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An Experimental Investigation of the Effects of Combustion on the Mixing of Highly Reactive Liquid Propellants

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ABSTRACT

The effects of combustion on the liquid-phase mixing of several storable liquid bipropellants were investigated. It was found that combustion effects were severe when nitrogen tetroxide was used as the oxidizer with various storable fuels, including hydrazine, unsymmetrical dimethylhydrazine, and monomethylhydrazine. Other combinations tested were found to be less affected by the combustion process. Several attempts were made to induce propellant mixing by mechanical means, and the effects of chemical inhibitors on the mixing process were investigated. None of the mechanical and chemical techniques studied influenced the prereaction mixing of the propellants to an appreciable extent.

I. INTRODUCTION

To achieve high performance in a liquid-bipropellant rocket engine, it is necessary to obtain good mixing of the two propellants in the combustion chamber. Mixing can result directly from the hydraulic injection process (primary, or liquid–liquid, mixing) or from the mixing action of the high-velocity combustion products (secondary, or liquid–gas, mixing). This Report is concerned with the primary mixing of the propellants.

The results of the primary mixing process can be evaluated with nonreactive fluids (Ref. 1) if it can be assumed that the combustion process will have a negligible effect on the mixing process when the actual propellants are used. The results of the experiments described in this Report establish the fact that combustion can have a major effect on the primary mixing process of several hypergolic propellants.

II. INVESTIGATION OF 2000-LB-THRUST SINGLE-ELEMENT THROTTLABLE INJECTOR

A. Injector Design

The experiments described in this Section were conducted as part of the injector development effort in the *Advanced Liquid Propulsion Systems* (ALPS) program. The ALPS injector was required to be throttlable over a 10-to-1 thrust range, space-storable, and restartable. The nominal flow rate of this injector was 6.67 lbm/sec at a design chamber pressure of 150 psia. To simplify the system, and thus promote reliability, it was decided to use a single-element injector.

The ALPS system was designed to use the nitrogen tetroxide and hydrazine (N_2O_4–N_2H_4) propellant combination at a mixture ratio of 1.2. However, the first

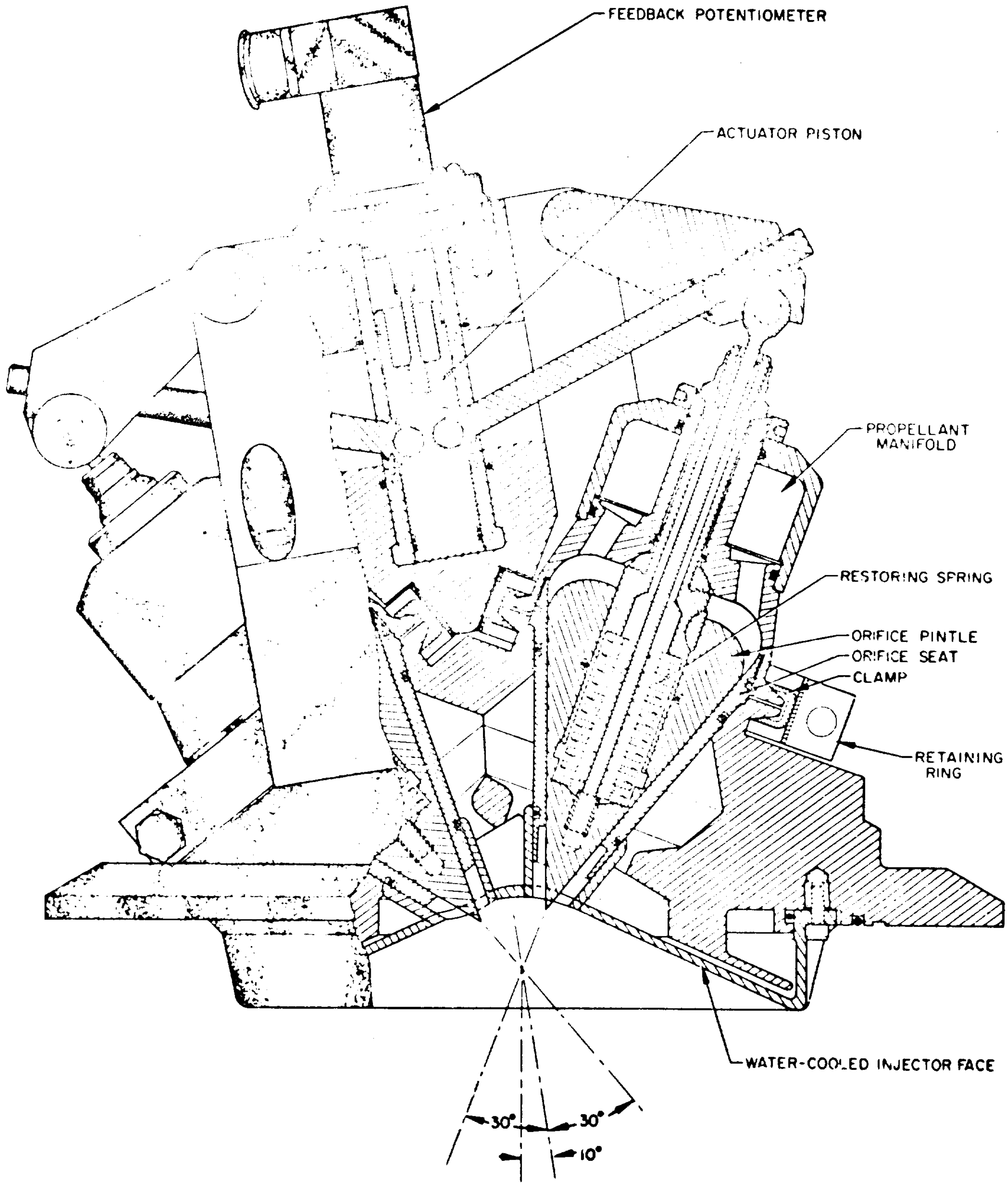


Fig. 1. Configuration of 2000-lb-thrust throttlable injector

injector was designed to burn unsymmetrical dimethylhydrazine (UDMH) as the fuel at a mixture ratio of 2.5. It was believed that the N_2O_4–UDMH combination would be smoother-burning and thus more suitable for early tests with the ALPS pyrolytic graphite thrust chambers that were under development.

An impinging-jet doublet element was chosen for this injector (Fig. 1). In each orifice, the flow was throttled by a conical pintle, which was moved along the flow axis to vary the annular flow area. The use of interchangeable orifice seats allowed the orifice-exit area ratio (oxidizer/fuel) to be varied from unity for N_2O_4–N_2H_4 to 2.2 for N_2O_4–UDMH. These values of the orifice area ratio were such that the resulting jets satisfied Rupe's uniformity criterion (Ref. 2) for nominal mixture ratios of 1.2 with N_2O_4–N_2H_4 and 2.5 with N_2O_4–UDMH. In operation, the annular liquid stream coalesces at the pointed exit end of the conical pintle into a solid cylindrical jet which looks much like the jet produced by a conventional orifice. The velocity profile of the jet coming off the pintle, however, has a double peak with a depressed value along the centerline. The double maximum in the jet velocity profile, as contrasted with the single peak in the profile of a jet from a conventional orifice, does not appear to have an appreciable effect on the spray properties of the element.

The spray properties of the single-element throttlable injector were measured in a hydraulic spray facility, described in Ref. 3. Nonreactive fluids were used to simulate both the N_2O_4–UDMH and the N_2O_4–N_2H_4 propellant combinations. The mass and mixture-ratio distributions of nonreactive fluids simulating the N_2O_4–UDMH and N_2O_4–N_2H_4 sprays produced by this injector are shown, respectively, in Figs. 2 and 3. A computation was performed which indicated that 97 and 94% of theoretical characteristic velocity c^* could be realized with N_2O_4–UDMH and N_2O_4–N_2H_4, respectively, if it is assumed that the reaction goes to completion at each local value of mixture ratio.

Similar tests were made with an element having the same impingement angle, orifice areas, and free-jet lengths as the N_2O_4–UDMH element described above, but incorporating conventional orifices with length-to-diameter ratios of 100. For these elements, it appears that the velocity profile of the jets had little effect on the mass and mixture-ratio distributions in the resultant sprays. The spray properties were similar to those of the dual-pintle elements.

B. Test Results

The first series of firings was conducted with the N_2O_4–UDMH propellant combination in an 8-in.-diameter uncooled chamber having a characteristic length L^* of 40 in. and a contraction area ratio of 4.65. Characteristic velocities of approximately 2100 ft/sec were measured. This value is approximately 38% of theoretical shifting c^* for these operating conditions. To determine the effect of L^*, a section 20 in. in length was added to the chamber, increasing the L^* to 170 in. With this modification, the performance increased to about 54% of theoretical c^*.

The interchangeable orifice seats were then replaced to provide orifices having equal flow areas, and the injector was fired in the 170-in.-L^* chamber with the N_2O_4–N_2H_4 propellant combination. The measured c^* at nominal flow rate and mixture ratio was 3800 ft/sec, which is 65% of theoretical c^* at that mixture ratio.

When the N_2O_4–N_2H_4 propellant combination was used, the performance of this injector varied considerably with both flow rate and mixture ratio, as shown in Figs. 4 and 5. Because the injector was designed for N_2O_4–UDMH, the bisector of the angle between the orifices was 10 deg off the chamber axis. For the propellant combination N_2O_4–N_2H_4 at a mixture ratio of 1.2, and with equal orifice areas, this bisector is coincident with the resultant momentum line. The injector could thus be fired in two configurations with N_2O_4–N_2H_4: that is, the fuel orifice could be oriented 40 deg from the chamber axis and the oxidizer orifice 20 deg, or vice versa. The effects of this variation can be seen in Figs. 4 and 5. For both configurations, peak performance was attained at a low mixture ratio and reached 92% of theoretical c^* at rated flow. Tests also showed that a 25% increase in jet velocities had no effect on c^* at the nominal mixture ratio of 1.2; at a mixture ratio of 0.7, the higher velocity produced a 3% increase in performance.

A few tests were also made with injectors having unequal orifice areas (Fig. 6); i.e., one orifice-exit area was held at the nominal value while the other was decreased. These results show that minimum performance was obtained at the design area ratio of unity. The maximum c^* measured was 4830 ft/sec (83% of theoretical) at an area ratio A_o/A_f of 0.7. It was postulated that the low performance of this injector was caused by extremely rapid liquid-phase reactions between the fuel and oxidizer, which disrupted the impingement and mixing processes.

