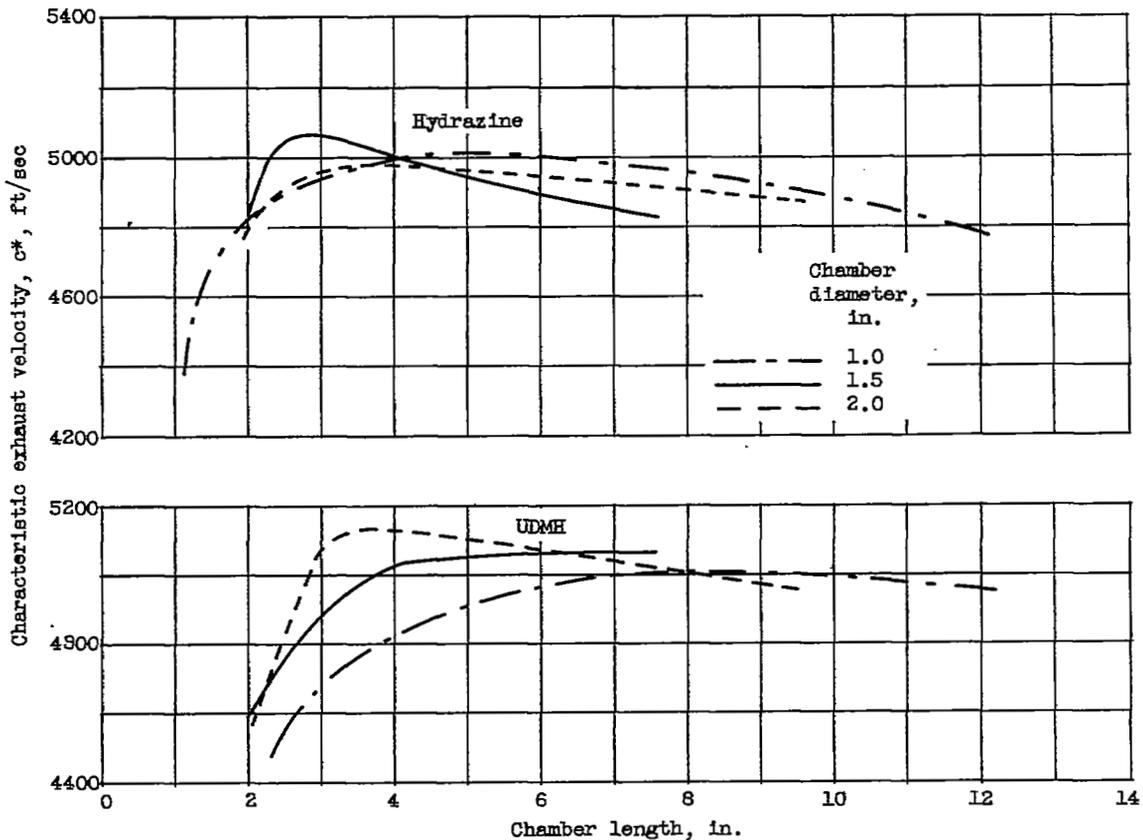


(a) As function of characteristic length.

Figure 7. - Effect of chamber diameter on characteristic exhaust velocity c^* at a β of 0.80.

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(b) As function of chamber length.

Figure 7. - Concluded. Effect of chamber diameter on characteristic exhaust velocity c^* at a β of 0.80.

