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HYPERGOLIC STREAM IMPINGEMENT PHENOMENA –NITROGEN TETROXIDE/HYDRAZINE

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BY

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SUMMARY

Stream separation limits were experimentally determined for impinging liquid N_2O_4/N_2H_4 streams using both two-dimensional and circular jets. The two-dimensional apparatus allowed photographic observation of both the impingement point and the propellant spray from which separation was determined. A semi-empirical equation was developed which correlates the data and defines the mix/separate limit. All tests were run at atmospheric pressure and with a 60° impingement angle.

Injector "popping" was found to occur when circular jets are operated in the mix regime at D/V values greater than approximately 0.1 milliseconds. The "popping" appears to be associated with an intermittant ignition of mixed propellants in the impingement mixing zone.

Based on the two-dimensional and circular jet test data, design curves were constructed which define the mix/separate/pop regimes for doublet injector elements in terms of the injection velocity, orifice diameter, and propellant inlet temperature.

INTRODUCTION

The understanding of the processes that occur when unlike liquid hypergolic streams impinge is essential, if rocket engine combustion problems are to be solved because the impingement process strongly influences both the uniformity of mixture ratio distribution and resultant droplet sizes.

The mixing efficiency of impinging streams has been adequately investigated by Rupe (Ref. 1) using nonreactive fluids. However, the mixing efficiency criteria established for nonreactive sprays is not applicable under the conditions of interfacial reaction and stream separation. Likewise injector spray droplet size distribution determined with nonreactive fluids may not be applicable to reactive sprays.

The objective of this work was to determine the mechanism and the critical design parameters affecting reactive stream mixing and separation using N_2O_4/N_2H_4.

HYPERGOLIC IMPINGEMENT MODEL

Examination of the preliminary impingement tests show that either mixing or separation can be produced by a change in propellant temperature of only a few degrees centigrade. Based on this and observations of the impingement photographs of nonreactive flow tests,a model was developed for correlating the separation data.

Conditions of jet mixing and separation for reactive streams are shown diagrammatically in Figure 1 and 2. Under mixing conditions a mixing zone is exhibited similar to that of the nonreactive streams. This zone extends from the point of initial contact down to some distance, L, which is a function of the orifice geometry. Hypergolic ignition occurs some distance downstream of the mixing zone.

The condition of jet separation is characterized by a reaction interface within the mixing zone. The reaction interface extends from the initial point of contact downward and prevents liquid phase mixing. The interface exists along the entire mixing plane because heat transfer in the liquid phase is sufficient to spread the ignition from any point within the mixing zone to the point of contact. Therefore, it appears that predominately two conditions exist, mixing or separation. Mixing occurs when hypergolic ignition takes place downstream of the mixing zone and separation occurs when ignition occurs within the mixing zone.

Associated with the hypergolic ignition is an ignition delay time, τ_{ign}, and likewise a mixing time, τ_{mix}, is associated with the mixing. The criteria for jet separation can be stated $\tau_{ign} \leq \tau_{mix}$ and at the limit of separation the ignition delay time should just be equal to the mixing time, $\tau_{ign} = \tau_{mix}$.

The ignition delay time is the time required to generate sufficient heat by hypergolic reaction to cause ignition and product gas generation. For a first order, single step reaction, the ignition delay time can be related to the liquid phase reaction rate by

$$\tau_{ign} = \frac{1}{k} \ell n \, C_{ign}/C_o$$

where, k = reaction rate constant, C_{ign} = reactant concentration at ignition, C_o = initial reactant concentration.