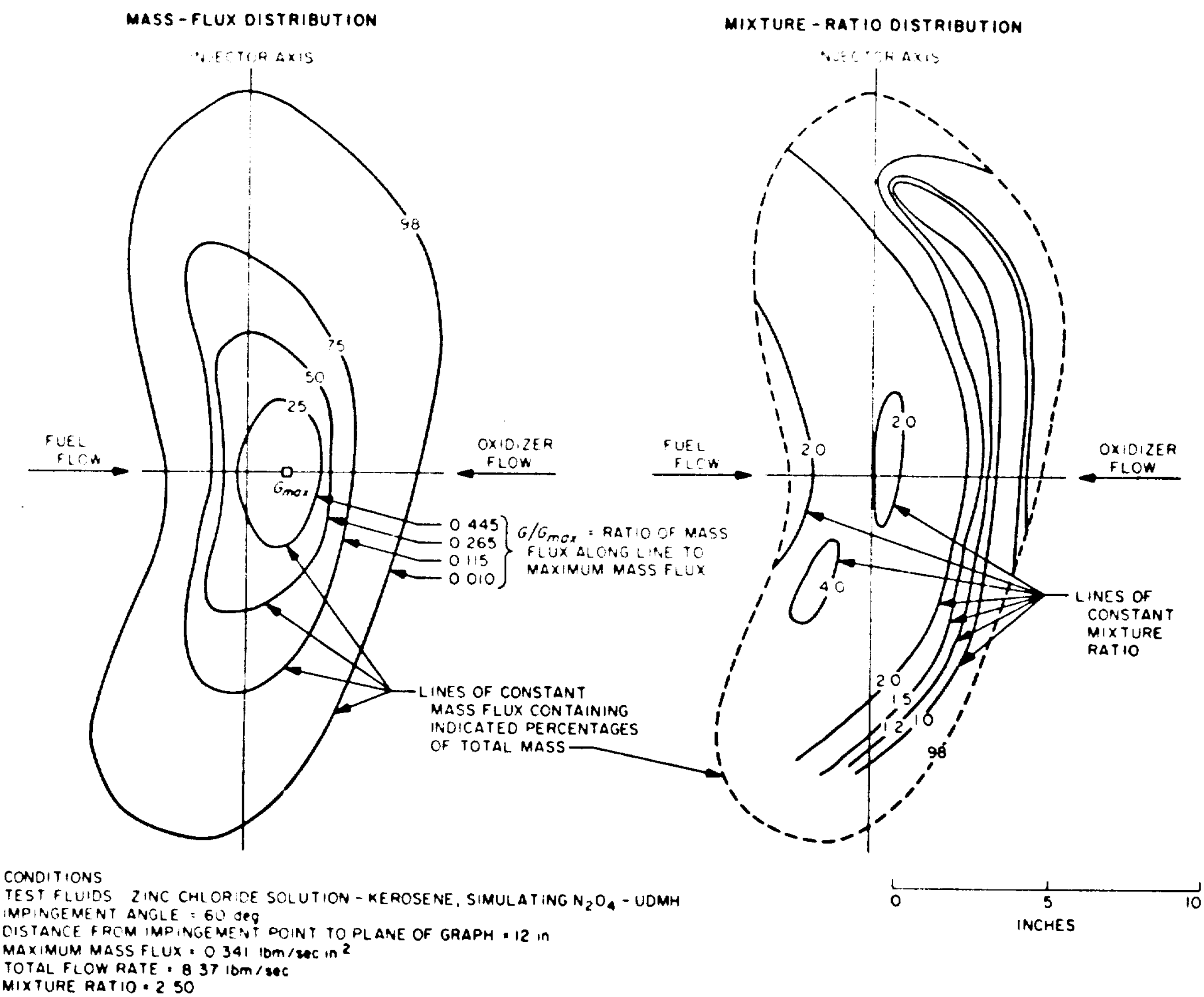


Fig. 2. Nonreactive-spray properties of 2000-lb-thrust throttlable injector with simulated N_2O_4–UDMH propellants

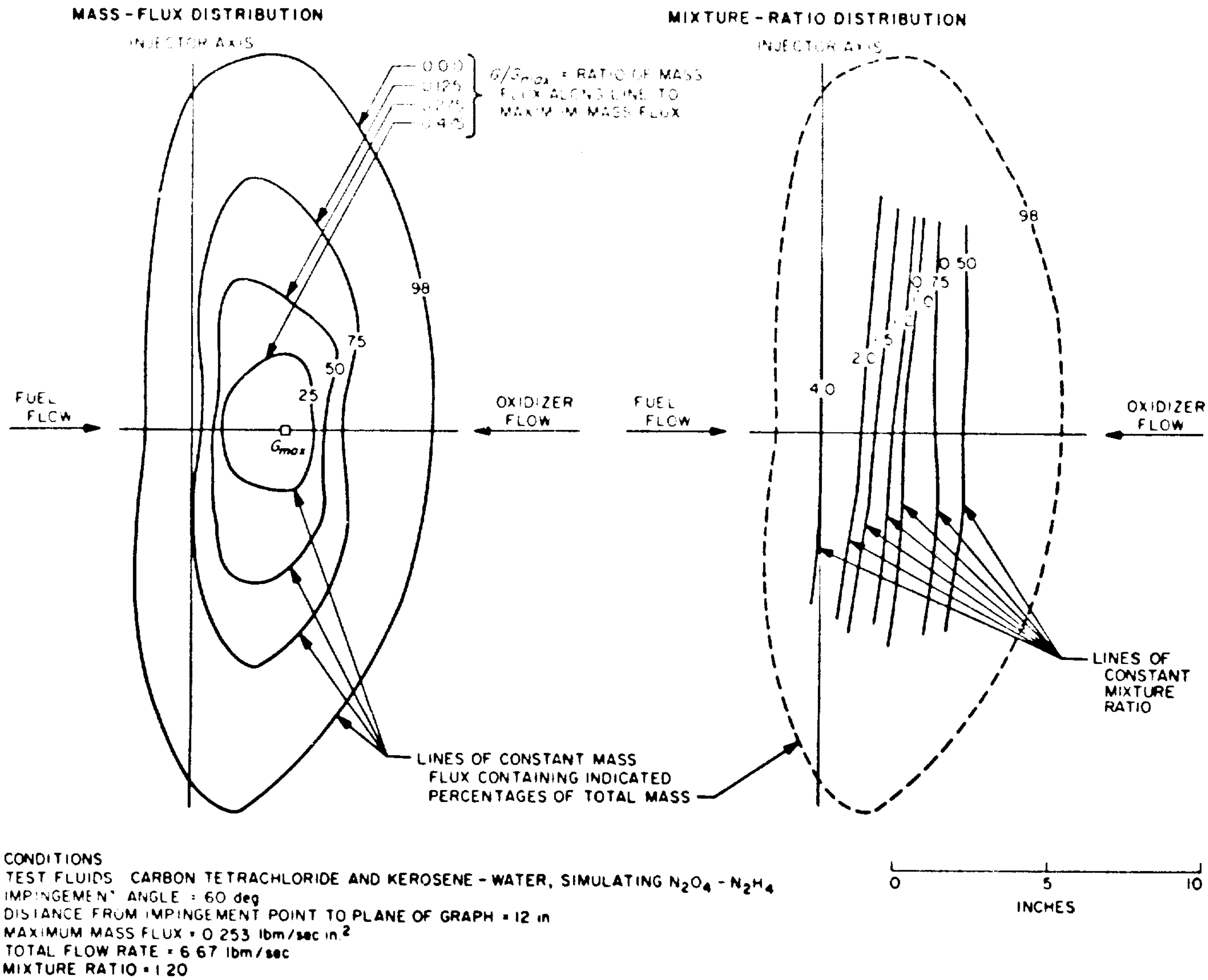


Fig. 3. Nonreactive-spray properties of 2000-lb-thrust throttlable injector with simulated N_2O_4–N_2H_4 propellants

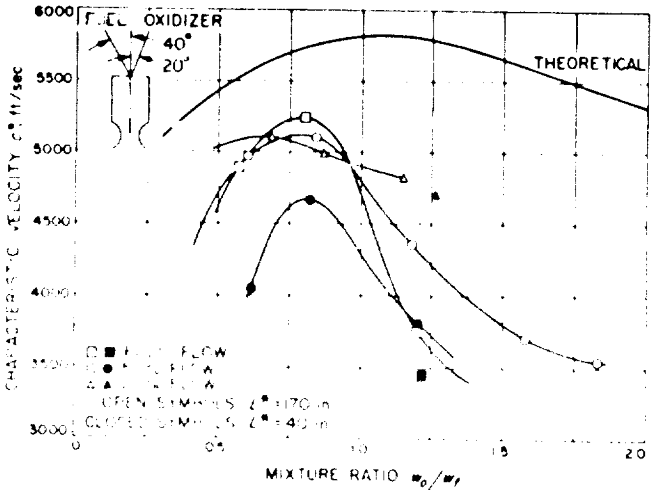


Fig. 4. Performance of 2000-lb-thrust throttlable injector with fuel orifice at 40-deg angle from chamber axis

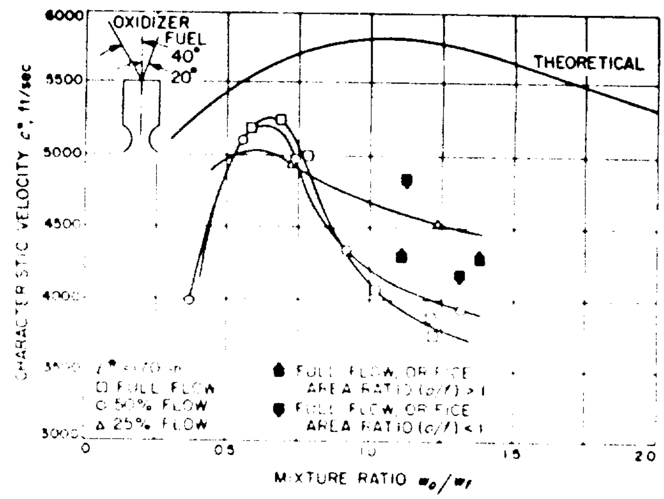


Fig. 5. Performance of 2000-lb-thrust throttlable injector with oxidizer orifice at 40-deg angle from chamber axis

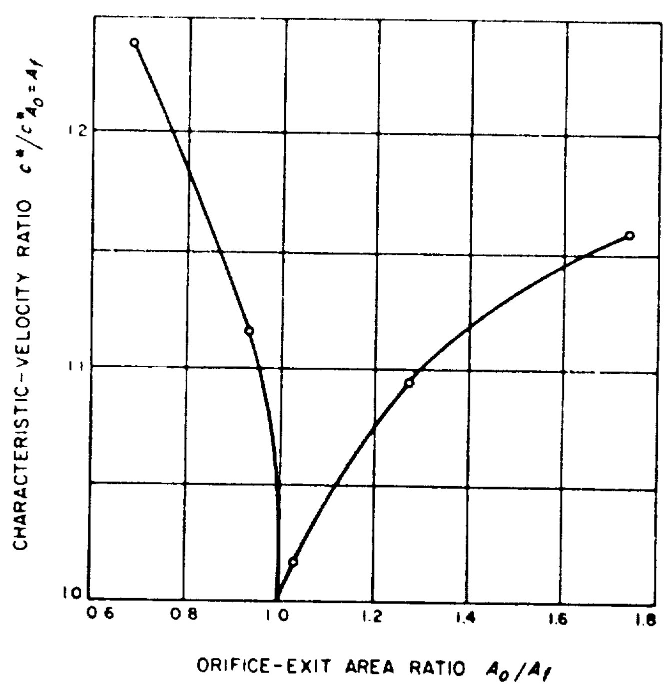


Fig. 6. Variation in performance with orifice-exit ratio for 2000-lb-thrust throttlable injector

III. COMBUSTION-EFFECTS EXPERIMENT

In Ref. 4, Elverum reported evidence that rapid liquid-phase reactions radically affect the mixing of N_2O_4 and N_2H_4. His evidence, however, consisted primarily of color photographs which were subject to differing interpretations, since no means existed for determining the mass flows in the regions which appeared to be oxidizer-rich (red) and fuel-rich (yellow). It could be argued that excesses of one propellant representing only a small fraction of the total flow rate could cause the observed colorations. A determination whether such phenomena could exert a major influence on mixing was obviously of great importance to ALPS injector development. The most definitive method of settling this question would have been to measure the local mass and mixture-ratio distribution in the combustion zone. This, however, would have required the development of suitable measuring techniques in a research effort beyond the scope of the ALPS program. Therefore, the simple experiment described below was designed to determine whether or not the mixing of the propellant streams was strongly affected by combustion.