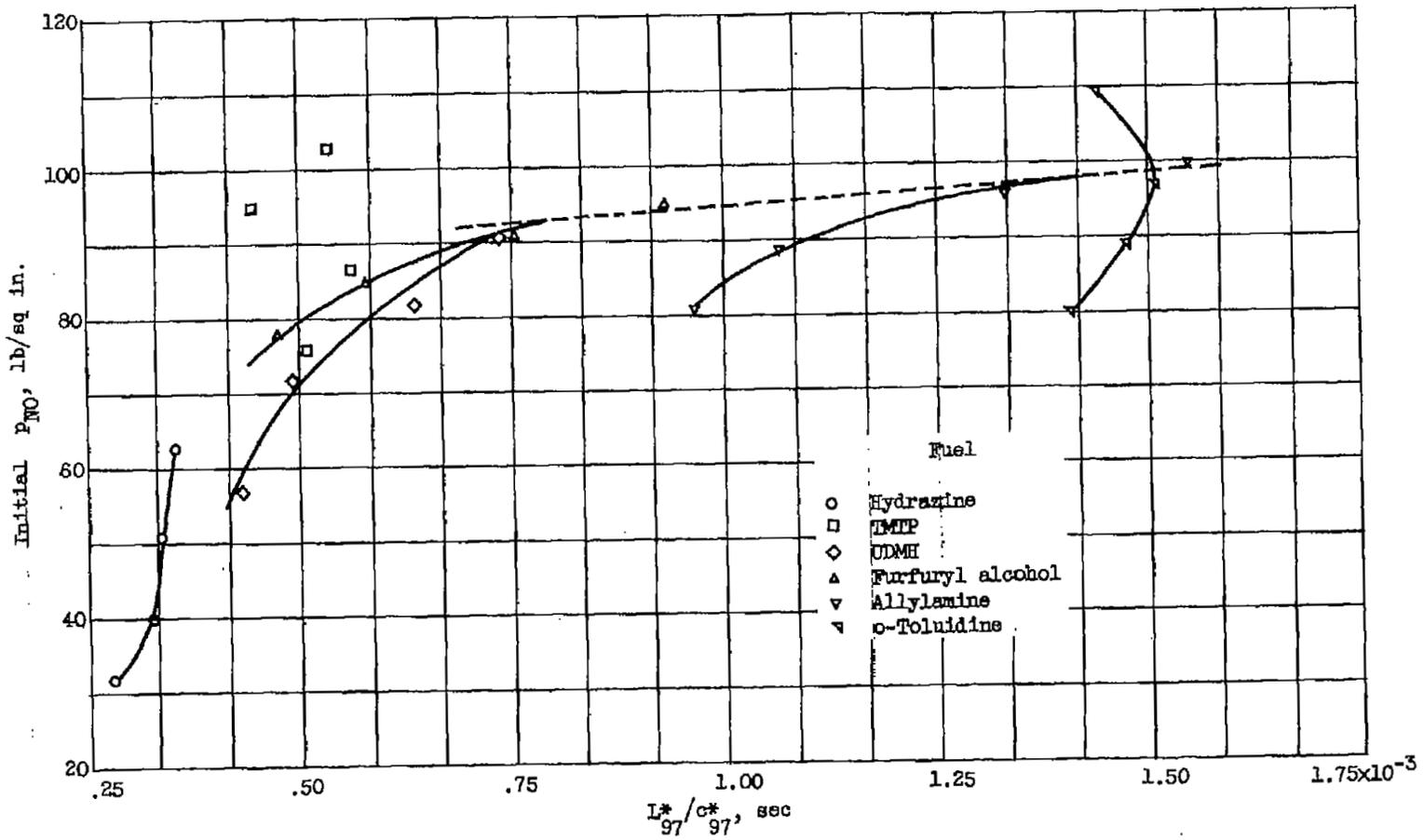
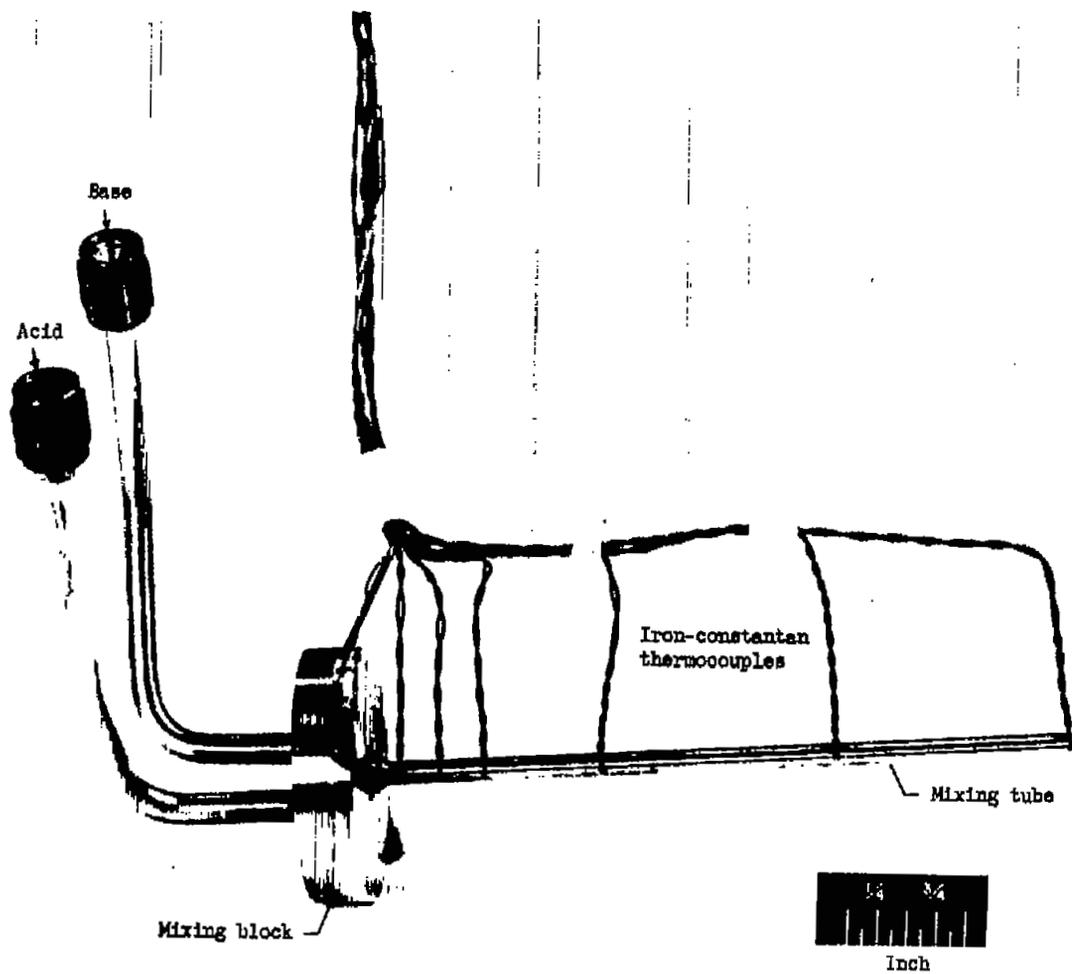


