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NASA TN D-4984

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DYNAMIC RESPONSE OF HYDRAZINE - NITROGEN TETROXIDE COMBUSTION TO TRANSVERSE GAS FLOW

by Marshall C. Burrows

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Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • FEBRUARY 1969

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Film supplement C-262 available on request

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ABSTRACT

Liquid Jets within a two-dimensional combustor were subjected to tangential nitrogen flow which induced high-frequency instability. Two types of response were obtained: one which was coupled to transverse gas flow, and one which was self-coupled or independent of gas flow after initiation. Photographs showed marked differences in atomization of jets within the two response regions. Atomization extended over longer distances in the coupled response region and was concentrated close to the impingement point in the self-coupled response region. Predicted breakup lengths were somewhat longer than observed values. Atomization was retarded when the injection tube diameter or its length was increased.

Technical Film Supplement C-262 available on request.

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SUMMARY

Combustion stability of a hypergolic system was studied for several variations of triplet element design. Tangential nitrogen flow induced the traveling transverse mode of instability within the chamber. Two types of unstable combustion were initiated by the nitrogen flow. In one type, the amplitude of the transverse wave was coupled to the tangential flow of nitrogen in that the oscillatory amplitude was proportional to the nitrogen flow. The second type of unstable combustion was induced by the nitrogen flow but continued with undiminished amplitude when nitrogen flow decreased making it a self-coupled response. The coupled response was characterized by the distribution of combustion over a large area due to the relatively slow atomization and vaporization of the center jet in each element. The self-coupled response was characterized by gross breakup of both fuel and oxidant jets near their impingement followed by concentrated combustion. The self-coupled response could be eliminated when center jet stability was increased sufficiently by increasing center jet velocity, diameter, or extending tube length downstream from the injector face.

Observed jet breakup was correlated with an atomization model based on the progressive spreading of the liquid jets prior to impingement. The effect of transverse gas flow on jet breakup is evaluated. The breakup of jets prior to impingement can produce nonaxial flow sufficient to initiate combustion instability in a combustor. Sustained oscillations can also be driven by in-phase fuel decomposition and interfacial reactions. Proper shielding, alinement, and impingement of the jets within each injector element will minimize the generation of nonaxial flows which are conducive to unstable combustion.

INTRODUCTION

The dynamic stability of various combustion processes in liquid propellant rockets has been studied to discover the design criteria necessary for the prevention of self-induced oscillations. These studies have included drop vaporization (ref. 1), vapor phase mixing (ref. 2), gas flow coupling (ref. 3), and jet atomization (ref. 4). A study of the hydrazine - nitrogen tetroxide reaction should also include possible liquid-phase reactions (ref. 5) and propellant decomposition (ref. 6).

Recent studies have demonstrated that a traveling transverse mode of oscillation can be induced by a steady tangential or vortex velocity. This effect was examined in detail for liquid-oxygen - gaseous-hydrogen combustion (ref. 7), and the oscillatory amplitude varied almost directly with the induced tangential gas velocity.

In this study, the response characteristics of hydrazine and nitrogen tetroxide propellants to a transverse velocity were evaluated. Triplet elements similar to those used in other storable studies were used. The oscillatory response of the storable propellants in this study is compared with previous hydrogen-oxygen data. Photographs show impingement characteristics and atomization during stable and unstable combustion. The effects of interfacial reactions and dissociation in the atomization zone are discussed. Experimental jet breakup is correlated with an atomization model developed in reference 8 which was based on the progressive spreading that occurs in each jet before impingement.

A motion-picture supplement C-262 has been prepared and is available on loan. A request card and a description of the film are included at the back of this report.

EXPERIMENTAL COMBUSTOR

The combustion data were obtained from a two-dimensional combustor similar in characteristics to the one developed for liquid oxygen and gaseous hydrogen (ref. 9). The chamber cavity was 0.5 inch (1.27 cm) high, 8 inches (20.3 cm) in diameter, and equipped with quartz windows or a transparent plastic top plate. Injection was provided by eight triplet elements located on the combustor circumference (fig. 1). Three configurations of the injector elements were used in the test series. The principal arrangement consisted of two 0.025-inch- (0.063-cm-) diameter jets impinging 0.5 inch (1.27 cm) downstream from the injector face, intersecting the 0.035-inch- (0.089-cm-) diameter center jet. The combined area of the outside tubes in each element nearly equaled that of the center tube. This permitted interchange of the propellants without appreciable change in manifold pressure drop. A brief series of tests was conducted with the center jet in each element enlarged to 0.052 inch (0.132 cm) in diameter.

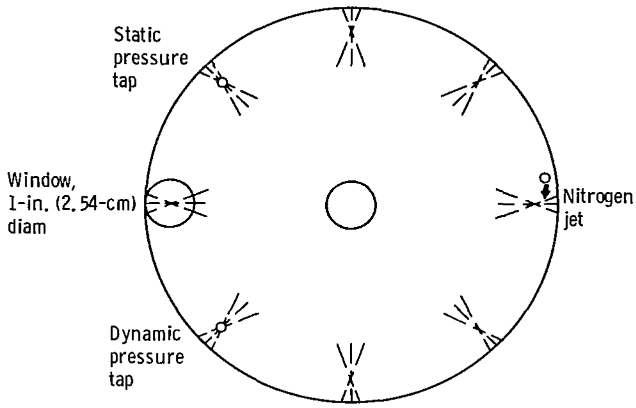


Figure 1. - Hydrazine - nitrogen tetroxide combustor. Included angle, 40°; chamber diameter, 8 inches (20.3 cm); chamber depth, 1/2 inch (1.27 cm); nozzle diameter, 1 inch (2.54 cm).

Final tests were made with tubes inserted in the center jet holes (0.032 in. (0.081 cm) i.d.) which extended 0.375 inch (0.95 cm) downstream from the injector face and prevented propellant mixing before impingement. Injector elements were supplied by individual tubes to reduce pressure feedback and manifold accumulation effects.

The transverse velocity was induced by a tangential gaseous nitrogen jet near the chamber circumference. Gaseous nitrogen was supplied through an orifice at a continually changing rate, determined by an accumulator, second orifice, and supply valve. An increasing transverse flow of nitrogen was produced by simultaneously filling the accumulator tank and injecting directly into the transverse combustor jet. When the source was shut off, gas from the accumulator provided a decreasing flow until combustor shutdown.

The top plate of the combustor was either stainless steel with a quartz window centered on one injector element, or fully transparent plastic. A quartz window located in the bottom plate permitted the triplet element to be photographed as a silhouette. The transparent top provided access to all eight injector elements. In both setups, a motion-picture camera operated at 3200 frames per second photographed the response of the hydrazine and nitrogen tetroxide jets to the tangential nitrogen jet.

MEASUREMENTS

Pressure

Dynamic chamber pressures were measured by a piezoelectric transducer mounted in a water-cooled holder and shielded from combustion gases by a layer of silicone oil.

Pressure signals were recorded on a direct-writing oscillograph with a frequency response from zero to 5000 hertz. Wave shape was analyzed by time expanding the taped signal and recording it on a pen recorder. Steady-state chamber pressures were monitored by a strain-gage transducer attached to the combustor by nitrogen-purged, small-diameter tubing.

Photographs

Color photographs were taken at framing rates of about 3200 pictures per second with a 16-millimeter camera. Exposure times varied from about 62 microseconds for the full-sized combustor image to 3 microseconds for silhouette photographs of one element. Backlighting for the silhouette photographs was provided by a concentrated arc lamp. The lamp was focused on the camera lens by a quartz lens placed between the lamp and the combustor. With a framing rate of 3200 frames per second, combustion oscillations at 3200 to 3300 cycles per second were stroboscopically scanned at low relative rates. Hence, the effect of the transverse wave on jet breakup was distributed over a number of frames. Good cycle-to-cycle reproducibility of the transverse wave was required for accurate analysis of the breakup data.