A. Test Apparatus and Procedure

The apparatus used in the combustion-effects tests is shown in Fig. 7. The injector consisted of two 0.236-in.-ID straight tubes having a length-to-diameter ratio (L/D) of 50. These were mounted in a flat plate to form 30-deg angles with the chamber axis. The free-jet length to the impingement point was 0.944 in. With N_2O_4–N_2H_4 propellants at a mixture ratio of 1.2, the momenta of the two jets were equal. The nonreactive-spray mass and mixture-ratio distributions produced by this element are shown in Fig. 8.

The 170-in.-L^* chamber described above was used in the combustion-effects experiment. Provision was made for mounting a flat baffle plate along the chamber axis to divide the chamber into two channels of equal volume. With the baffle in place, the throat area was reduced, thus increasing the L^* to 187 in. The top of the baffle was placed 10 in. from the injector plate, in order to avoid interference with the impingement process, and the bottom of the baffle was in the plane of the nozzle throat. In the event of an extremely rapid reaction (in which the propellant jets flowing from the main injector would be repelled from each other to form a fuel-rich zone on the fuel-orifice side and an oxidizer-rich zone on the oxidizer-orifice side of the chamber), a baffle located in a plane perpendicular to the plane of the two orifices should prevent secondary mixing due to turbulence and diffusion. Two full-cone spray nozzles were located in the chamber wall, one on each side of the baffle, 15 in. from the injector plate. Provision was also made to mount turbulence rings in the chamber, downstream of the spray nozzles.

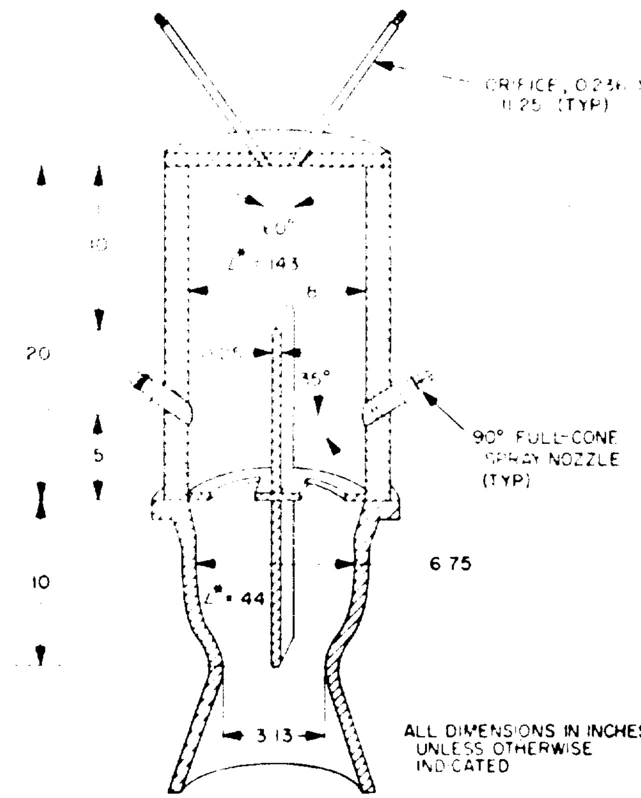
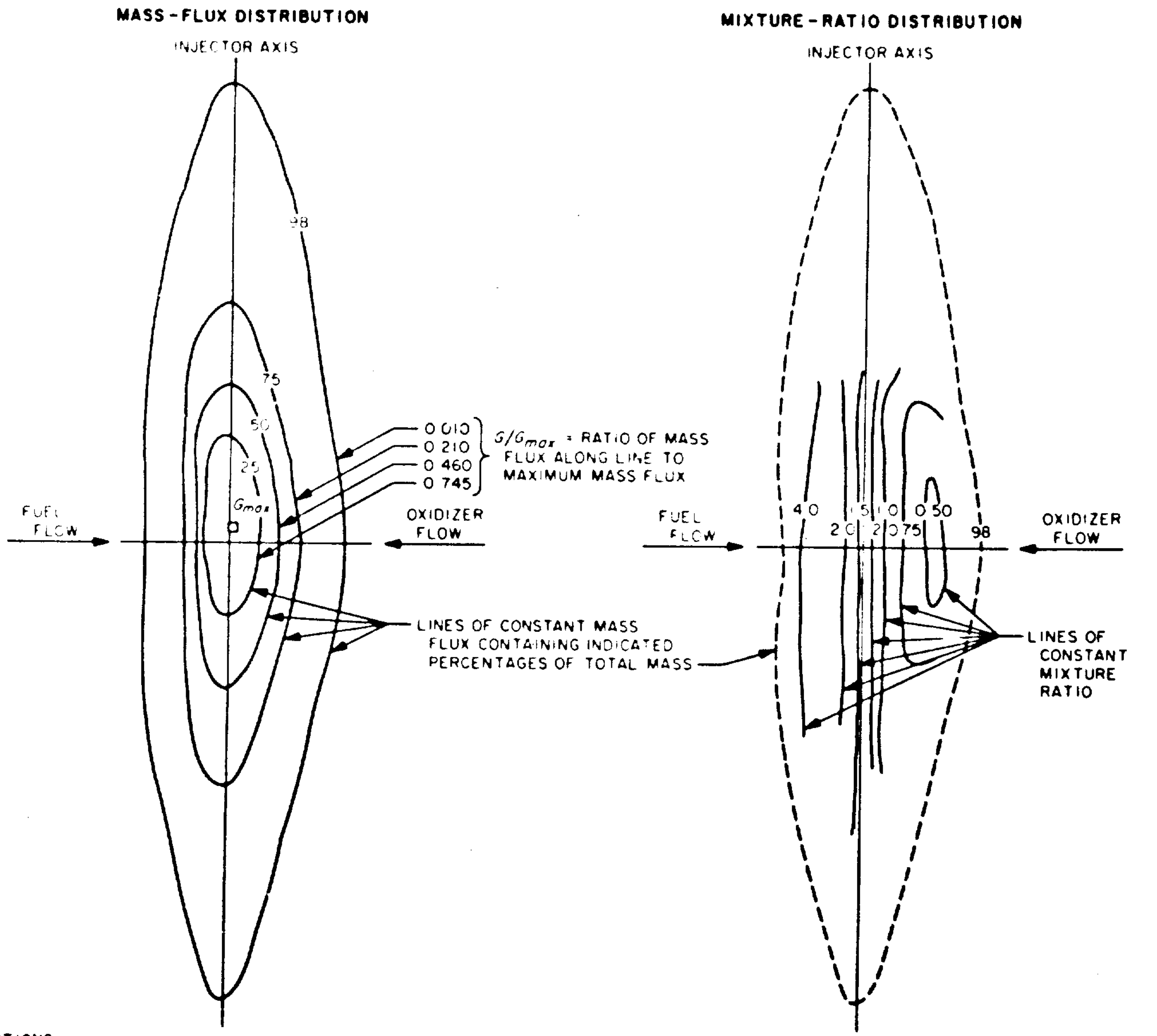


Fig. 7. Combustion-effects test apparatus

The experiment was conducted by measuring the difference in performance obtained when the propellants sprayed from the side nozzles were reversed. The hypothesis for the experimental procedure was as follows: if the streams are repelled, as postulated, then spraying oxidizer into the fuel-rich gases and fuel into the oxidizer-rich gases (labeled *opposite* in Fig. 9) should increase performance; spraying fuel into fuel-rich gases and oxidizer into oxidizer-rich gases (labeled *like* in Fig. 9) should reduce performance; if the streams from the main



CONDITIONS
TEST FLUIDS TRICHLOROETHYLENE - WATER, SIMULATING $N_2O_4 - N_2H_4$
IMPINGEMENT ANGLE = 60 deg
DISTANCE FROM IMPINGEMENT POINT TO PLANE OF GRAPH = 12 in.
MAXIMUM MASS FLUX = 0.142 lbm/sec in.^{2}
TOTAL FLOW RATE = 4.22 lbm/sec
MIXTURE RATIO = 1.22

Fig. 8. Nonreactive-spray properties of injector used in combustion-effects test apparatus

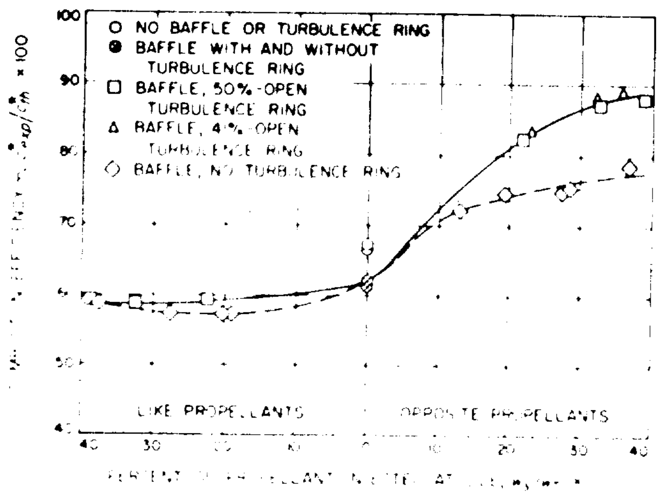


Fig. 9. Combustion-effects test results for N_2O_4–N_2H_4 propellants

injector are not repelled, and if a nearly uniform mixture-ratio distribution exists in the chamber, then performance should remain relatively unchanged when the propellant sprays are reversed; if the streams penetrate through each other, then the fuel-rich and oxidizer-rich channels will be reversed, and the performance changes should indicate this condition, also.

To minimize the variables, the main-injector flow rate was maintained for all tests at a level of 4.2 lbm/sec. This value was chosen to yield a total flow rate of 6.67 lbm/sec at the side flow rates expected to give maximum performance. The side flow rates from the spray nozzles were varied to maintain a constant overall mixture ratio. The amount of side flow needed to maximize performance was an indication of the degree of mixture-ratio maldistribution resulting from disturbances in the impingement zone. Performance changes were accompanied by chamber-pressure changes; however, over the limited range encountered, the chamber-pressure effect was believed to be of second order.