Figure 8. - Correlation of reactivity with initial NO concentration.



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Figure 9. - Experimental apparatus for determining mixing efficiency of injectors.

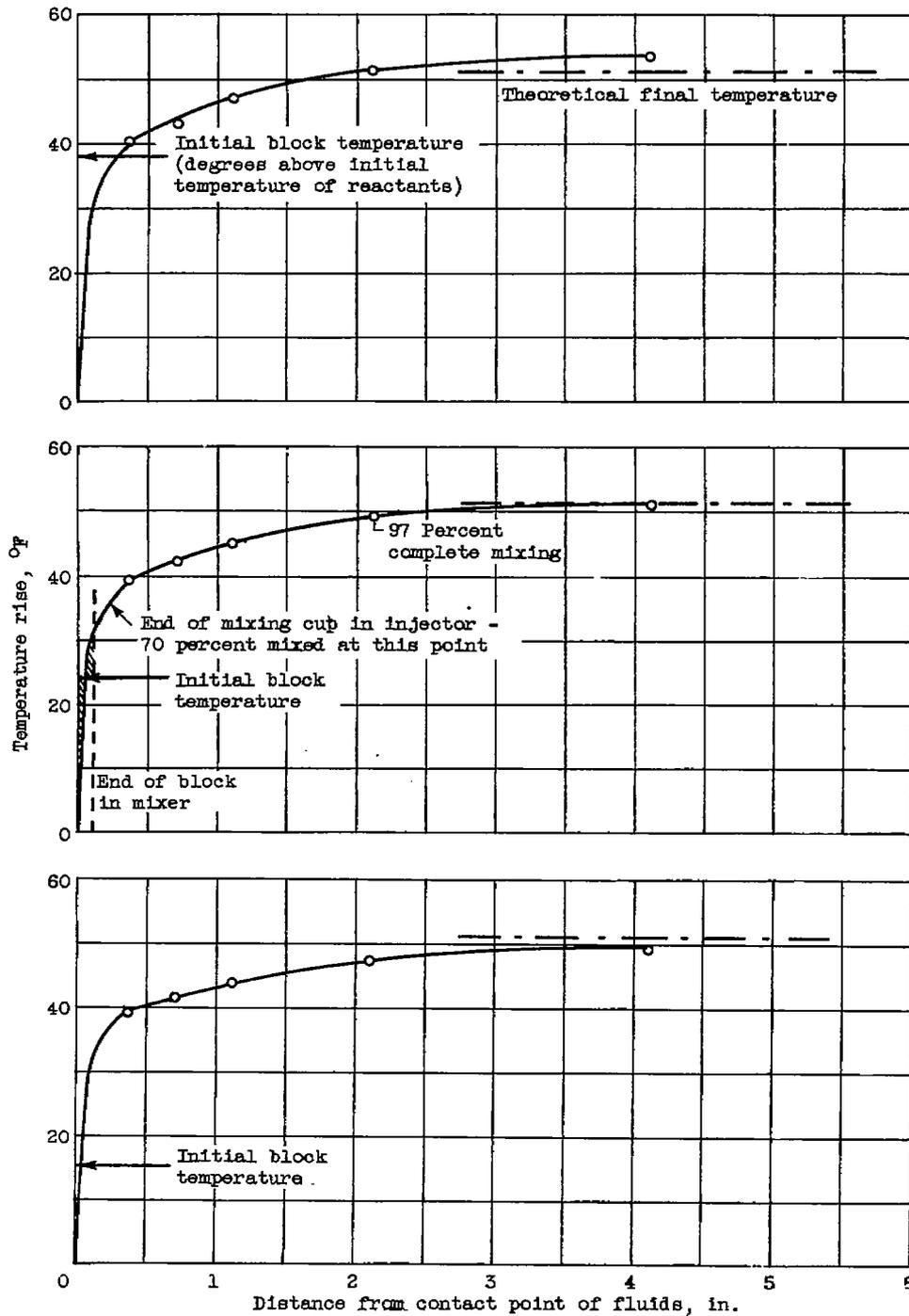