PROCEDURE

A pressurized tank system controlled propellant flows to the combustor. Turbine-type flowmeters measured the propellant flow rates. An oxidant lead of approximately 0.1 second was followed by full fuel flow. Equilibrium propellant flows were established approximately 0.1 second after ignition. Stable combustion was established for about 0.5 second before the initiation of transverse gas flow. The transverse gas flow induced by the nitrogen was assumed to be that derived from a momentum balance (ref. 10):

$$\overline{U}_\theta w_t = w_n U_n + (\Delta P)A_n g \tag{1}$$

All symbols are defined in the appendix. The induced gas flow calculated from typical run data is plotted as a function of run time in figure 2. The maximum induced velocity of 249 feet per second (76 m/sec) corresponded to a nitrogen weight flow of 0.22 pound per second (0.10 kg/sec) and propellant weight flow of 1.37 pounds per second (0.62 kg/sec). The run terminated before transverse gas flow decreased to zero. The predominent instability mode induced by the nitrogen flow was the first transverse mode, with higher harmonic modes usually present at reduced amplitudes. Occasionally, on

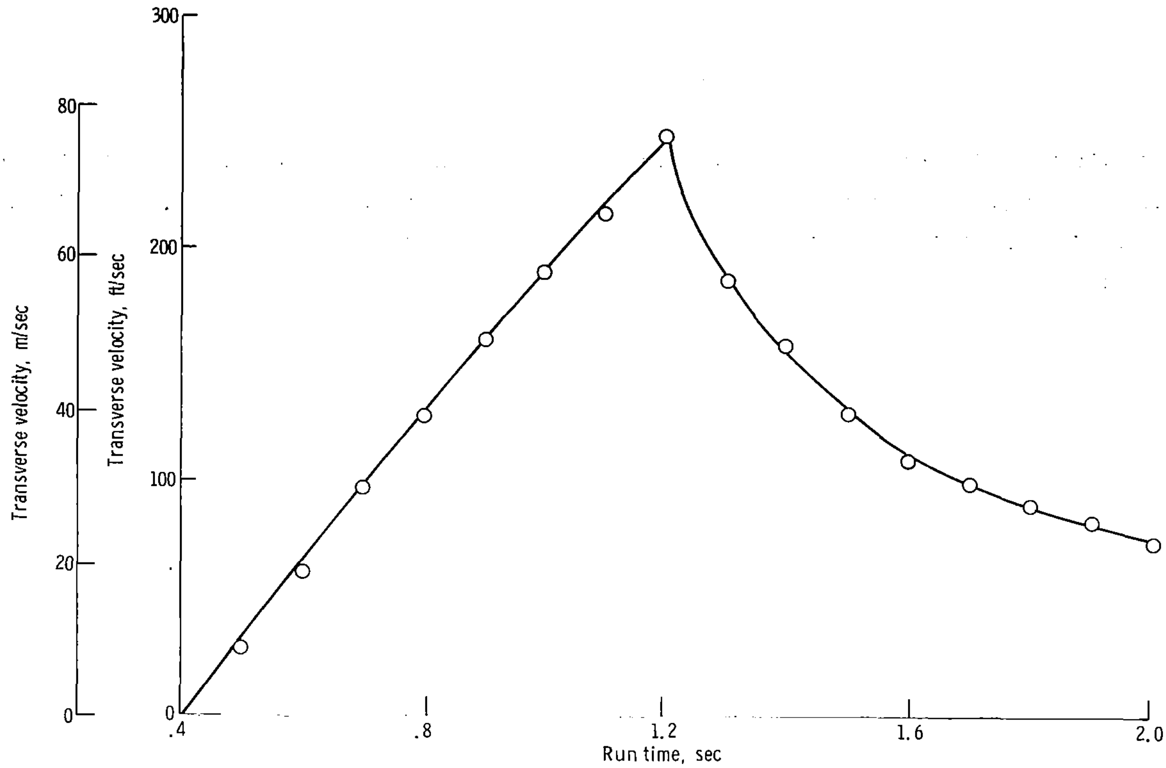


Figure 2. - Induced transverse gas velocity as function of run time.

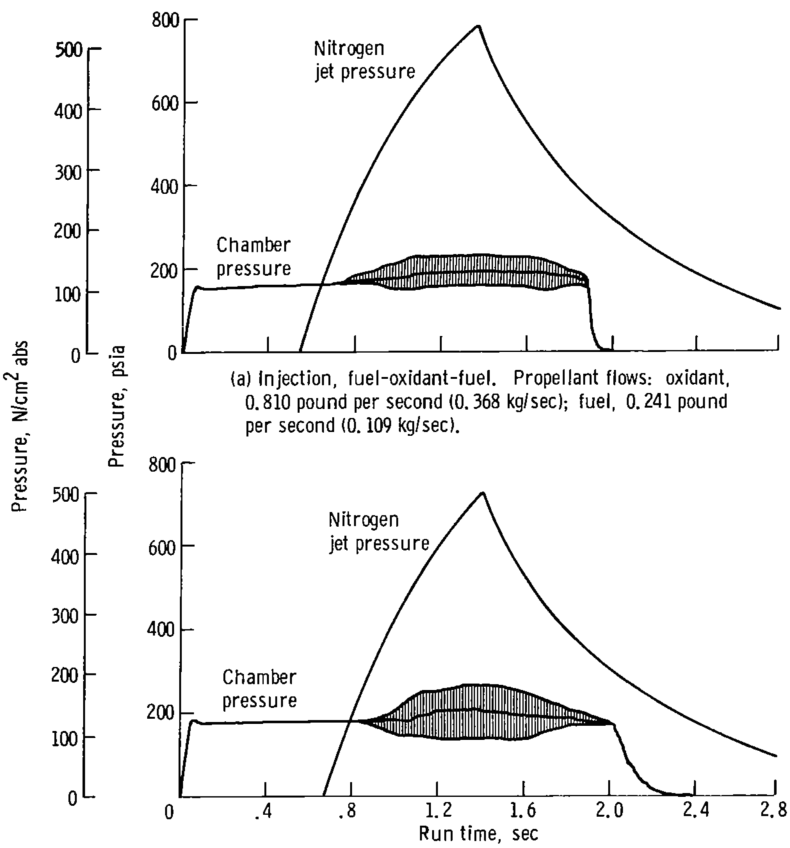
cessation of nitrogen flow, the combustion instability reverted to a low-amplitude radial mode. No chugging type instability was encountered with the hardware used in this study.

The combustor was operated with fuel in the outer jets of each element and oxidant in the center jets (F-O-F) or reversed, with oxidizer jets impinging on center fuel jets (O-F-O). Oxidant flow rates varied from 0.15 to 0.9 pound per second (0.068 to 0.409 kg/sec), and fuel flow rates varied from 0.1 to 0.7 pound per second (0.045 to 0.32 kg/sec). With a nominal nozzle diameter of 1.0 inch (2.5 cm), chamber pressures varied from 150 to 250 psia (103 to 172 N/cm^2 abs). At the maximum transverse flow of nitrogen, 0.22 pound per second (0.10 kg/sec), dilution of the combustion products varied from 40 percent of the lowest total propellant flow rate to 15 percent of the highest total flow rate. Nitrogen flow was less than 9 percent of the total propellant flow on initiation of unstable combustion.

RESULTS AND DISCUSSION

Coupled Oscillation

Heidmann anf Feiler (ref. 7) found the unstable combustion of hydrogen and oxygen to be closely coupled to the induced transverse gas velocity. Increasing the transverse flow of nitrogen resulted in a corresponding increase in the oscillatory amplitude $\Delta P/P_c$. The hydrogen-oxygen combustor reverted to stable combustion on termination of transverse nitrogen gas flow. In the present study, the transverse gas flow was varied during each run in the manner shown in figure 2. For the coupled oscillation, the oscillatory amplitude varied directly with nitrogen flow, as shown by the data in figure 3.