Assuming the reaction rate to follow an Arrhenius reaction rate form then,

$$k = A\,e^{-E/RT}$$

where, A = kinetic frequency factor, E = activation energy, R = gas constant, T = reactant temperature. Therefore, the ignition delay time is

$$\tau_{ign} = \frac{\ln C_{ign}/C_o}{A\,e^{-E/RT}}$$

Assuming the ratio of ignition concentration to initial concentration to be a constant,

$$\tau_{ign} = \frac{Y}{e^{-B/T}}$$

where

$$Y = \frac{\ln C_{ign}/C_o}{A} \quad \text{and } B = E/R$$

The mixing time is characterized by the residence time of the propellants within the mixing zone. This time is a function of the stream diameter, the velocity, and the impingement angle.

$$\tau_{mix} = L_{mix}/V = X(D/V)$$

where D is the stream diameter, V is the stream velocity and X depends upon the impingement angle.

Equating the mixing time to the ignition delay time

$$X(D/V) = \frac{Y}{e^{-B/T}}$$

or,

$$D/V = K\,e^{B/T}$$

where,

$$K = Y/X$$

taking the log of both sides, $\ln (D/V) = \ln K + B(1/T)$

shows that the mix/separate limit should be a straight line when plotted on semilog paper.

APPARATUS AND PROCEDURES

The experimental approach is based on photographic observation of the impingement plane of a pair of two-dimensional jets. Cold flow tests were first conducted to determine the impingement point mixing of non-reactive streams and to provide a baseline for the reactive stream tests. Jet separation or mixing was determined by observing the degree of mixing at the impingement point. Tests were also conducted with circular jets to determine the validity of the two-dimensional jet data.

To minimize the test variables, all of the impingement tests were run with a single value of impingement angle of 60°. Also the tests were all conducted at one atmosphere total pressure. The principal variables investigated were stream diameter, propellant velocity, and propellant temperature.

Equal fuel and oxidizer jet diameters were chosen to provide a well-defined impingement point. A nominal mixture ratio of 1.2 was used to provide equal stream momentums which give optimum mixing for nonreactive streams.

Apparatus

The two-dimensional tests were conducted with the apparatus shown in Figure 3. It consists of an aluminum block with orifice slots on which a lucite observation window is bolted with a heavy retaining plate. The injector orifice slots are milled to a depth of 0.015 inches and the width (D_{ORF}) is made to the simulated orifice diameter. The block is cut away at the impingement point to allow free jet impingement and fan formation away from the lucite window. This model allows the phenomena at the impingement plane to be clearly observed.

The blocks are provided with coolant passages to allow temperature control and are lapped flat to provide sealing with the lucite window. Three test models of this design were fabricated having jet widths of 0.100 in., 0.050 in., and 0.025 in.

Two circular jet injectors having orifice diameters of 0.025 in. and 0.050 in. were designed and tested. These injectors, shown in Figure 4 are made from aluminum blocks with the orifices drilled to impinge at an included angle of 60°.

Photography

The impingement point was photographed by backlighting with a 10μ sec duration strobe light. The camera and lighting arrangement are shown in Figure 5. The camera is a Graflex View camera with a poloroid film holder. The strobe light was synchronized with the camera shutter. The pictures were taken at an f stop of 4.5 and a shutter speed of 1/400 sec. Overexposure of the film due to the flame light was not a problem because of the slow film speed of the poloroid color film.

Some of the tests were photographed from the back side of the lucite plate so that the spray uniformity could be observed. In these cases, direct photography was used.

Test Facility

A schematic of the propellant flow system for the impingement tests is shown in Figure 6. The propellant flow systems are fabricated with 304 stainless steel lines and tanks and are designed for a working pressure of 1000 psia. Each system is capable of delivering a maximum flow of 0.300 lb/sec. The tank capacities are approximately 1/3 gallon.

The propellant flows are controlled with variable area cavitating venturies. The flow controllers have motor driven pintles that throttle the throat area of the cavitating venturies. These devices speed the process of setting the propellant flowrates. The propellant flowrates are measured with a turbine type flowmeter whose output signals are fed directly into a CEC Mod 5-124 recording oscillograph.