B. Test Results with N_2O_4–N_2H_4 Propellant Combination

The results of these tests indicate that the propellant streams reacted strongly and repelled each other at the impingement point. The severity of the resulting mixture-ratio maldistribution is illustrated in Fig. 9, where it is seen that combined side flow rates $\dot{w}_s$ equal to 40% or more of the total overall flow rate $\dot{w}_T$ were required to maximize performance.

To check the experiment, the apparatus was tested with the injector rotated 90 deg with respect to the chamber. The baffle was then in the plane of the orifices and, by symmetry, separated the main-injector propellant spray into two regions, each a mirror image of the other. Each region thus had the same bulk mixture ratio as the other, with equivalent mass and mixture-ratio distributions.

With this configuration, maximum performance was 75% of theoretical, realized when no side sprays were used. With side flows representing 33% of the total flow rate, performance dropped to 72%, and to 73% when the side sprays were reversed. Since the original turbulence rings were not sufficiently effective in promoting mixing, a test was made without side sprays, but with a turbulence ring having smaller holes (23% open area compared with the 41% open area normally used). The smaller holes, however, increased performance by only 3% (78% of theoretical).

After some of the tests made with the baffle in place, it was noticed that the baffle was bowed by as much as 0.20 in. in the region of the throat, probably because of thermal expansion in the constrained material. To determine whether the test results were appreciably affected by this change in configuration, the baffle was removed and the auxiliary spray nozzles were mounted on the injector plate. Each nozzle was mounted in the plane of the injector orifices, parallel to its neighboring injector orifice. The tips of the nozzles extended ½ in. into the chamber from the injector plate and were located 2.5 in. from the injector centerline. The test results were essentially identical with those of the previous tests, in which the baffle had been used and the spray nozzles had been mounted along the chamber wall. An upward shift in performance was noted, probably due to increased secondary mixing. A single test was made without the combustion-chamber extension section, so that the chamber L^* was reduced from 170 to 40 in. In this case, with 36% of the total propellant injected through the spray nozzles, performance dropped from 92 to 84% of theoretical c^*

In two tests made as above, auxiliary spray nozzles were used to produce a very flat spray rather than a full-cone spray. The major axes of the flat sprays were located perpendicular to the plane of the spray nozzles. Performance with the flat sprays was about 2% higher than that obtained with the full-cone sprays.

C. *Test Results with Propellants Other Than N_2O_4–N_2H_4*

The test results presented above indicate that the impingement and mixing processes in a single-element doublet using N_2O_4–N_2H_4 propellants are strongly affected by combustion. (The effects of flow rate, velocity, and jet diameter were not investigated.) Several other propellant combinations were tested with the combustion-effects apparatus: N_2O_4–UDMH, N_2O_4–monomethylhydrazine (MMH), *Corporal* propellant (a fuel containing, by weight, 46.5% aniline, 46.5% furfuryl alcohol, 7% hydrazine, and an oxidizer containing 83.5% nitric acid, 13% nitrogen dioxide, 3% water, and 0.5% hydrofluoric acid), and N_2O_4–furfuryl alcohol. In each case, the propellant flow rate through the main injector was 4.2 lbm/sec. The mixture ratio was chosen to give equal jet momenta for the fuel and the oxidizer when equal orifice areas were used.

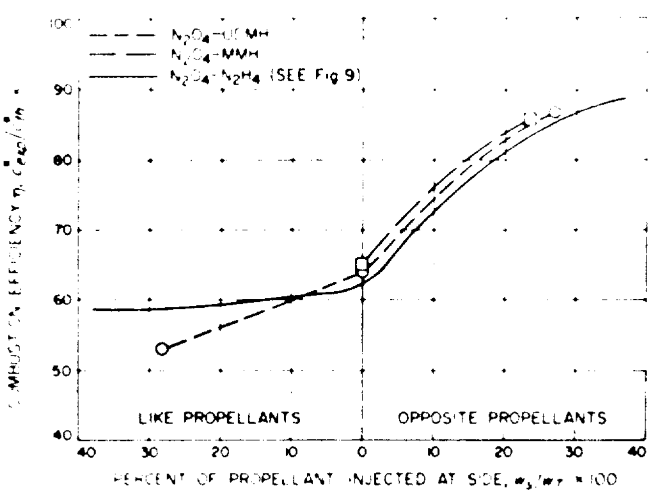


Fig. 10. Combustion-effects test results for N_2O_4–UDMH and N_2O_4–MMH propellants

As shown in Fig. 10, the N_2O_4–UDMH and N_2O_4–MMH propellant combinations produced essentially the same results as those obtained with N_2O_4–N_2H_4, again indicating strong effects of combustion on the mixing process. The *Corporal* propellant combination was tested because its reactions are apparently slower than those of N_2O_4 with the hydrazine family. Reported ignition-delay times for the *Corporal* propellant vary from 10 to 30 msec, whereas N_2O_4–N_2H_4 has an ignition-delay time of about 3.0 msec (see Section IV-B). Test results with the *Corporal* propellant combination (Fig. 11) indicate that the effect of combustion on the impingement process was less than that observed with the N_2O_4–hydrazine-family combinations; performance without side sprays was higher, and less side flow was required for maximum performance. In tests with N_2O_4–furfuryl alcohol, a nonhypergolic combination, an aniline start slug was used for ignition. The results for this combination (Fig. 12) indicate that the propellants penetrate each other in a manner similar to that observed with nonreactive fluids in the spray facility; the impingement process does not seem to be affected by combustion.

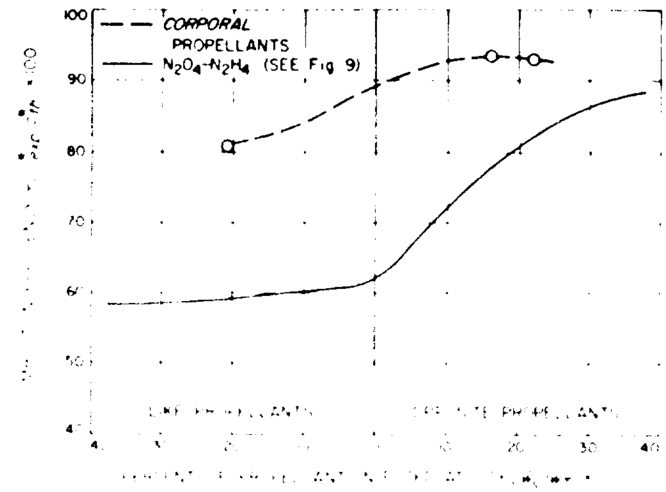


Fig. 11. Combustion-effects test results for *Corporal* propellant

Thus, it appears that the effects of combustion on the mixing process can be related to the ignition-delay time, and that propellant combinations having shorter ignition-delay times show greater combustion effects.

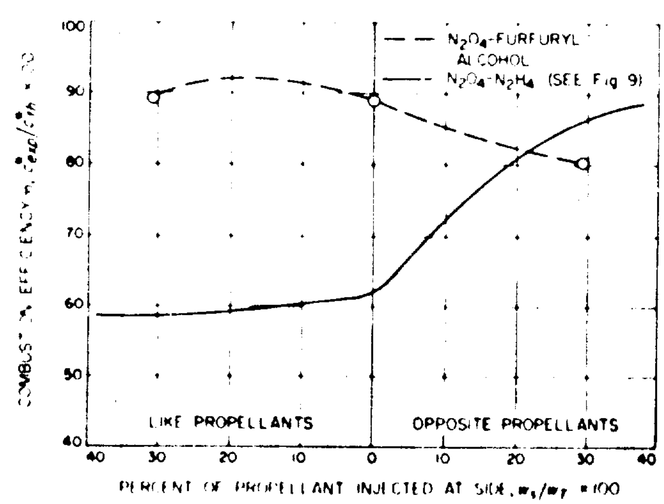


Fig. 12. Combustion-effects test results for N_2O_4–furfuryl alcohol propellants

IV. ATTEMPTS TO REDUCE EFFECTS OF COMBUSTION ON MIXING

A. Mechanical Methods

In the course of the ALPS injector development program several approaches were taken in an effort to decrease the effects of combustion on the impingement and mixing processes of a single-element doublet injector using the propellant combination N_2O_4–N_2H_4.

In an attempt to increase the mixing of these propellants, a pair of vaned orifices was fabricated with the same exit areas as the 0.236-in.-diameter orifices used previously. The purpose of the vanes was to produce a velocity profile having several maxima and minima. It was predicted that, when the impingement of these jets was such that the maxima of one jet velocity profile were aligned with the minima of the other (Fig. 13), more thorough mixing would result, both in the impingement process and in the secondary combustion-chamber mixing. However, when this element was tested with and without side sprays in the apparatus shown in Fig. 10, the results were the same (within 3%) as those obtained when long orifices were used without vanes. The nonreactive mass and mixture-ratio distributions produced by this element are shown in Fig. 14. It is interesting to note that these changes in the jet properties had such a negligible effect on the performance of the element.

In another attempt at improved mixing, four parallel fuel jets were arranged side by side and directed against a similar arrangement of oxidizer jets so that the jets interlaced. This orifice arrangement is shown in Fig. 15. The total flow area for each set of orifices was equal to that of a 0.236 in.-diameter orifice. The two sets of elements were fabricated with spacings between jets of 1/4 and 1/2 jet diameters (1/4 D and 1/2 D). Also, the elements could be rotated so that the jet centerlines would impinge rather than interlace. The nonreactive mass and mixture-ratio distributions produced by these elements are shown in Figs. 16 to 18. Three tests were made of these elements, with the following variations: (1) 1/2-D spacing, jets interlacing, (2) 1/2-D spacing, jets impinging, and (3) 1/4-D spacing, jets interlacing. The combustion efficiency η (c^*_{exp}/c^*_{th}) measured for these elements in the 170-in.-L^* chamber, at a flow rate of 4.2 lbm/sec and a mixture ratio of 1.2, was 75% with the 1/2-D interlacing-jet geometry, 73% with the 1/2-D impinging jets, and 73% with the 1/4-D interlacing jets. Thus, despite the drastic changes produced in the nonreactive-spray properties, the combustion efficiency was insensitive to the changes made in this element.

In another effort to reduce the effects of combustion on the impingement process, a series of tests was conducted with impinging full-cone spray nozzles.[1] Computations based on nonreactive-spray tests with these

[1] Commercial nozzles (type 1HSS7 Full Jet) manufactured by Spraying Systems Co., Bellwood, Ill., modified for mounting in the injector.