(a) Injection, fuel-oxidant-fuel. Propellant flows: oxidant, 0.810 pound per second (0.368 kg/sec); fuel, 0.241 pound per second (0.109 kg/sec).

(b) Injection, oxidant-fuel-oxidant. Propellant flows: oxidant, 0.203 pound per second (0.092 kg/sec); fuel, 0.686 pound per second (0.312 kg/sec).

Figure 3. - Chamber and nitrogen jet pressures as function of run time (coupled growth and decay).

Chamber pressure and nitrogen jet pressure are shown as a function of time for F-O-F (fig. 3(a)) and O-F-O (fig. 3(b)) injection patterns. Center jet velocities exceeded those of the impinging outer jets for both injection patterns.

Hydrazine - nitrogen tetroxide (N_2H_4-N_2O_4) data are compared with hydrogen-oxygen (H_2-O_2) data from reference 7 in figure 4. The H_2-O_2 system, which used concentric injection, appeared to be more sensitive to low induced transverse velocities than the N_2H_4-N_2O_4 system which used triplet injection. The threshold velocity for the run cited in reference 7 was 30 feet per second (9.15 m/sec), while the threshold velocity

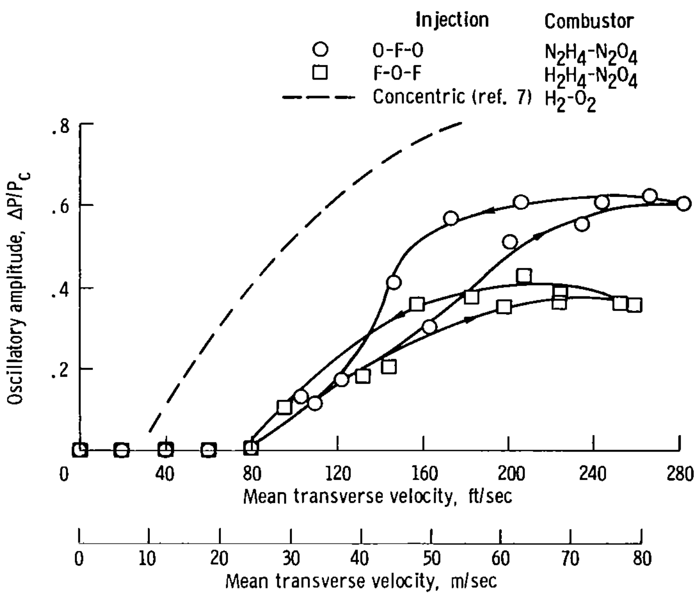


Figure 4. - Oscillatory amplitude as function of transverse flow (coupled response).

shown for the N_2H_4-N_2O_4 system in figure 4 is 80 feet per second (24.4 m/sec). This variance is not appreciable considering the difference in propellants and injection methods. The oscillatory amplitude was greater for the O-F-O injection pattern than for the F-O-F injection pattern at high transverse gas flows. Combustor response was also somewhat dependent on the rate of change in mean transverse velocity, since a slight hysteresis or delayed response was observed between increasing and decreasing transverse flows. The H_2-O_2 response was only obtained for various constant nitrogen flows.

Self-Coupled Oscillation

The coupled response shown in figure 4 was obtained only when the center jet velocity was appreciably larger than the side jet velocities. When the center jet velocity was equal to or less than the side jet velocities, combustor response to the transverse gas jet was essentially self-coupled (fig. 5). The self-coupled response characteristic is inferred from the observation that the amplitude remained high even when the transverse gas flow decreased or was shut off (fig. 6). The threshold velocity for self-coupled response in both injection types was 100 to 120 feet per second (30.5 to 36.6 m/sec). Steady-state oscillatory amplitudes exceeded 0.6 $\Delta P/P_c$ with O-F-O injection; oscillatory amplitudes were somewhat lower with F-O-F injection.

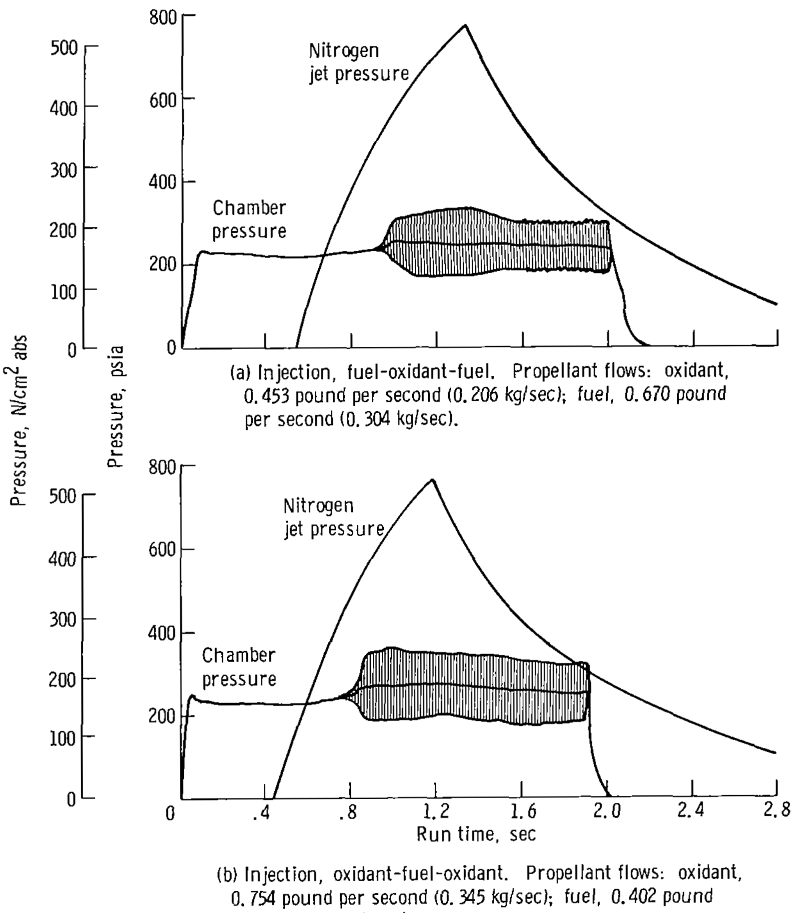


Figure 5. - Chamber and nitrogen jet pressures as function of run time (self-coupled oscillation).