The propellant tank and lines are provided with heat exchangers through which isopropyl alcohol is flowed for propellant temperature control. The alcohol temperature is regulated by throttling the flow through heat exchangers located on the evaporator and condenser of a refrigeration unit. The temperature can be controlled from $0^{o}C$ to $60^{o}C$. Temperatures are measured with I/C thermocouples using an ice bath reference junction. The thermocouple output is recorded on the oscillograph. The temperature measurements are accurate to $\pm 1^{o}C$.

The pressure measuring system uses strain gage transducers powered by 6V batteries. The transducer output is fed to a zero balance circuit and then into the oscillograph galvanometer. The frequency response of the system is limited by the magnatically damped galvanometer which has a flat response to 190 CPS.

RESULTS AND DISCUSSION

Nonreactive Flow Tests

A series of cold flow tests were run to define impingement plane spray mixing of nonreactive liquids and to demonstrate the utility of the two-dimensional impinging jet test model in observing impingement plane flow phenomena. Fuel and oxidizer simulators were chosen on the basis of density similarity. Water was used to simulate hydrazine, whereas Freon was used to simulate the nitrogen tetroxide. The water was dyed red for flow visualization. Flow tests were run with the 0.100" and 0.050" wide jets at various velocities and momentum ratios. Color photographs of the impingement point were taken using front lighting with a 10 microsecond duration strobe light.

Photographs of impinging Freon/water streams under conditions of equal momentum ratio are shown in Figure 7. The spreading of the colored water indicates that a zone of liquid phase mixing exists within the impingement region. The mixing begins at the initial point of contact and appears to be complete at about 2 jet diameters downstream. The mixing zone is shown schematically in Figure 1.

The mixing criteria established by Rupe (Refs. 1 and 2) state that the optimum spray mixture ratio distribution is obtained with a doublet injector when:

$$\frac{\rho_1 V_1^2 D_1}{\rho_2 V_2^2 D_2} = 1.0$$

The Freon/water cold flow tests show agreement with this criteria. The impingement mixing zone was observed to have a maximum length when the stream momentum ratio is unity and is decreased when the momentum ratio deviates to either side of unity.

The cold flow tests clearly indicate that the spray mixture ratio uniformity of nonreactive streams is controlled by the liquid phase mixing at the impingement point.

Downstream of the mixing zone, the impingement fan breaks up into ligaments and droplets. The distance from the start of impingement to the start of atomization was measured for the optimum mixing case. The nondimensionalized breakup length (L/D) is plotted versus the water jet velocity in Figure 8. L/D is seen to be approximately proportional to 1/V.

N_2O_4/N_2H_4 Impingement Tests

When separation of the N_2H_4/N_2O_4 streams occurs, a thin dark interface is exhibited at the impingement plane, as shown in Figures 9, 10, and 11. The dark interface extends from the initial point of contact down to a point of vapor generation. The point of vapor generation is seen to move downstream with increasing velocity (Figs. 9, 10, and 11), although the dark interface persists. The dark interface is believed to be due to the dissociation of N_2O_4 to NO_2, which is known to be dark at high concentrations, caused by heat generation by chemical reaction at the impingement plane. The reaction interface acts as a barrier which prevents intermixing of the propellant streams at the impingement plane which in turn prevents mixing of the resultant spray as evidenced by the nonuniformity of the spray.

Similar photographs taken of the nonseparation case, as evidenced by the uniformity of the spray color and luminosity, show a high degree of mixing at the impingement plane similar to that of the cold-flow Freon/water jets, (Fig. 12).

From the photograph of each such test run, a judgment was made as to whether mixing or separation occurred. Mixing is defined by the absence of a reaction interface within the impingement plane and by a uniform spray color and luminosity. Separation is defined by the occurrence of the reaction interface and by the distinct nonuniformity of the combustion spray. In some tests a clear distinct mixing or separation was not observed. These tests were characterized by a slight amount of unreacted N_2O_4 in the spray and a dark impingement zone rather than a distinct reaction interface.