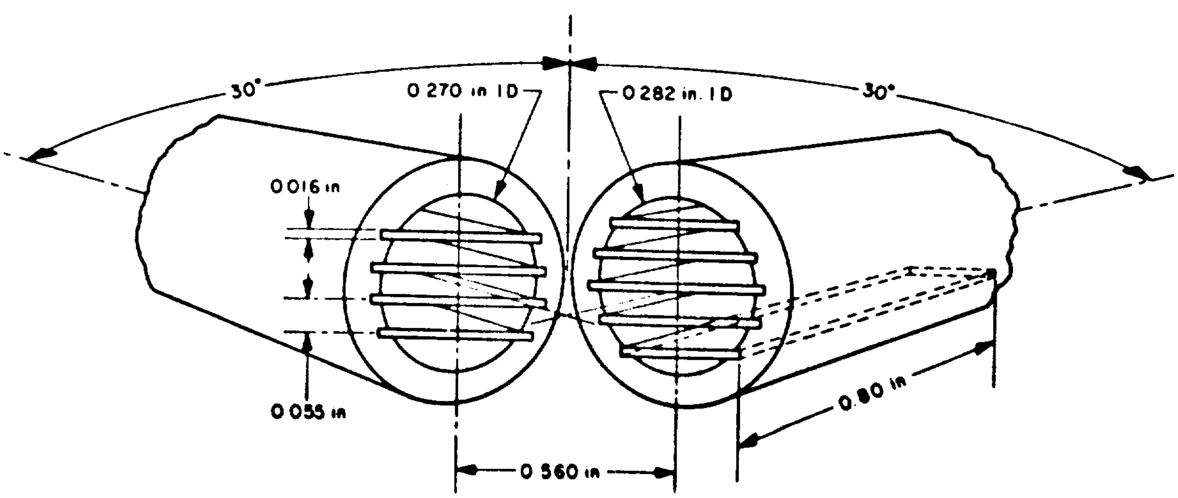
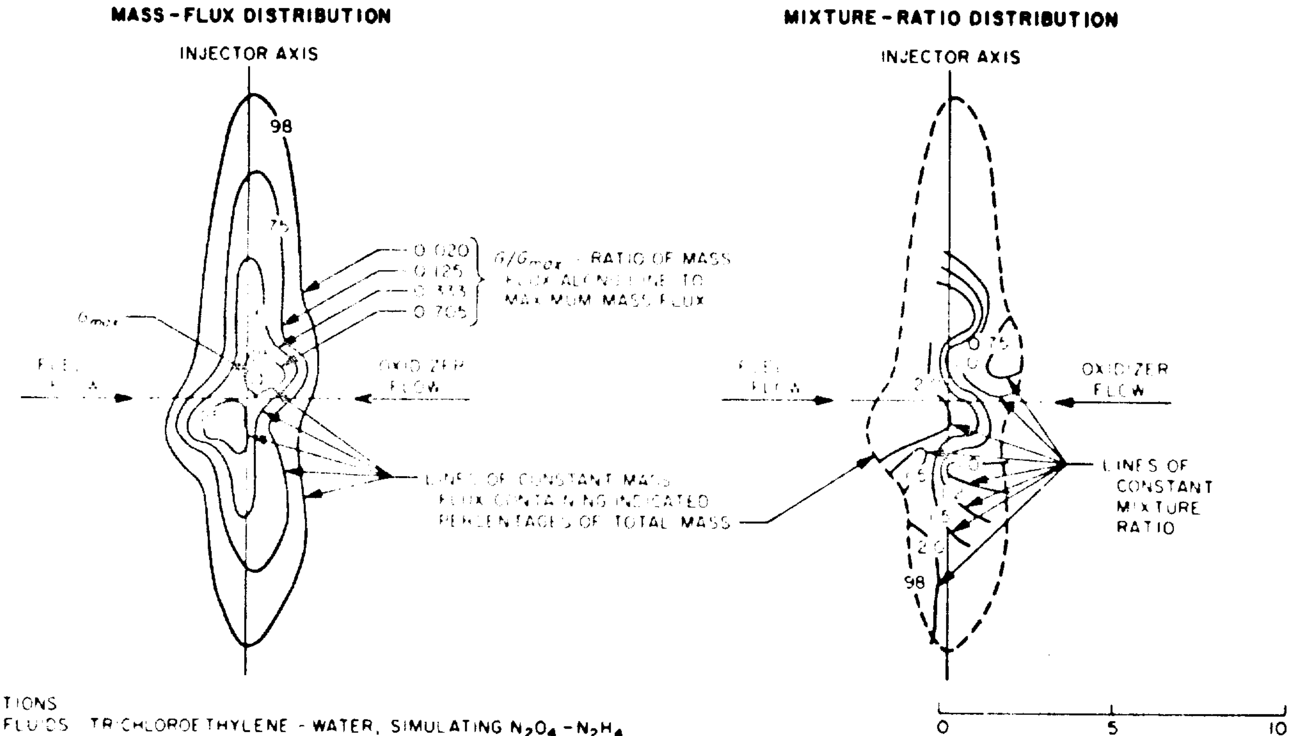


Fig. 13. Doublet injector element with vaned orifices



CONDITIONS
TEST FLUIDS: TRICHLOROETHYLENE - WATER, SIMULATING N_2O_4 - N_2H_4
IMPINGEMENT ANGLE = 60 deg
DISTANCE FROM IMPINGEMENT POINT TO PLANE OF GRAPH = 12 in
MAXIMUM MASS FLUX = 0.335 lbm/sec in²
TOTAL FLOW RATE = 4.29 lbm/sec
MIXTURE RATIO = 1.23

Fig. 14. Nonreactive-spray properties of doublet injector element with vaned orifices

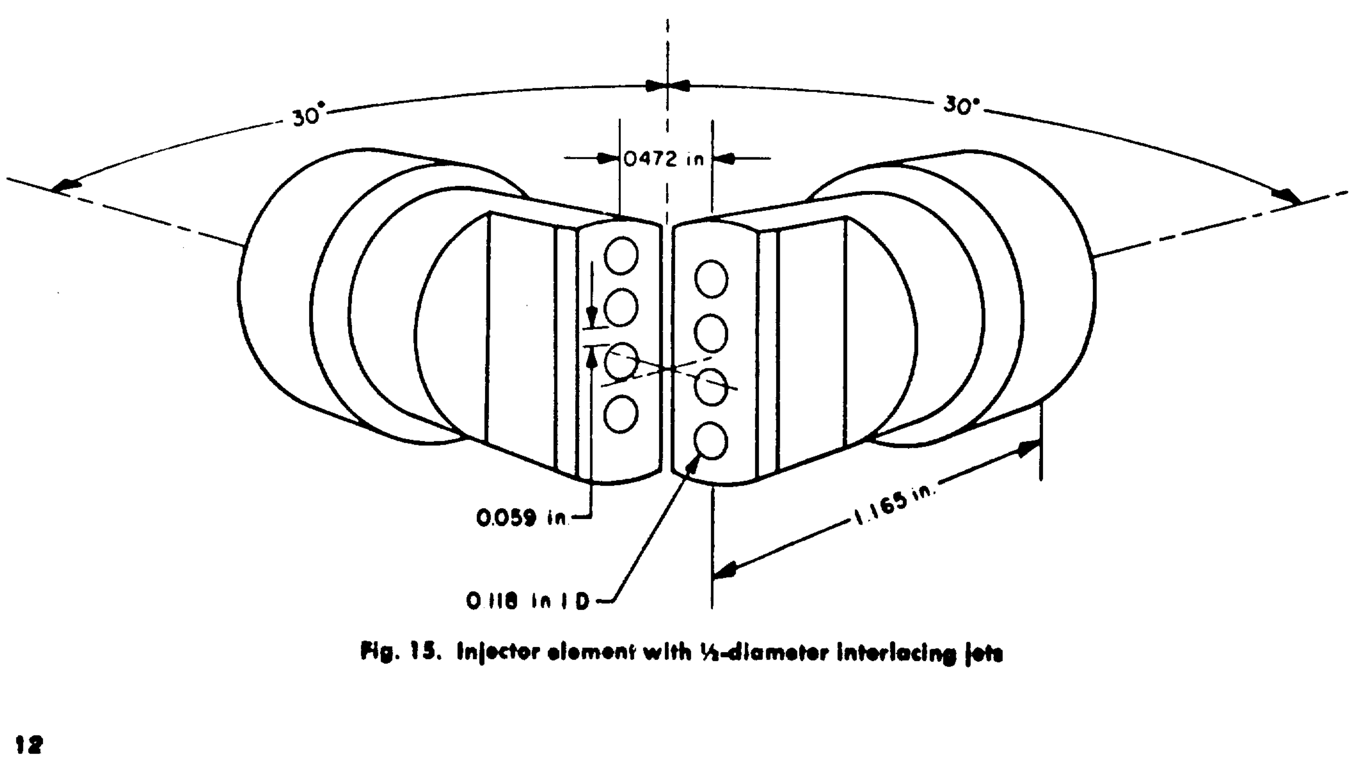
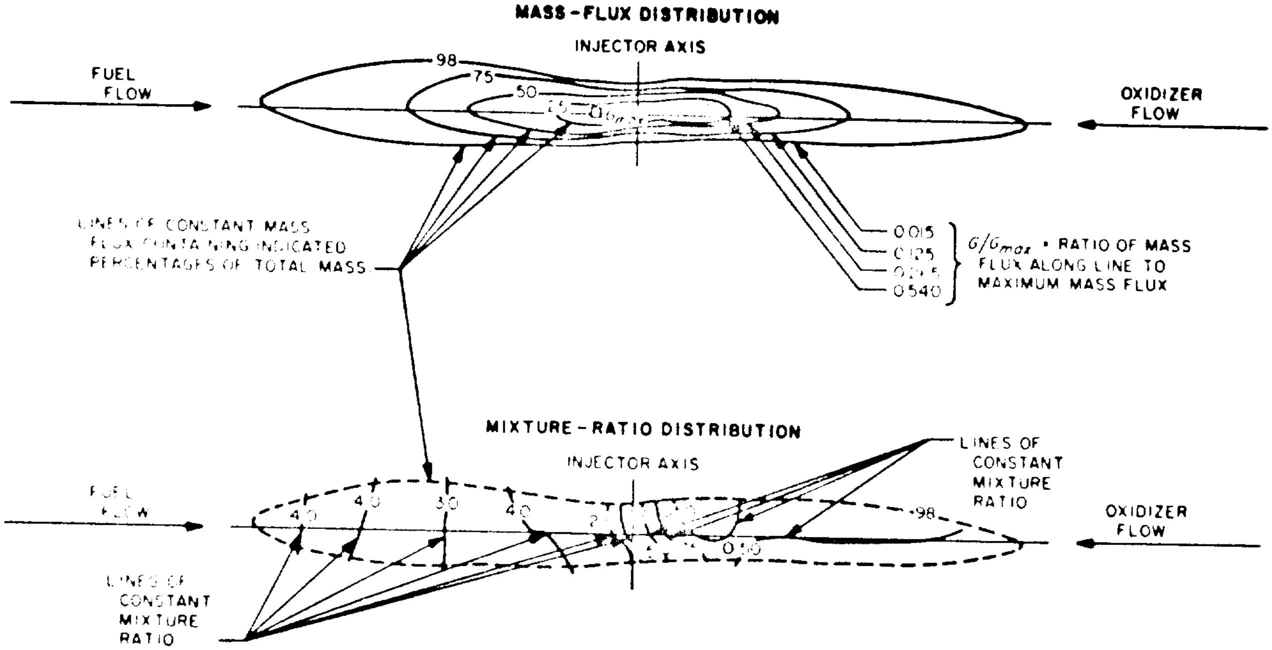