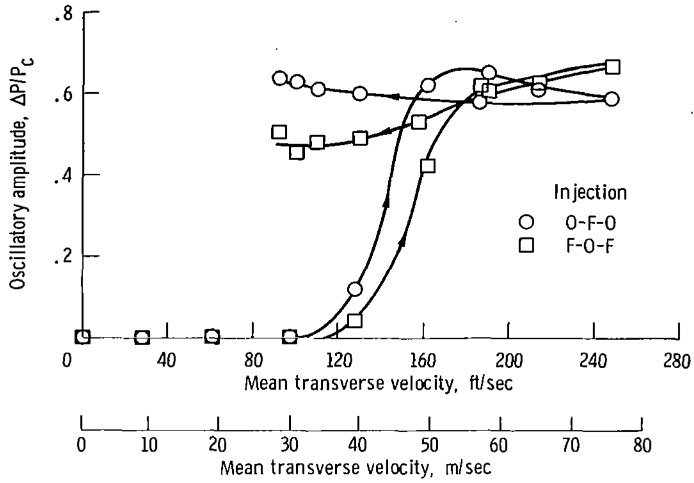
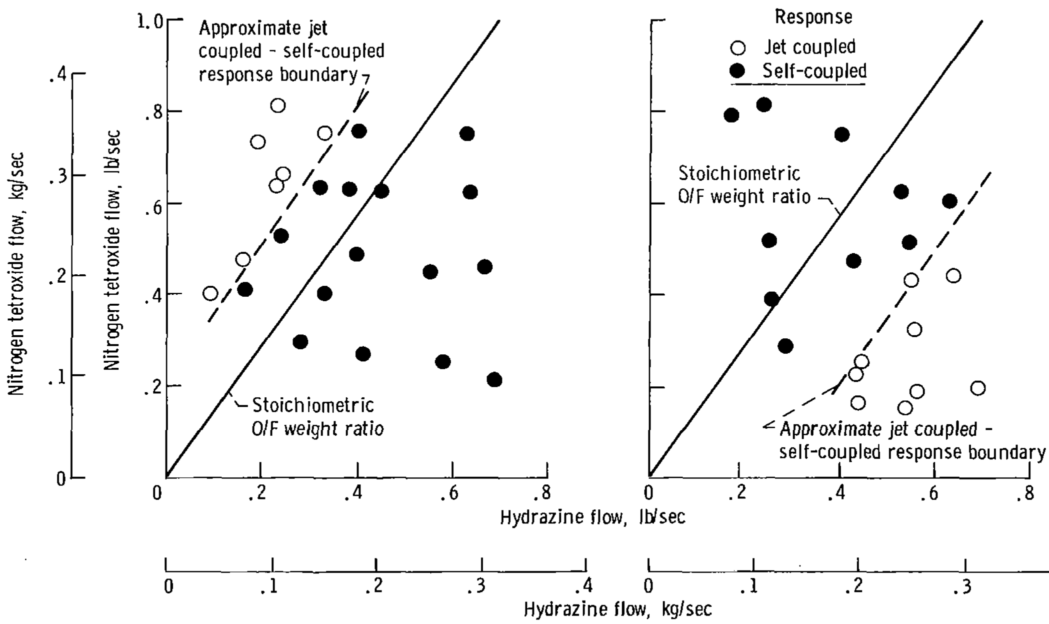


Figure 6. - Oscillatory amplitude as function of transverse flow (self-coupled oscillation).



(a) Injection, fuel-oxidant-fuel.

(b) Injection, oxidant-fuel-oxidant.

Figure 7. - Response of triplet elements as function of propellant flows.

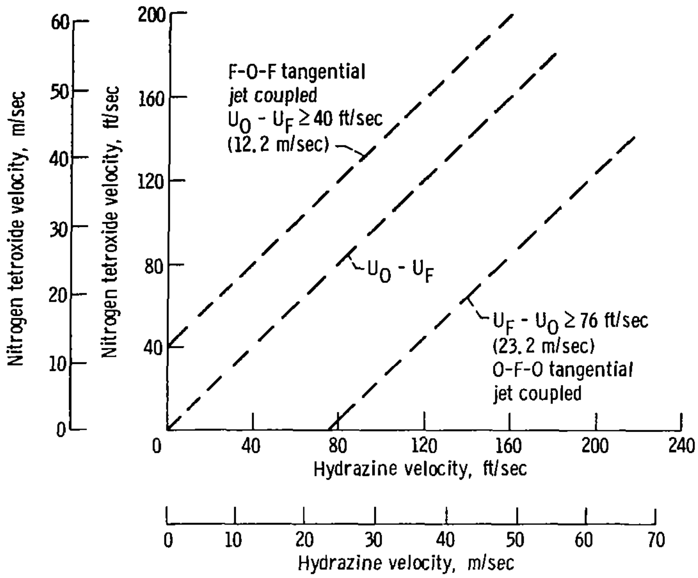


Figure 8. - Stability regions as function of propellant velocities.

Coupled - Self-Coupled Boundaries

Since the combustor response to transverse nitrogen flow depended on the type and velocity of injection, a series of runs was made to obtain the approximate boundary of the jet coupled - self-coupled regions (figs. 7(a) and (b)) for F-O-F and O-F-O triplets, respectively. The boundaries occurred along lines of constant O/F, velocity, or momentum ratio. If the boundaries are plotted as a function of each of the propellant velocities, they vary as shown in figure 8. For F-O-F injection, the center jet velocity must exceed the side jet velocity by more than 40 feet per second (12.2 m/sec) to obtain combustor response which is coupled to the transverse jet. On the other hand, when the center jet contains fuel (O-F-O injection), its velocity must exceed the side jet velocity by more than 76 feet per second (23.2 m/sec) for coupled response.

Effect of Injector Element Configuration

Since jet atomization and vaporization are considered velocity-sensitive processes (ref. 7), changes in the injection elements should have a large effect on the stability characteristics of the combustor. Increasing the area of the center jet 2.2 times in each element increased the combustor stability with F-O-F injection, as shown in figure 9. Combustor response was coupled to the transverse gas flow over a wider range of propellant flows when compared with the initial configuration in figure 7. A

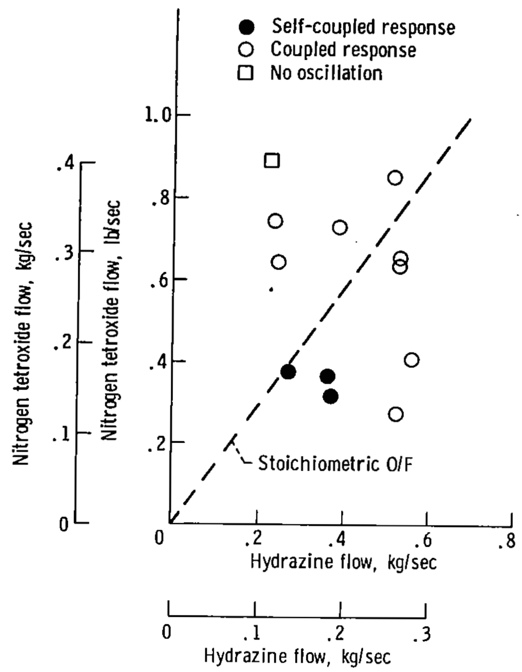
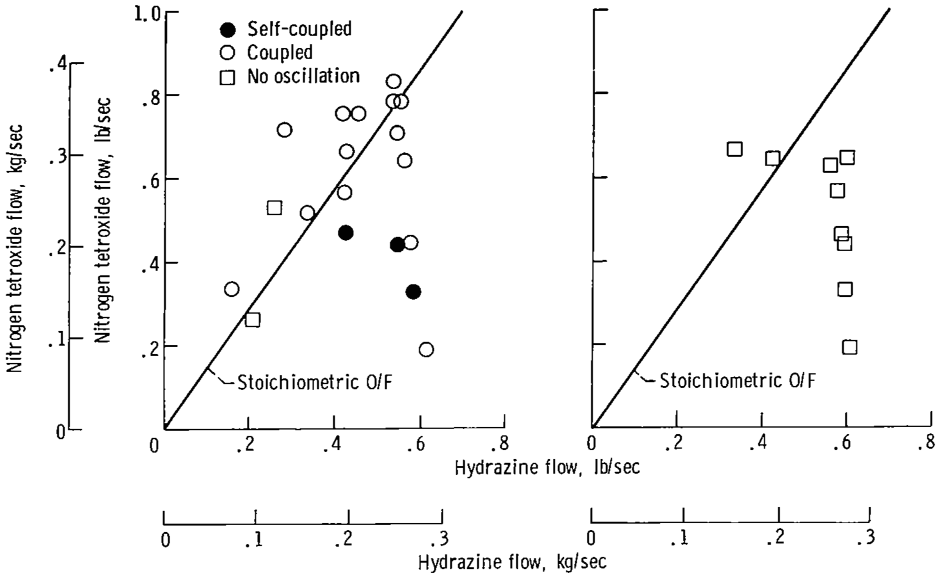


Figure 9. - Response of fuel-oxidant-fuel elements with enlarged oxidant tubes.

low-amplitude self-coupled oscillation occurred at low near-stoichiometric flow rates. Lenghtening the tube on the center jet in each element also increased stability by decreasing the incidence of self-coupled oscillations, as shown in figure 10. The center tube extended 0.375 inch (0.95 cm) to the impingement zone of fuel and oxidizer. The liquid in the center tube was thus protected from gas velocity effects on its atomization, vaporization, and mixing with the other propellant.