The data are shown in Figure 13 for the two-dimensional and circular jets in the form of ℓn (D/V) versus (1/T). The popping phenomena by which some data points are represented is discussed later. As shown in the figure the mix/separate regions are reasonably well defined by a straight line at their limit thus supporting the model derived earlier. The data was plotted using a value of (D/V) based on the hydrazine stream velocity and an absolute temperature based on an average between the hydrazine and N_2O_4 inlet temperatures which were approximately equal. The slope of the limit curve is a measure of the activation energy, E, for which a value of approximately 24 Kcal/mole of reactant is indicated. The intercept of the limit curve is a measure of the reaction frequency factor, A, for which a value of the order of 10^{17} is indicated. This correlation indicates the importance of liquid phase kinetics on the separation phenomena. Because of this importance of kinetics it is expected that additives to the hydrazine can significantly modify the N_2H_4/N_2O_4 separation limit.

From the data it appears that there exists only a small range in temperature over which any condition other than complete mixing or complete separation can occur. This agreement observed between the two-dimensional jet data and the circular jet data adds a degree of confidence to extrapolating the two-dimensional data to practical injector design.

At D/V values longer than about 0.9×10^{-4} seconds, a loud repetitive machine gun-like noise with a frequency estimated to be from 300-500 cps often occurred. This "popping" was observed with the circular jets and with the .100 inch two-dimensional jets when an aluminum plate was used in place of the lucite window. The data tend to show that the phenomena occur at the lower injection temperatures associated with the mix regime.

The phenomena appear to be due to intermittant ignition and quenching within the impingement plane. The dependence on D/V might be related to the jet breakup length which was also found to be proportional to D/V for non-reactive sprays (Fig. 8). It is suspected that heat transfer may play an important role in the "popping" since for the 2-D apparatus "popping" resulted only when an aluminum plate was used. The plate would serve to conduct heat to the impingement point. For the circular jets heat transfer may occur by recirculation of combustion gases.

It is postulated that the "pop" is caused by the following sequence of events. The propellants mix with resultant spray combustion, however, due to a temperature rise in the mixing zone, either by heat transfer from the flame or by hypergolic self-heating, ignition occurs. The ignition results in an explosion of the well mixed propellants in the mixing zone causing flow shutoff. Flow is re-established and the sequence repeated.

The injector design curves shown in Figure 14 were cross-plotted from Figure 13. The design curves define the regions of mix, separate, and "pop" for a single 60° impingement angle doublet in terms of propellant temperature, orifice diameter, and N_2H_4 injection velocity.

These design curves are intended only as guidelines in designing N_2O_4/N_2H_4 rocket injectors. It should be noted that the propellant temperature plotted in Figure 14 is the temperature at the orifice inlet. Therefore, heating of the propellants in the injector manifolds must be taken into account when using these curves.

CONCLUSIONS

A photographic study of the events occurring in the vicinity of the impingement region of N_2H_4/N_2O_4 jets has been made. The results show in general that two regimes can exist depending upon the injection temperature, the jet diameters, and jet velocities. In one regime the fluids appear to react after mixing as evidenced by a uniform appearing combustion zone. In the second regime, the fluids appear to react along the interface between the two jets with the result that the streams separate as evidenced by a very nonuniform combustion. The occurrence of the jet separation increased with increasing fluid temperature and with increasing values of the parameter D/V. A "popping" type of combustion was observed at some conditions generally associated with lower injection temperatures and higher D/V values. A semi-empirical model describing the separation limit and based on the observed results was obtained. From this correlation it appears that the separation of impinging N_2O_4/N_2H_4 streams is controlled by liquid phase mixing and kinetics. Design parameters that affect these processes should also affect rocket engine performance.