Figure 10. - Temperature rise as function of distance along mixer for three initial block temperatures.

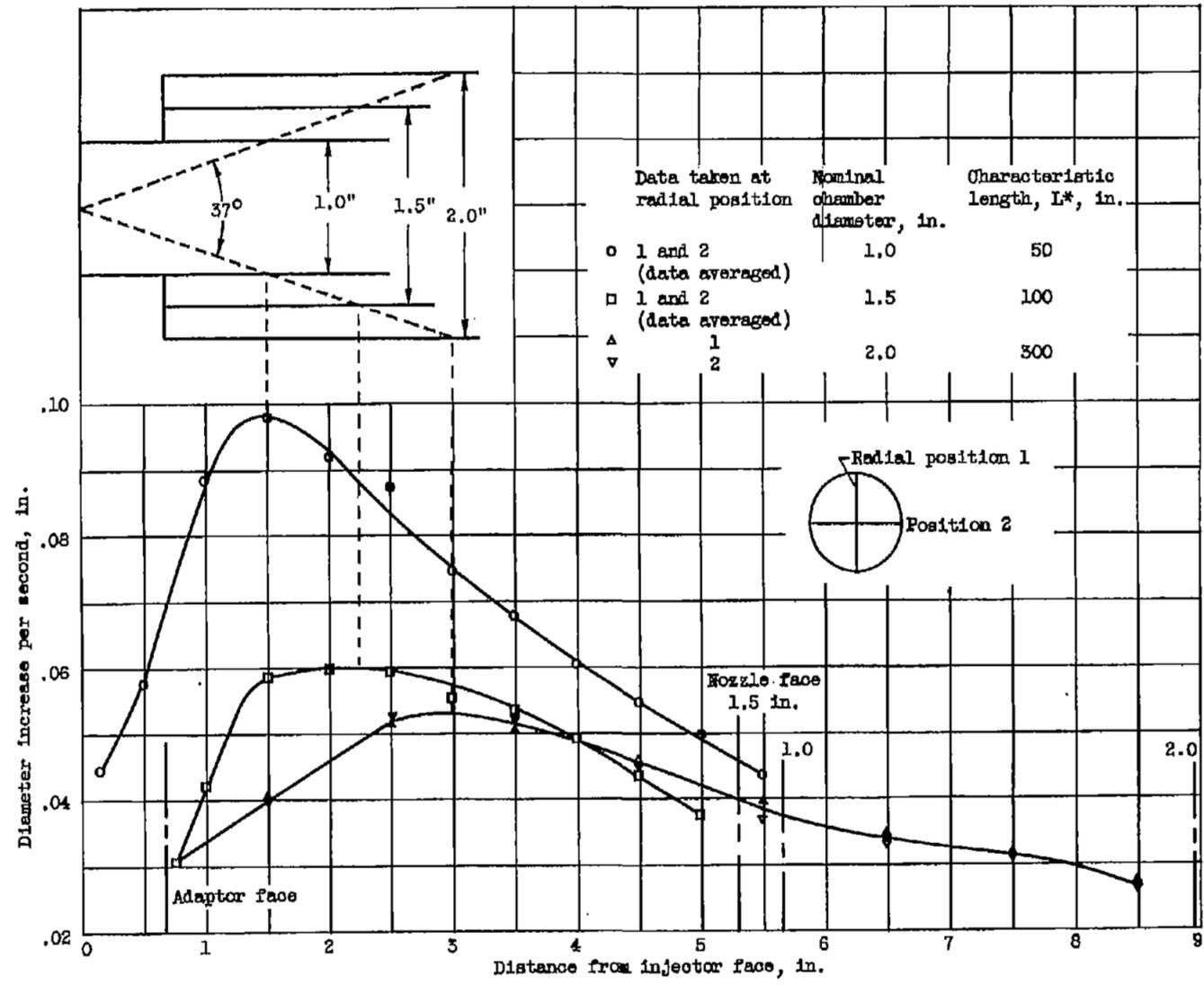


Figure 11. - Erosion pattern and its relation to diameter and chamber geometry. Fuel, hydrazine.