No clear boundary separated the coupled and self-coupled regions with the F-O-F injection arrangement (fig. 9(a)). Two runs showed no dynamic effect on chamber pressure from the transverse gas flow. Completely stable combustion was obtained with or without transverse gas flow (fig. 10(b)) for the O-F-O injection pattern with extended center tubes.

The experimental data clearly show the stability improvement which is obtained by enlarging or extending the center tubes of the injector elements. The characteristics of the propellant jets before impingement are therefore an important part of the overall atomization and vaporization process. The extended tubes prevent mixing or reaction between unlike propellants before their impingement. Therefore, atomization, vaporization, and combustion will be distributed over a longer distance downstream.



(a) Injection, fuel-oxidant-fuel.

(b) Injection, oxidant-fuel-oxidant.

Figure 10. - Response of triplet elements with extended oxidant tubes.

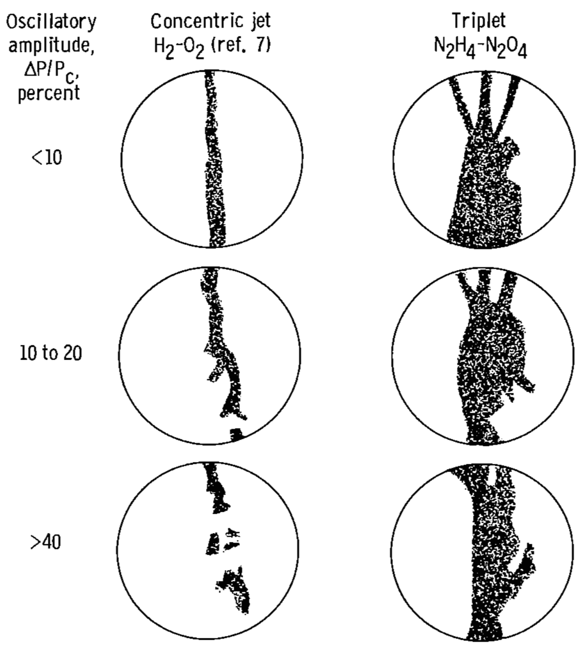


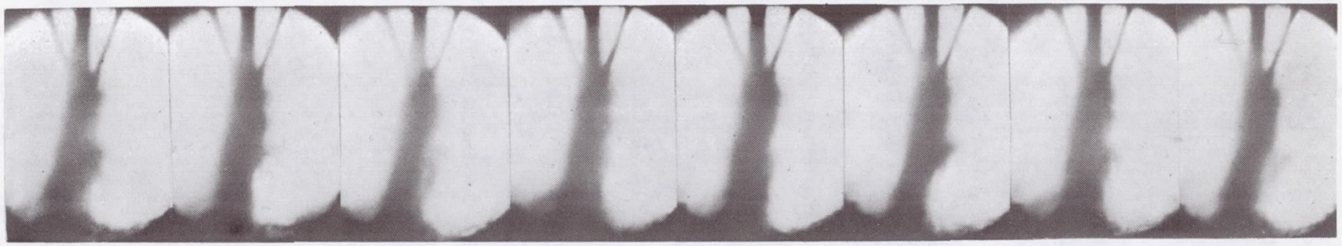
Figure 11. - Liquid jet behavior with coupled transverse instability.

Photographs

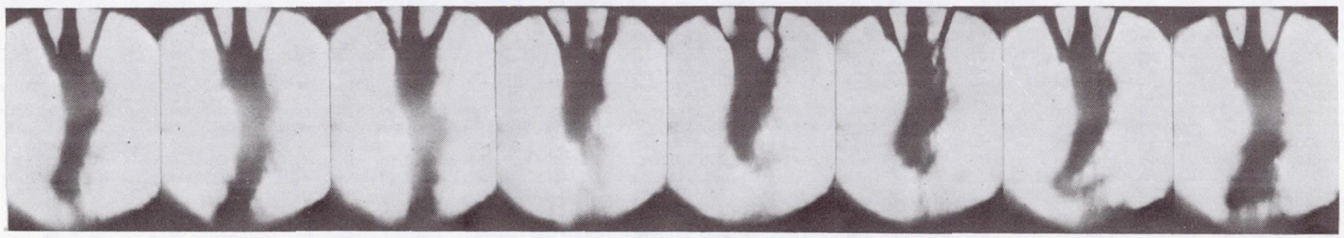
Jets from an F-O-F N_2H_4-N_2O_4 triplet element were photographed during stable and unstable combustion, and their appearance was compared with an O_2 jet from an H_2-O_2 concentric element in reference 9. The sketches in figure 11 represent typical jet photographs in each system. Both elements were coupled to the transverse gas flow induced by the nitrogen jet. At an oscillatory amplitude less than 10 percent of the chamber pressure, neither the triplet nor the concentric jet showed appreciable breakup. Increasing the transverse nitrogen flow decreased the breakup distance of both elements. In addition, impingement of the outer fuel jets in the triplet element was displaced to one side of the center oxidant jet. This displacement decreased the effectiveness of the collision process in causing breakup and atomization. Combustion of N_2H_4 and N_2O_4 remained coupled to the transverse gas flow as long as center jet breakup occurred far downstream from the impingement and breakup zones of the outer jets. This behavior was photographed for triplet elements with and without extended center tubes.

Jet breakup during oscillatory combustion, which was not coupled to the transverse flow of nitrogen, is shown in the sequence of photographs in figure 12. Stable combustion photographs of F-O-F and O-F-O elements, figures 12(a) and (c), respectively, resemble the low amplitude sketches in figure 11 where breakup and atomization occur at an appreciable distance downstream from impingement. During high-amplitude combustion instability with both injection patterns, the fuel and oxidant streams broke up and atomized before or approximately at their impingement point (figs. 12(b) and (d)). This is most easily seen in the motion picture (16 mm) which is available as a film supplement (C-262) to this report. Information on the film is included at the back of this report. A sequence of any six photographs stroboscopically covers 1 cycle of the pressure and velocity wave. With either pattern, initial breakup of the impinging outer fuel jets starts about 0.1 inch (2.54 mm) downstream from their orifices. All the jets lose mass in response to the unstable wave such that their flow appears to be cyclic.

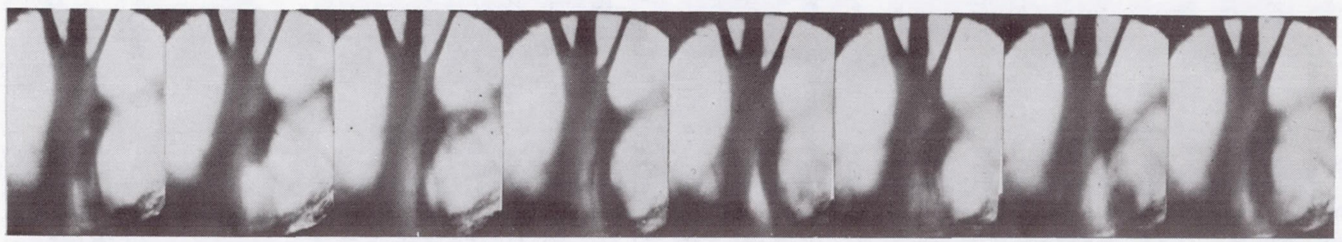
Opaque nitrogen dioxide (NO_2) is more prevalent in photographs of O-F-O injection and it obscures the jet breakup (figs. 12(c) and (d)). Interfacial reactions are apparent in the impingement zones of the O-F-O element. The jets remain separated instead of mixing at the impingement point (fig. 12(d)). This behavior causes the O-F-O triplet elements to resemble parallel jets in their characteristics. Hence, data on the atomization of nonhypergolic propellants cannot be used for evaluating a hypergolic system. Like-on-like doublets, on the other hand, are not influenced by liquid surface reactions, and small elements result in small mean drop sizes and high performance (ref. 9).