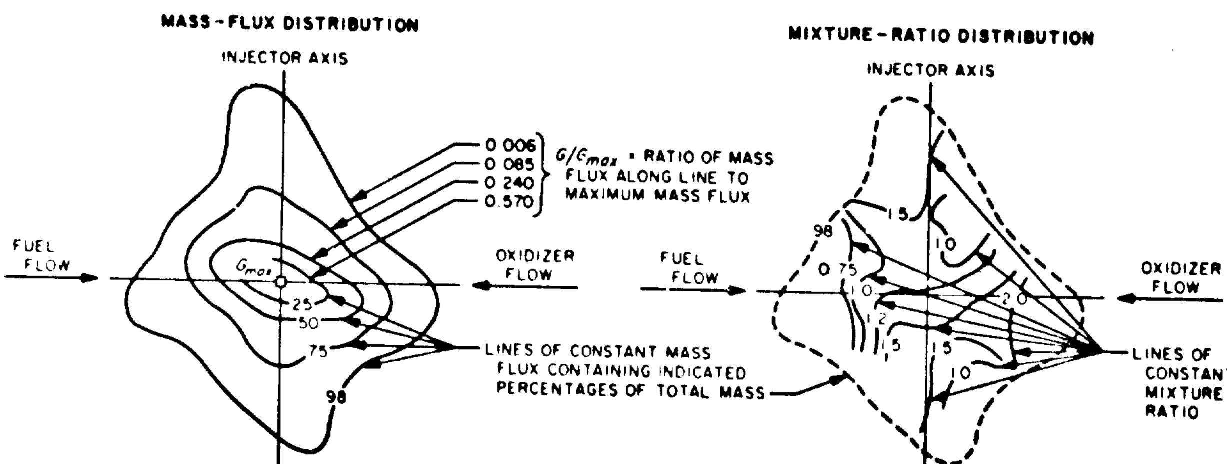
Fig. 15. Injector element with ½-diameter interlacing jets



CONDITIONS
TEST FLUIDS TRICHLOROETHYLENE - WATER, SIMULATING $N_2O_4 - N_2H_4$
IMPINGEMENT ANGLE = 60 deg
DISTANCE FROM IMPINGEMENT POINT TO PLANE OF GRAPH = 12 in.
MAXIMUM MASS FLUX = 0.450 lbm/sec in.^{2}
TOTAL FLOW RATE = 4.27 lbm/sec
MIXTURE RATIO = 1.23

0 5 10
INCHES

Fig. 16. Nonreactive-spray properties of injector element with ½-diameter interlacing jets



CONDITIONS
TEST FLUIDS TRICHLOROETHYLENE - WATER, SIMULATING $N_2O_4 - N_2H_4$
IMPINGEMENT ANGLE = 60 deg
DISTANCE FROM IMPINGEMENT POINT TO PLANE OF GRAPH = 12 in
MAXIMUM MASS FLUX = 0.509 lbm/sec in.^{2}
TOTAL FLOW RATE = 4.27 lbm/sec
MIXTURE RATIO = 1.23

0 5 10
INCHES

Fig. 17. Nonreactive-spray properties of injector element with ½-diameter impinging jets

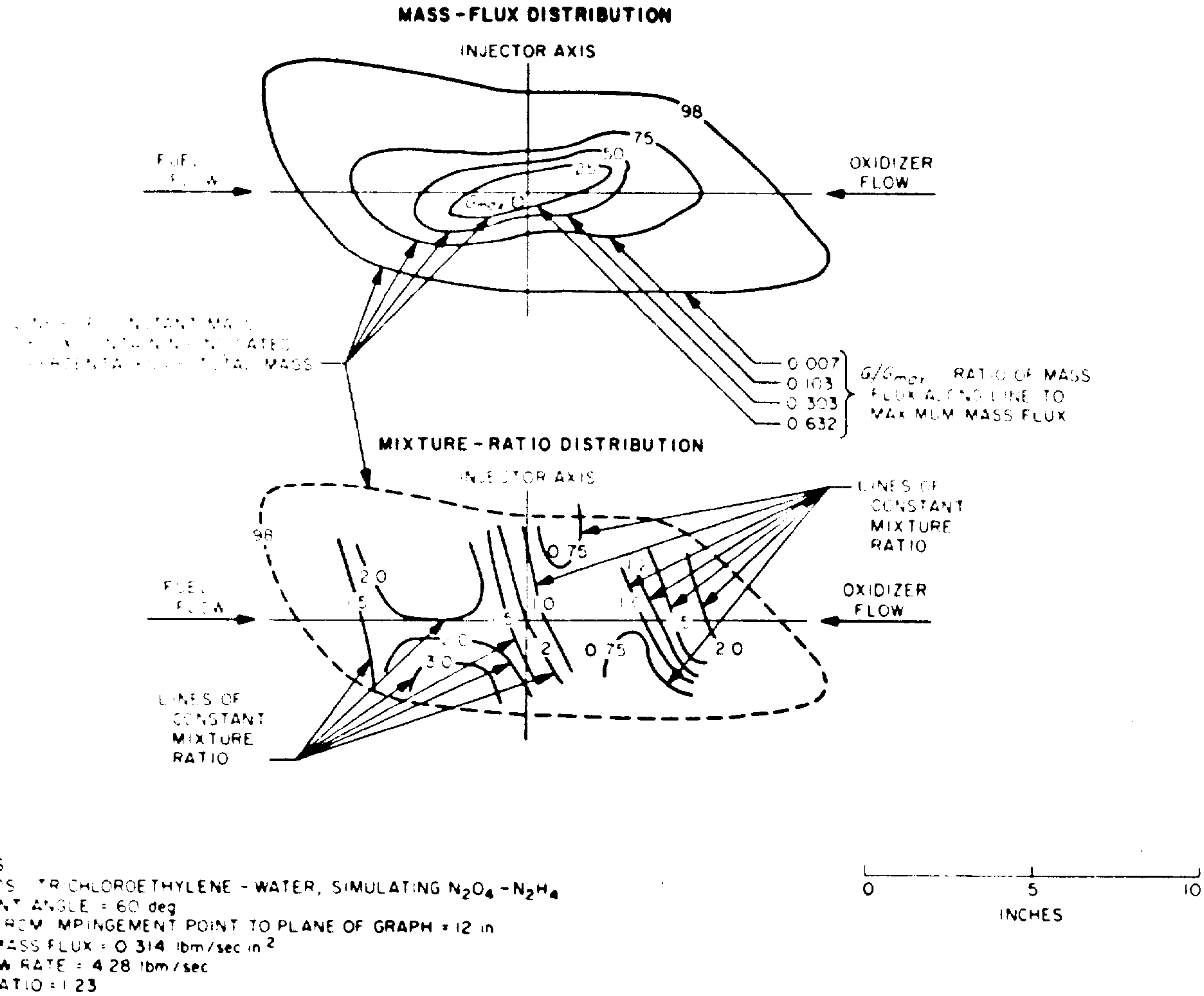
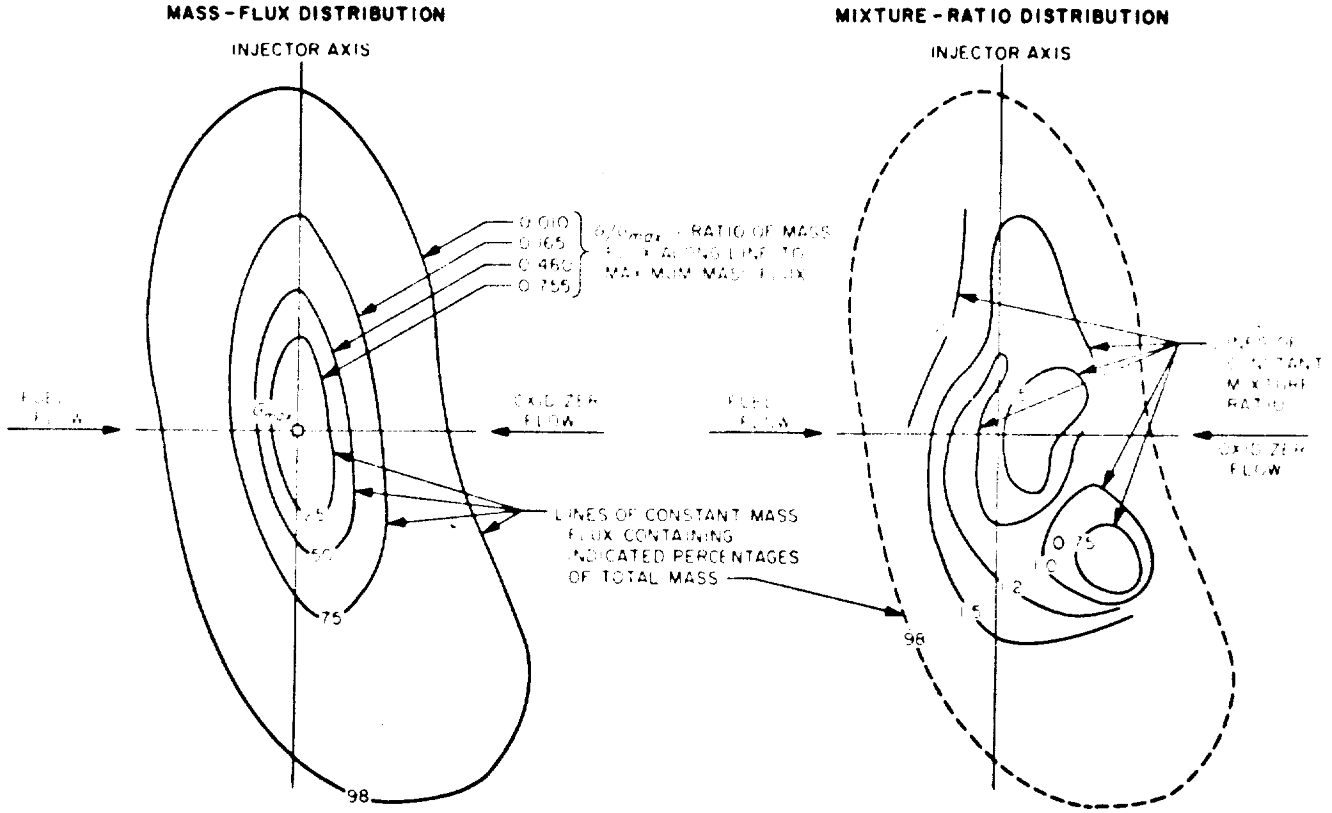


Fig. 18. Nonreactive-spray properties of injector element with ¼-diameter interlacing jets

elements indicated that 96% of theoretical c^* could be realized with N_2O_4–N_2H_4 if it is assumed that the reaction goes to completion at each local value of mixture ratio. The impinging full-cone spray element was tested with N_2O_4–N_2H_4 in the 170-in.-L^* chamber, at a nominal flow rate of 6.67 lb/sec and a nominal mixture ratio of 1.2. The injector plate contained four pairs of holes, permitting the two spray nozzles to be located with four different impingement geometries. With the inpingement angle of the spray-nozzle centerlines at 60 deg, the tips of the spray nozzles could be located 1.0, 3.5, or 5.0 in. from the impingement point. At an impingement angle of 90 deg, the impingement distance was 3.5 in. Holes were also located in the wall of the thrust chamber about 4.5 in. from the injector plate, so that the spray nozzles could be mounted at an impingement angle of 180 deg, with an impingement distance of 3.5 in. The nonreactive mass and mixture-ratio distributions for this element at the 90-deg impingement angle and 5.0-in. impingement distance are shown in Fig. 19.