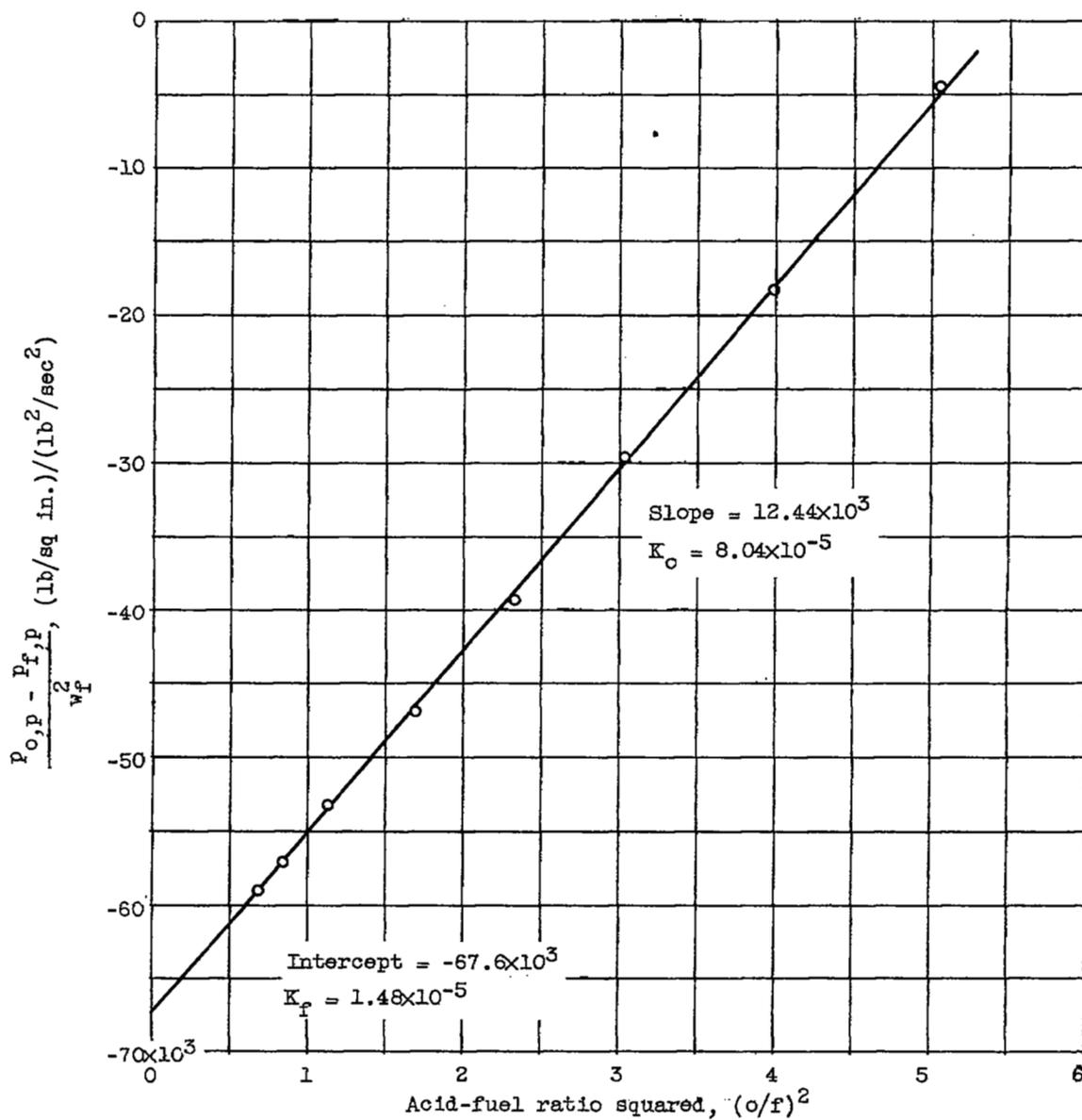


Figure 12. - Example of graphical calculation of flow constants K_o and K_f for hydrazine.



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