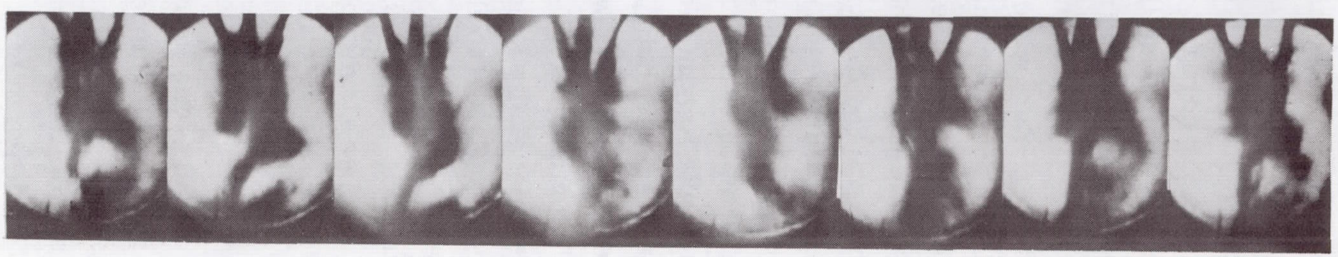
(a) Injection, fuel-oxidant-fuel; stable combustion.



(b) Injection, fuel-oxidant-fuel; self-coupled oscillation.



(c) Injection, oxidant-fuel-oxidant; stable combustion.



(d) Injection, oxidant-fuel-oxidant; self-coupled oscillation.

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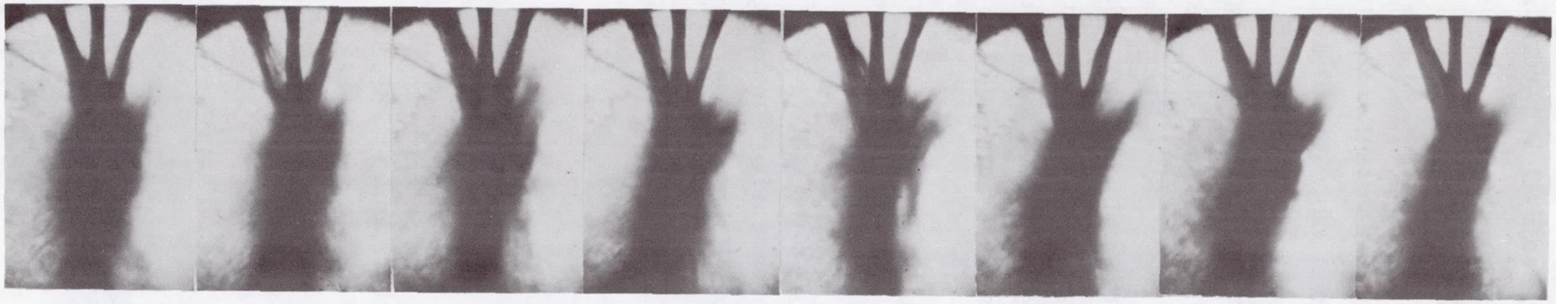
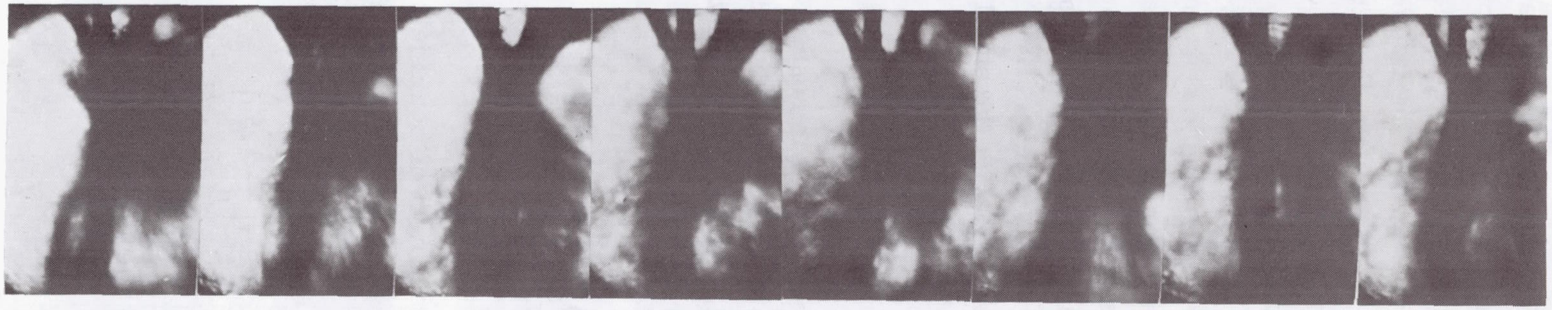
Figure 12. - Silhouette photographs of triplet elements.

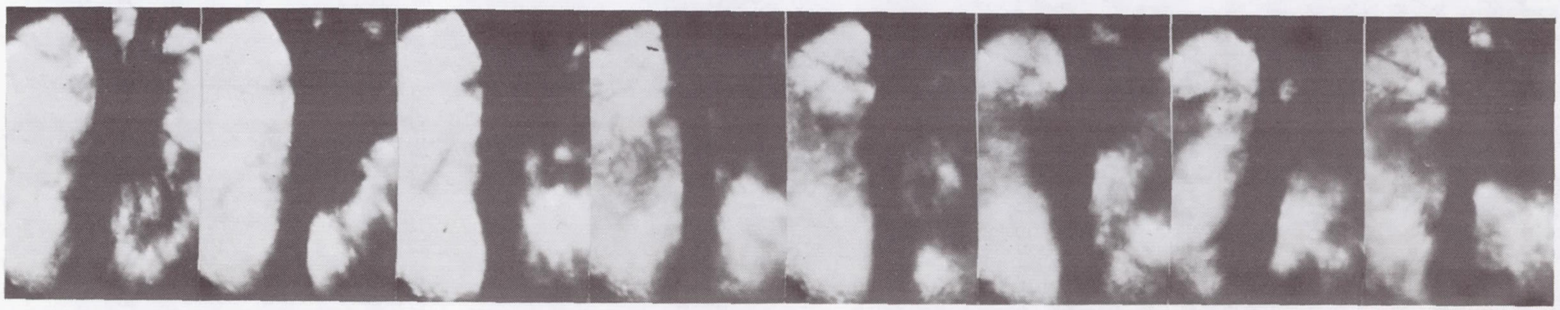


(a) Oscillatory amplitude, $\Delta P/P_c$, < 10 percent.

0.1 in. (2.54 mm)



(b) Oscillatory amplitude, $\Delta P/P_c$, 10 to 20 percent.



(c) Oscillatory amplitude, $\Delta P/P_c$, > 40 percent.

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Figure 13. - Silhouette photographs of triplet elements. Injection, fuel-oxidant-fuel; center jet shielded.