Tests of the full-cone nozzles made at the 60-deg impingement angle showed the best performance (80% of theoretical c^*) at an impingement distance of 3.5 in.; however, the performance was almost the same at the 5.0-in. spacing (Fig. 20). At the 3.5-in. impingement distance, the best performance (85% of theoretical c^*) was measured at an impingement angle of 90 deg, with peak performance apparently obtained at an impingement angle between 90 and 180 deg (Fig. 21).



CONDITIONS
TEST FLUIDS: CARBON TETRACHLORIDE AND KEROSENE - WATER, SIMULATING $N_2O_4 - N_2H_4$
IMPINGEMENT ANGLE = 90 deg
DISTANCE FROM IMPINGEMENT POINT TO PLANE OF GRAPH = 4.46 in.
DISTANCE FROM IMPINGEMENT POINT TO SPRAY NOZZLE = 5.0 in.
MAXIMUM MASS FLUX = 0.261 lbm/sec in.^{2}
TOTAL FLOW RATE = 6.57 lbm/sec
MIXTURE RATIO = 1.16

Fig. 19. Nonreactive-spray properties of injector element utilizing impinging full-cone spray nozzles

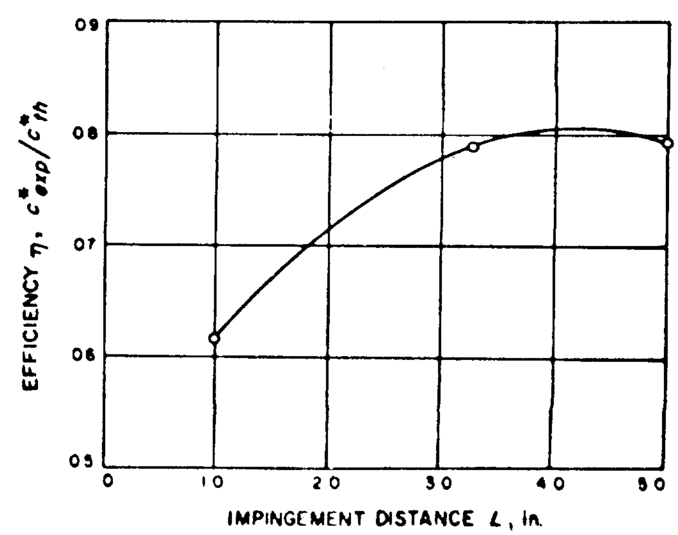


Fig. 20. Variation in performance with impingement distance for injector element utilizing impinging full-cone spray nozzles

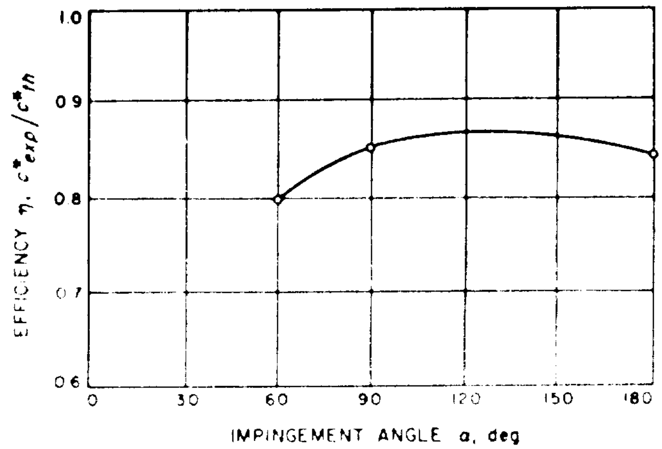


Fig. 21. Variation in performance with impingement angle for injector element utilizing impinging full-cone spray nozzles

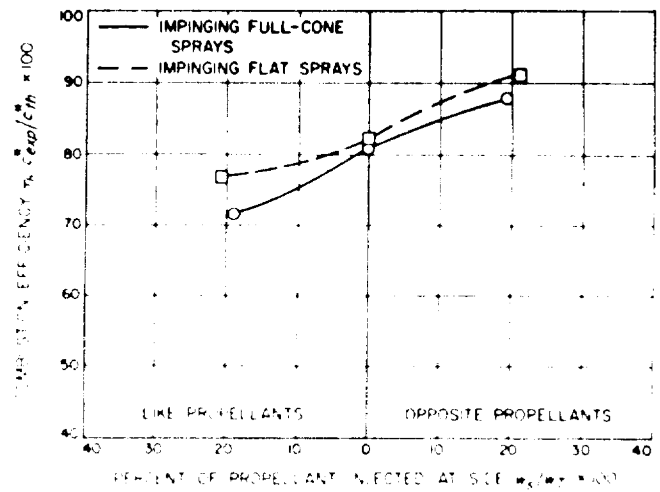
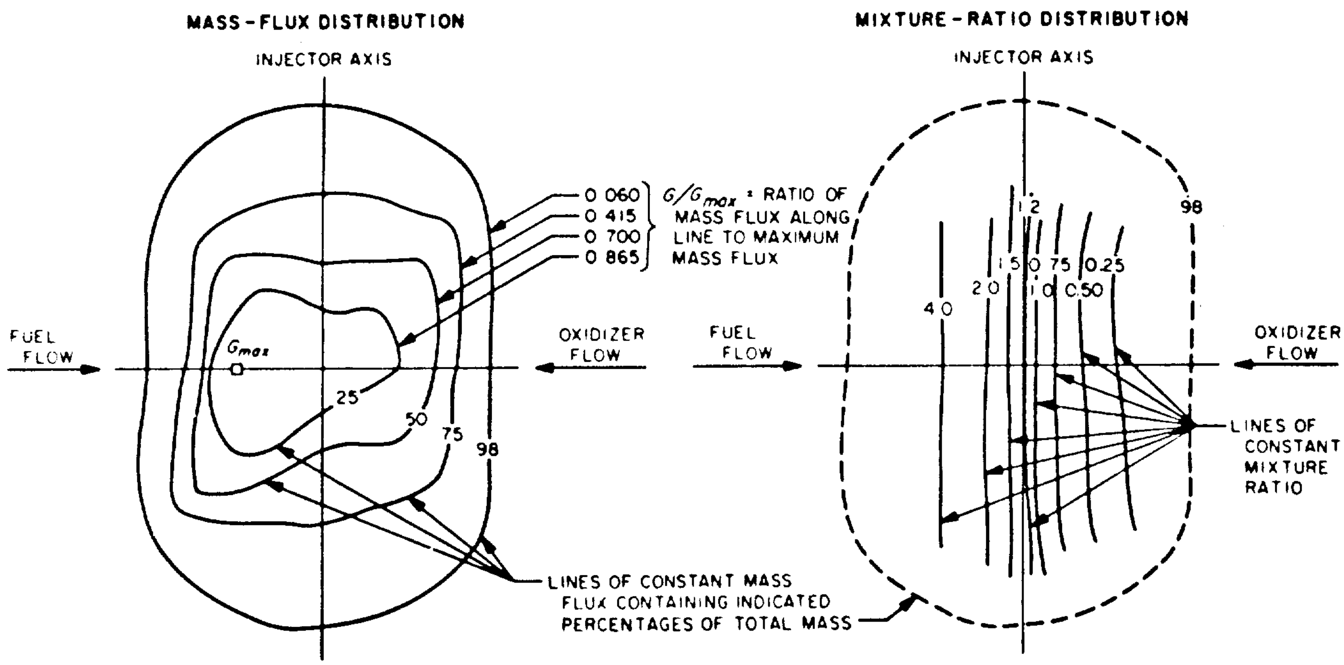


Fig. 22. Combustion-effects test results for injector element utilizing impinging full-cone spray nozzles



CONDITIONS
TEST FLUIDS TRICHLOROETHYLENE - WATER, SIMULATING $N_2O_4 - N_2H_4$
IMPINGEMENT ANGLE = 90 deg
DISTANCE FROM IMPINGEMENT POINT TO PLANE OF GRAPH = 4 46 in.
DISTANCE FROM IMPINGEMENT POINT TO SPRAY NOZZLE = 5.0 in.
MAXIMUM MASS FLUX = 0 093 lbm/sec in^2
TOTAL FLOW RATE = 6 84 lbm/sec
MIXTURE RATIO = 1 24

0 5 10
INCHES

Fig. 23. Nonreactive-spray properties for injector element producing impinging flat sprays

At a spray impingement angle of 90 deg and an impingement distance of 3.5 in., tests showed that the variation of c^* with mixture ratio was slight, decreasing from 5000 ft/sec at a mixture ratio of 0.80 to 4800 ft/sec at a mixture ratio of 1.78. At the same impingement angle and impingement distance, other tests showed that combustion efficiency decreased from 85% at the nominal flow rate of 6.7 lb/sec to 72% at 3.8 lb/sec, and increased to 87% at 10.0 lb/sec. Since the throat area was constant for these tests, chamber pressure varied directly with the propellant flow rate. For the same impingement geometry, the efficiency dropped from 85% at an L^* of 170 in. to 70% at an L^* of 40 in.

The impinging full-cone spray element was then tested with the baffle and side sprays in the thrust chamber, as described above for the impinging-jet element. The 90-deg impingement angle was used, with the spray nozzles 3.5 in. from the impingement point. The results, shown in Fig. 22, indicate that combustion interferes with the propellant mixing of impinging full-cone sprays, although the effects are not as severe as those observed previously with impinging jets (see Fig. 9).

After nonreactive-spray tests showed that flat sprays gave much more penetration of one propellant through the other than that produced by full-cone sprays (Fig. 23), test firings were conducted with impinging flat-spray nozzles.[2] However, the performance measured with these elements was nearly identical with that of the full-cone spray element, and the effects of combustion on mixing were also the same (Fig. 22).

A modification of the impinging flat sprays was also tested at the 90-deg impingement angle and the 3.5-in. impingement distance. As shown in Fig. 24, two small flat-spray nozzles were added to the injector face, each of which impinged with one of the large sprays at a distance of 0.73 in. from the ends of the small nozzles. The total flow rate of the small nozzles was 1/20 of the total injector flow rate. The result was an impingement of a high- and a low-mixture-ratio flow. These flows were expected to be completely gaseous if the off-mixture-ratio reactions were rapid and the initial mixing was good. The measured performance of this injector was 88% of theoretical c^*, a 3% improvement over that of impinging sprays.

[2]Commercial nozzles (type ⅛ USS 80150) manufactured by Spraying Systems Co., Bellwood, Ill.

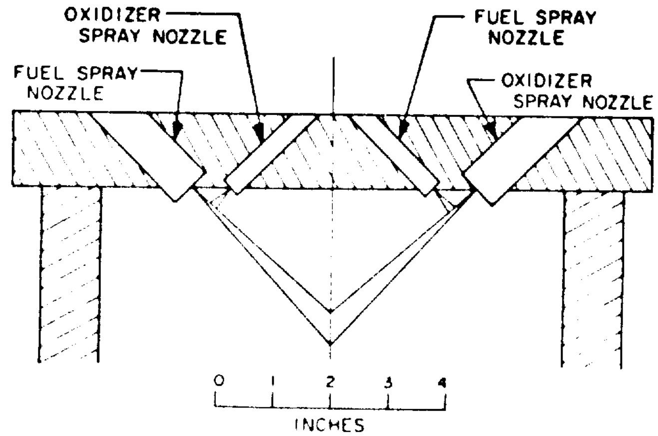


Fig. 24. Modified impinging-flat-sprays element

B. Chemical Methods

In conjunction with the attempts to increase the mixing properties of a doublet element by mechanical means, a program was initiated[3] to find a chemical inhibitor for the N_2O_4–N_2H_4 reaction (Ref. 5). Presumably, such an inhibitor would allow mixing to be accomplished before sufficient energy could be released to disrupt the impingement process. The ignition-delay time was chosen as a convenient parameter to be measured in testing a variety of chemicals for their effectiveness as inhibitors.

The apparatus used to measure ignition delay was quite similar to that developed by Kilpatrick and Baker (Ref. 6). It consisted of a closed bomb having a volume of about 450 cm^3, into which the propellants were injected as high-velocity jets. A high-response flush-mounted pressure transducer[4] and a photocell were used to detect ignition. The ignition-delay times were recorded by photographing the screen of an oscilloscope. In operation, a fast-opening solenoid valve (90% open in 2 msec) allowed 1500-psig nitrogen gas to act against a large driving piston. This piston first actuated a trigger mechanism for the oscilloscope and then moved the smaller fuel and oxidizer pistons, forcing the propellants to break their respective Teflon retaining discs and enter the bomb simultaneously through short orifices. The jets thus formed had a diameter of 0.06 in. and impinged tangentially in a swirl cup at a 90-deg angle to each other. The

[3]Work performed under a JPL subcontract by Dynamic Science Corp., Monrovia, Calif.

[4]Commercial transducer (Model 603) manufactured by Kistler Instrument Corp., Clarence, N. Y.

propellant pistons were sized to give a mixture ratio of 1.2. Before each test, the bomb was flushed with nitrogen gas to ensure an inert atmosphere.

A number of chemical additives to the N_2H_4 were tested in this apparatus, with the results shown in Fig. 25. The ignition-delay time was increased to 4.0 msec and decreased to 1.2 msec, in comparison with the 3.0-msec delay time measured for the neat propellants. Several of the more promising additives were tested in a rocket engine with a single-element doublet injector having an impingement angle of 60 deg and orifice diameters of 0.236 in. The chamber used had a characteristic length L^* of 170 in. The additives tested were: 1 and 2% ethylenediamine tetraacetic acid; 1 and 2% ethyl bromide; 1% fluorobenzene; 1% triethylborate; and 1, 2,

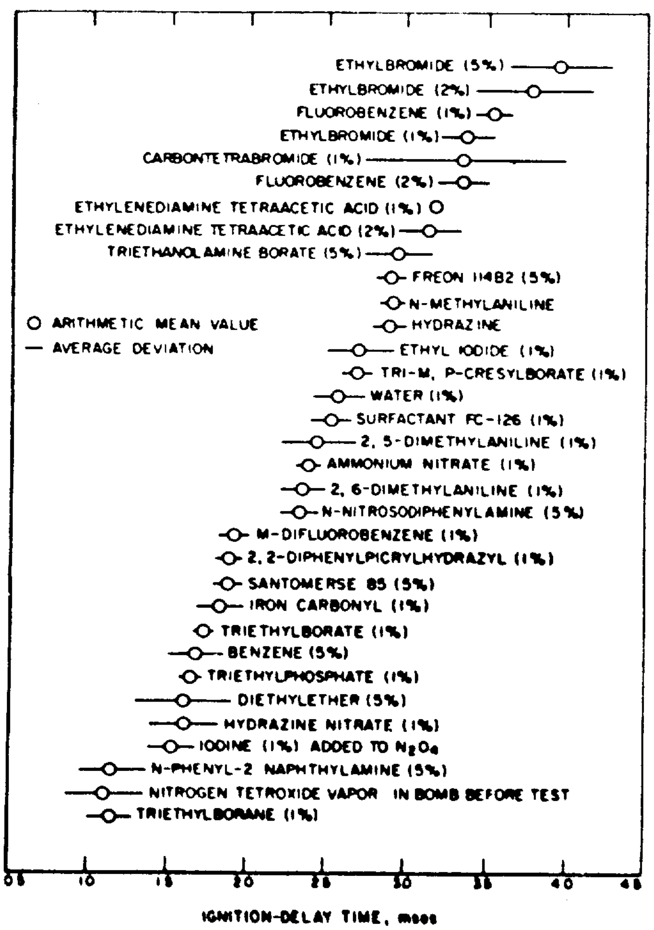


Fig. 25. Ignition-delay times for N_2O_4–N_2H_4 propellants with various fuel additives

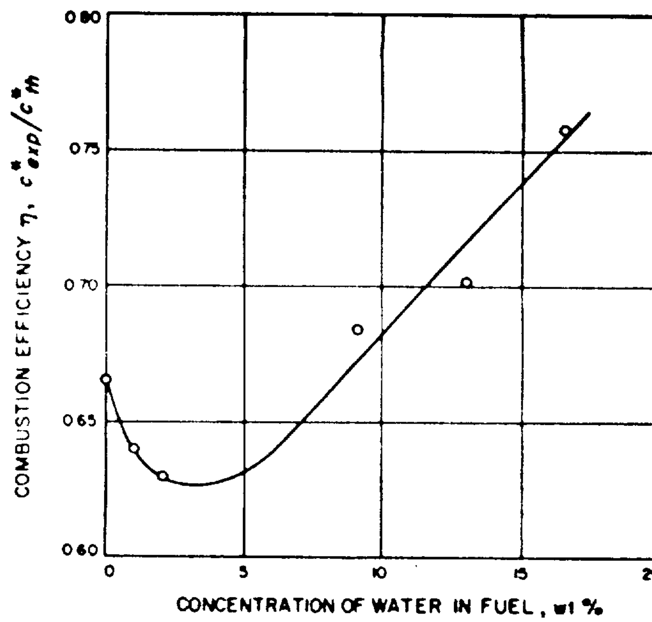


Fig. 26. Variation in performance of doublet element as a function of water concentration in fuel

9.1, 13.0, and 16.7% water. None of these additives, except high percentages of water, increased c^* in any amount or decreased c^* by more than 3% from the nominal efficiency of 66%. Figure 26 shows the effect of water concentration on the performance of this injector. The peak performance measured was 76% of theoretical c^*, obtained with 16.7% water in the fuel. Theoretical c^* is assumed to be that of N_2O_4–N_2H_4 at a mixture ratio of 1.2 (5810 ft/sec). An increase in combustion roughness was noted as the water content of the fuel was increased.

Another method tested for the use of water to decrease the effects of combustion on the mixing process was the addition of a water orifice to the doublet element described above. The water orifice was located in the plane of the propellant orifices and midway between them. The three orifices thus impinged at a common point. The 0.080-in. diameter for the water orifice was chosen to satisfy, at a water flow rate of 0.48 lbm/sec, the criterion presented in Ref. 7 for optimizing mixing in a triplet element using nonreactive fluids.

The peak performance obtained with this tripropellant element was 4150 ft/sec at the design water flow rate of

0.48 lbm/sec, or 72% of theoretical c^* for N_2O_4–N_2H_4 at a mixture ratio of 1.2. Decreasing the water flow rate to 0.41 lbm/sec lowered performance to 71%; increasing the water flow rate to 0.53 lbm/sec decreased performance to 67%.

It is encouraging to note that a fuel additive such as water can significantly increase performance. This technique will not be practicable, however, until an additive is found that is more effective than water and can be used in much lower concentrations.

V. SUMMARY AND CONCLUSIONS

An experiment was designed to explore the effects of combustion on the liquid-phase mixing of several storable liquid bipropellants at the 2000-lb thrust level and at a combustion-chamber pressure of 150 psia. Propellant combinations tested included N_2O_4–N_2H_4, N_2O_4–UDMH, N_2O_4–MMH, *Corporal* propellant, N_2O_4–furfuryl alcohol, and N_2O_4–N_2H_4 with several additives to the hydrazine.

It was found that combustion effects were severe for all the combinations utilizing a hydrazine derivative as the fuel. These effects were evidenced by an apparent repelling of the fluids from each other near the impingement point, of such magnitude that appreciable quantities of the individual propellants traveled down the chamber and out the nozzle exit without undergoing stoichiometric combustion. This effect was not observed with the nonhypergolic combination, N_2O_4–furfuryl alcohol. Several attempts were made to induce propellant mixing by mechanical means, and several tests were conducted with small quantities of chemical inhibitors in the fuel. All these attempts were unsuccessful in promoting propellant mixing before initiation of the liquid-phase reactions.

It is concluded that, under conditions similar to those of the experiment described here, the rapid liquid-phase reactions dominate the injection scheme to such a degree that the mass and mixture-ratio distributions typical of nonreactive-spray experiments cannot be obtained. The resulting combustion process is grossly inefficient because of the predominance of fuel-rich and oxidizer-rich regions in the combustion chamber. It is believed that a reduction in stream diameter will lead to more efficient combustion. The results of similar experiments, currently being conducted at 100 lb and 10 lb of thrust per element, will be reported subsequently.

REFERENCES

1. Rupe, J. H., *The Liquid Phase Mixing of a Pair of Impinging Streams*, Progress Report No. 20-195, Jet Propulsion Laboratory, Pasadena, California, August 6, 1953.

2. Rupe, J. H., *A Correlation Between the Dynamic Properties of a Pair of Impinging Streams and the Uniformity of Mixture Ratio Distribution in the Resulting Spray*, Progress Report No. 20-209, Jet Propulsion Laboratory, Pasadena, California, March 28, 1956.

3. Johnson, B. H., "Injector Development," *Space Programs Summary 37-17, Vol. IV*, Jet Propulsion Laboratory, Pasadena, California, October 1962, pp. 195–196.

4. Elverum, G. W., Jr., and Staudhammer, P., *The Effect of Rapid Liquid-Phase Reactions on Injector Design and Combustion in Rocket Motors*, Progress Report No. 30-4, Jet Propulsion Laboratory, Pasadena, California, August 25, 1959.

5. Weiss, H. G., Johnson, B. H., Fisher, H. D., and Gerstein, M., "Modification of the Hydrazine-Nitrogen Tetroxide Ignition Delay," *AIAA Journal*, Vol. 2, No. 12, December 1964, pp. 2222–2223.

6. Kilpatrick, M., and Baker, L. L., Jr., *Fifth Symposium on Combustion*, Reinhold Publishing Corp., New York, 1955, Paper No. 11, p. 196.

7. Elverum, G. W., Jr., and Morey, T. F., *Criteria for Optimum Mixture-Ratio Distribution Using Several Types of Impinging-Stream Injector Elements*, Memorandum No. 30-5, Jet Propulsion Laboratory, Pasadena, California, February 25, 1959.

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