The stability improvement obtained by extending the center jet tube in each element was shown in figures 10(a) and (b). The photographs of the modified F-O-F injection arrangement show the transition from stable to unstable combustion (fig. 13). During stable combustion (fig. 13(a)), the outer jets impinge on the end of the center tube. As the transverse gas flow is increased (fig. 13(b)), the impingement of the outer jets moves to the side. At the highest amplitude of oscillation, the outer fuel jets atomize and decompose in a region next to the center jet; the center jet continues unbroken for a considerable distance downstream (fig. 13(c)). The impingement of the outer jets again becomes centered on the center tube as soon as transverse gas flow is stopped as in figure 13(a). Photographs of the O-F-O injection arrangement are not shown since the jets were obscured by dense NO_2, especially during transverse gas flow. Since the presence of excess NO_2 in the window indicates relatively low temperatures in the impingement zone, the shielded center jet of hydrazine must remain unbroken and unmixed for a considerable distance downstream. The transverse gas flow will, therefore, have little effect on the combustion rate, in agreement with the stability data of figure 10(b).

Analysis of Data

Clark (ref. 8) analyzed the response of single nonreactive jets to a transverse flow of nitrogen. He correlated jet breakup with a model based on progressive spreading of the liquid stream. Initial breakup L_i defined as the point at which the liquid stream is 3 to 5 times its initial width, is written in the form

$$L_i = \frac{D_l U_l}{U_g}\left[\frac{P_l}{P_g}\ (1 \text{ to } 2)\right]^{1/2} \tag{2}$$

Povinelli (ref. 10) analyzed the displacement of liquid jets by a shock wave. The time required to displace the jet a distance equal to its initial diameter can be written as

$$t_{x=d} = \frac{D_l}{U_g}\left(\frac{\rho_l}{\rho_g}\ 1.43\right)^{1/2} \tag{3}$$

The jet length corresponding to that time is

$$L_{x=d} = \frac{D_l U_l}{U_g}\left(\frac{\rho_l}{\rho_g}\ 1.43\right)^{1/2} \tag{4}$$

Although the criteria defining initial breakup distance L_i and displacement length $L_{x=d}$ are different for the two studies, the functional forms are identical and the numerical values are essentially equal so that L_i equals $L_{x=d}$.

The principal variable in equation (4) is gas velocity which, during unstable combustion, can vary widely. The main gas velocity effects considered are (1) the induced transverse flow due to injected nitrogen and (2) the oscillatory transverse flow resulting from the traveling transverse mode of instability. The vector sum of gas and liquid velocities was used in place of the gas velocity alone, as suggested by the experimental results in reference 8. The complete expression for gas velocity is then $(\overline{U}_\theta^2 + \widetilde{U}_{rms}^2 + U_l^2)^{1/2}$, the vector sum of the induced velocity $\overline{U}_\theta$, root-mean-square velocity oscillation $\widetilde{U}_{rms}$, and liquid velocity U_l.

At the beginning of the test run, jet breakup is determined by the liquid velocity. On initiation of the transverse gas flow, first $\overline{U}_\theta$ and finally $\widetilde{U}_{rms}$ become important in determining breakup of the liquid jets. As soon as the transverse oscillatory mode is well established, velocities induced by the acoustic oscillation will far exceed those induced by the transverse nitrogen flow. Initial breakup lengths are plotted in figure 14 as a function of run time. Jet breakup shows similar trends for the two injection patterns where oscillations are coupled to the transverse flow (figs. 14(a) and (b)). Complete or final jet breakup length is approximately $3L_i$. During the coupled oscillatory period, the center jets start breaking up after impingement; side jets start breaking up soon after entering the chamber. This predicted behavior matches the photographed results in figures 11 and 12.

Where oscillations are not coupled to the transverse gas flow, jet breakup varies as shown in figures 14(c) and (d). Initial breakup of the side jets compares closely with initial breakup of the center jets after the oscillation has started. Complete jet breakup occurs in less than 1 inch (2.54 cm) during high-amplitude unstable combustion. Since both fuel and oxidizer jets break up in about the same distance, combustion is more concentrated on the perimeter of the chamber. This behavior contrasts with the extended breakup and distributed combustion of runs where oscillations were coupled to the transverse nitrogen flows.

The earliest disturbance to the side jets during self-coupled oscillatory combustion was approximately 0.1 inch (0.25 cm) after injection (fig. 12). This distance compares with a predicted minimum initial breakup distance of 0.28 inch (0.71 cm).

Final breakup in figure 12 showed a cyclic variation, but averaged 0.6 to 0.7 inch (1.5 to 1.8 cm). From the bushy appearance of the jets, there appear to be many ligaments and drops surrounding the original stream. The true breakup length would therefore be somewhat shorter. Predicted final breakup distance was about 0.84 inch (2.13 cm) for the self-coupled run conditions.

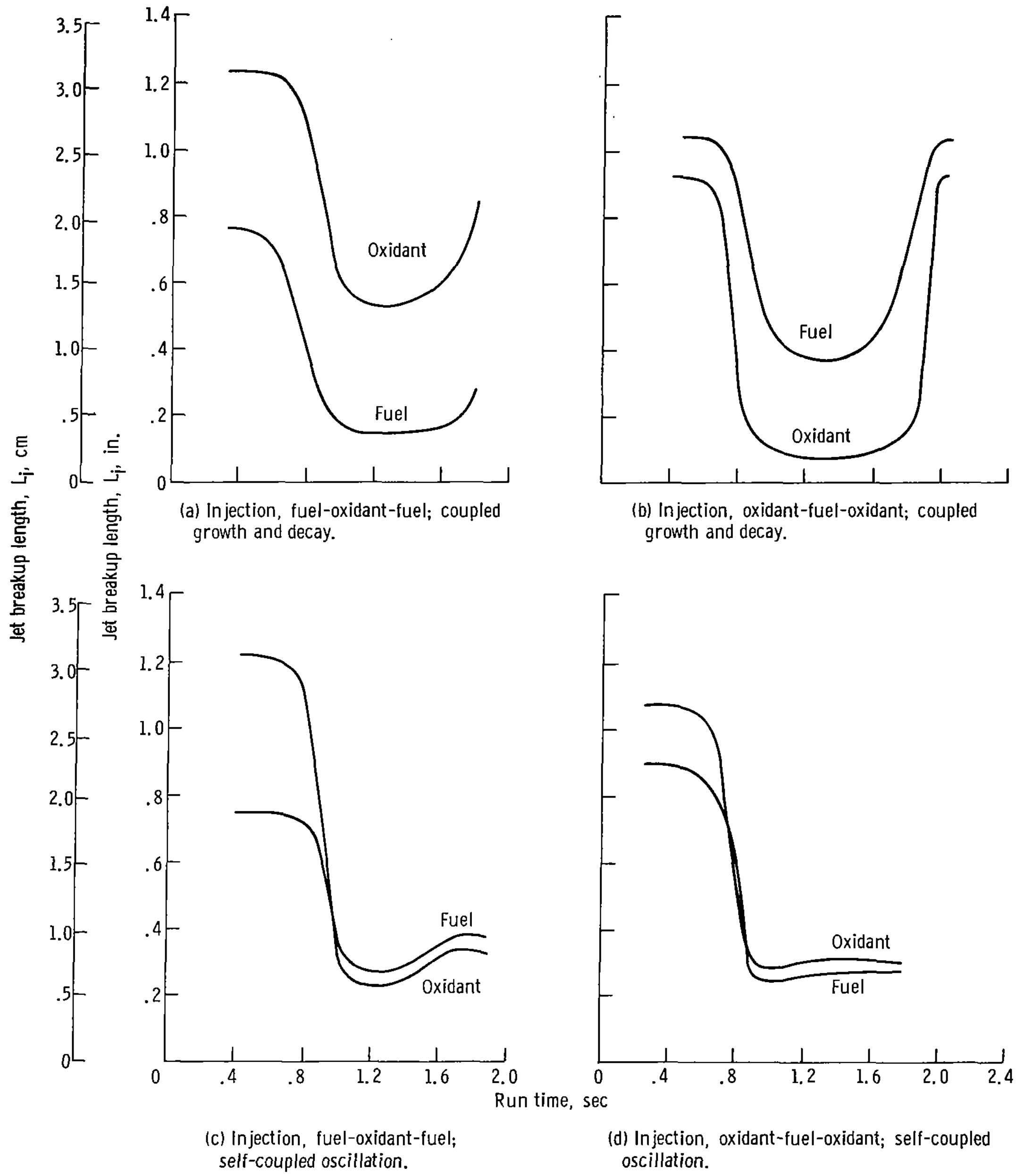

Figure 14. - Jet breakup as function of run time.

The merits of enlarging or lengthening the center tube in each element becomes evident on calculating the new breakup distances. Doubling the area of the center jet also doubles the breakup distance. For the same flow rates that previously produced equal breakup distances in center and outer jets, combustion will now be distributed. Atomization of the center jet will be retarded. Similarly, if the center tube is extended nearly to the impingement point, breakup distances will increase by a like amount, again extending atomization and distributing the combustion.

The results from these combustion tests demonstrate the improvement in stability characteristics which can be obtained by a small injector change. The greater the separation in atomization zones between the two propellants, the greater will be their stability in the presence of transverse flows.

SUMMARY OF RESULTS

The dynamic response of hypergolic propellants to transverse gas flow was evaluated in a two-dimensional combustor at pressures of 150 to 250 psia (103 to 172 N/cm^2 abs). Both fuel-oxidant-fuel and oxidant-fuel-oxidant triplet-type injector patterns were studied, and the tests included altered center jets in each element. The response, in terms of the amplitude of the dynamic pressure oscillation, varied with propellant flows and transverse gas flow induced by a tangential nitrogen jet within the combustor.

1. Two regions of unstable behavior were noted: In one region, the dynamic wave amplitude was coupled to the transverse nitrogen flow similar to previous work using hydrogen and oxygen. In the second region of instability, the dynamic oscillation became self-coupled and was self-sustaining after initiation.

2. The center jet in each element was higher in velocity and slower to atomize than the outer jets for coupled response characteristics. Photographs of a fuel-oxidant-fuel element showed atomization of outer jets to be rapid, especially during instability. Center jet atomization was comparatively slow, even during unstable combustion.

3. Self-coupled response characteristics resulted when initial transverse gas flow caused rapid atomization of both propellant streams near impingement. Combustion became concentrated on the perimeter of the combustor. The high-amplitude instability, once established, no longer required tangential nitrogen flow for sustenance.

4. Increasing the diameter or extending the tube on the center jet in each element improved the stability characteristics of the combustor. Jet breakup, atomization, vaporization, and combustion were correspondingly distributed over a larger volume and reduced the in-phase driving of the transverse oscillation.

5. Predicted atomization of the jets in each element was calculated as a function of run time and compared with the observed breakup characteristics in photographs. Calculated breakup lengths were somewhat longer than the observed breakup distances in the photographs. Atomization is retarded when the jet diameter is increased or the tube containing the jet is extended.

CONCLUDING REMARKS

Heidmann and Feiler (ref. 7) pointed out the extreme sensitivity of atomization and vaporization to a small transverse gas velocity in a hydrogen-oxygen combustor. The hydrazine - nitrogen tetroxide combustor in the present study was insensitive to very low transverse gas velocities. At higher velocities, the instability appeared to be a velocity-sensitive process for runs with coupled response. Hypergolic propellants were therefore similar to nonhypergolic propellants in their response to transverse gas flow. Atomization could be the rate-limiting process for all types of propellants. The decomposition of hydrazine could add sufficient in-phase driving to sustain the oscillations, once they were started.

Because triplet elements were used in this study, the propellant flows in the outer tubes of each element contained both axial and transverse velocity components. For an included angle of 40° between the outer jets, a maximum transverse velocity of 36 percent of the axial jet velocity can result from an extreme perturbation in flow or impingement. Self-induced velocities in the present combustor were not large enough to cause intrinsic combustion instability. However, in a larger combustor with close spacing of injector elements, any periodic variation of atomization can be amplified by the velocity perturbations and decomposition characteristics of hydrazine. Combustion can then become a self-sustained unstable process. This report showed the relatively large effect on stability produced by a small change in the injector. To help preclude the generation of nonaxial flows which can lead to self-sustained combustion oscillations, attention must be given to the details of element design, size, and placement on the injector face.

Lewis Research Center
National Aeronautics and Space Administration,
Cleveland, Ohio, December 13, 1968,
128-31-06-02-22.

APPENDIX - SYMBOLS

A_n	nitrogen orifice area
D_l	liquid jet diameter
g	gravitational constant
L_i	initial breakup length of liquid jet
$L_{x=d}$	length of jet displaced one diameter
ΔP	dynamic pressure amplitude
P_c	combustor pressure
$t_{x=d}$	time to displace jet a distance equal to its initial diameter
U_F	liquid fuel velocity
U_g	gas velocity
U_l	liquid jet velocity
U_n	nitrogen gas velocity
U_O	liquid oxidant velocity
$\tilde{U}_{rms}$	root-mean-square velocity oscillation
$\overline{U}_\theta$	mean transverse gas velocity
w_n	nitrogen gas flow rate
w_t	total gas flow rate
ρ_g	gas density
ρ_l	liquid density

REFERENCES

1. Heidmann, Marcus F.; and Wieber, Paul R.: Analysis of Frequency Response Characteristics of Propellant Vaporization. NASA TN D-3749, 1966.
2. Strahle, Warren C.: A Theoretical Study of Unsteady Droplet Burning: Transients and Periodic Solutions. Aeron. Eng. Rep. 671, Princeton Univ. (NASA CR-55516), 1963.
3. Feiler, Charles E.; and Heidmann, Marcus F.: Dynamic Response of Gaseous-Hydrogen Flow System and its Application to High-Frequency Combustion Instability. NASA TN D-4040, 1967.
4. Heidmann, M. F.; and Groeneweg, J. F.: Dynamic Response of Liquid Jet Breakup. AIAA J., vol. 6, no. 10, Oct. 1968, pp. 2033-2035.
5. Kushida, Raymond; and Houseman, John: Criteria for Separation of Impinging Streams of Hypergolic Propellants. Paper No. 67-38, Western States Section, Combustion Inst., Oct. 1967.
6. Burrows, Marshall C.: Mixing and Reaction Studies of Hydrazine and Nitrogen Tetroxide using Photographic and Spectral Techniques. NASA TN D-4467, 1968.
7. Heidmann, Marcus F.; and Feiler, Charles E.: Evaluation of Tangential Velocity Effects on Spinning Transverse Combustion Instability. NASA TN D-3406, 1966.
8. Clark, Bruce J.: Breakup of a Liquid Jet in a Transverse Flow of Gas. NASA TN D-2424, 1964.
9. Heidmann, Marcus F.: Oxygen-Jet Behavior During Combustion Instability in a Two-Dimensional Combustor. NASA TN D-2725, 1965.
10. Heidmann, Marcus F.: Oscillatory Combustion of a Liquid-Oxygen Jet with Gaseous Hydrogen. NASA TN D-2753 1965.
11. Hersch, Martin: Performance and Stability Characteristics of Nitrogen Tetroxide-Hydrazine Combustors. NASA TN D-4776, 1968.
12. Povinelli, Frederick P.: Displacement of Disintegrating Liquid Jets in Crossflow. NASA TN D-4334, 1968.

NASA-Langley, 1969 —— 27 E-4599