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

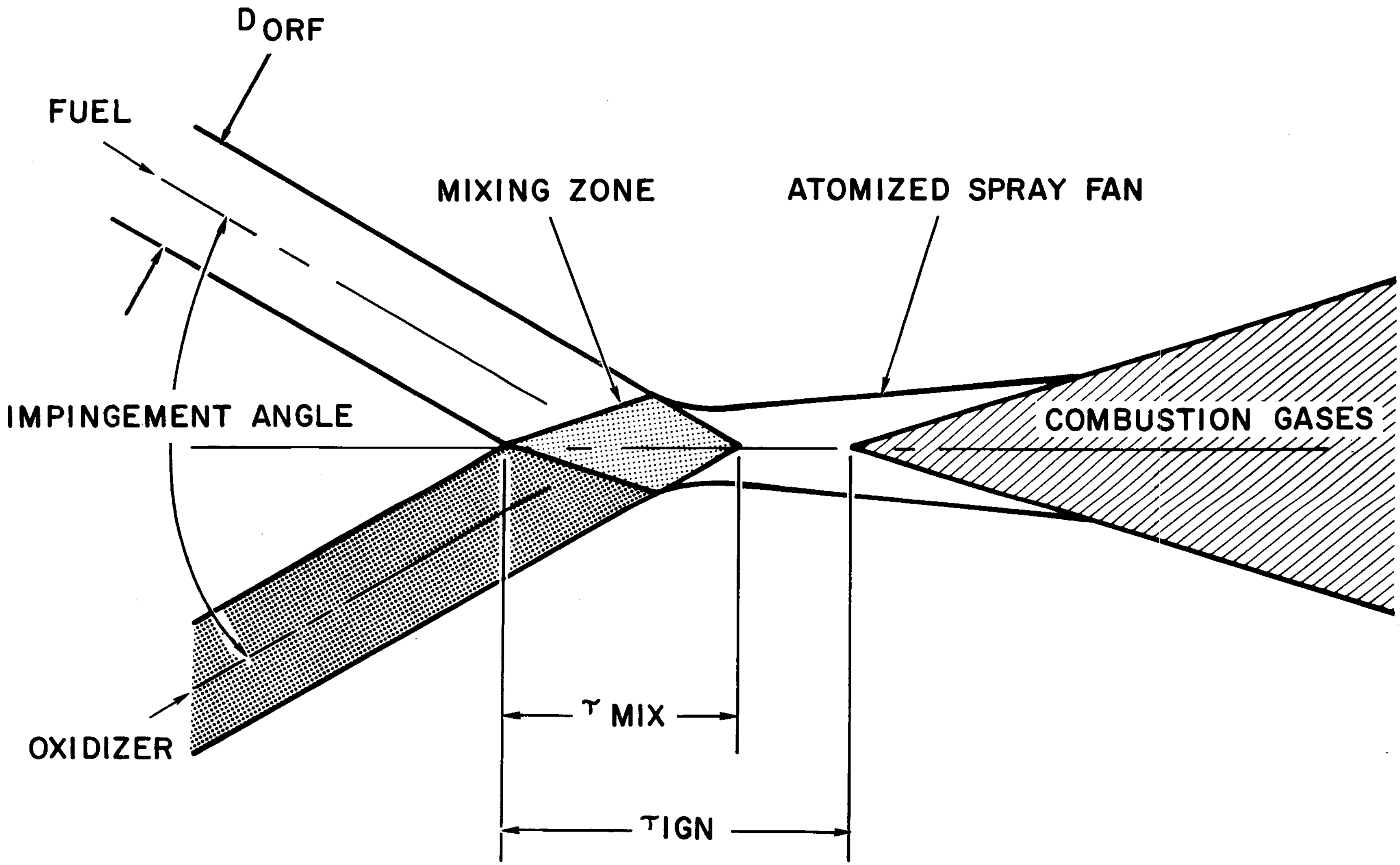


Figure 1. Mixing Model for Impinging Hypergolic Streams

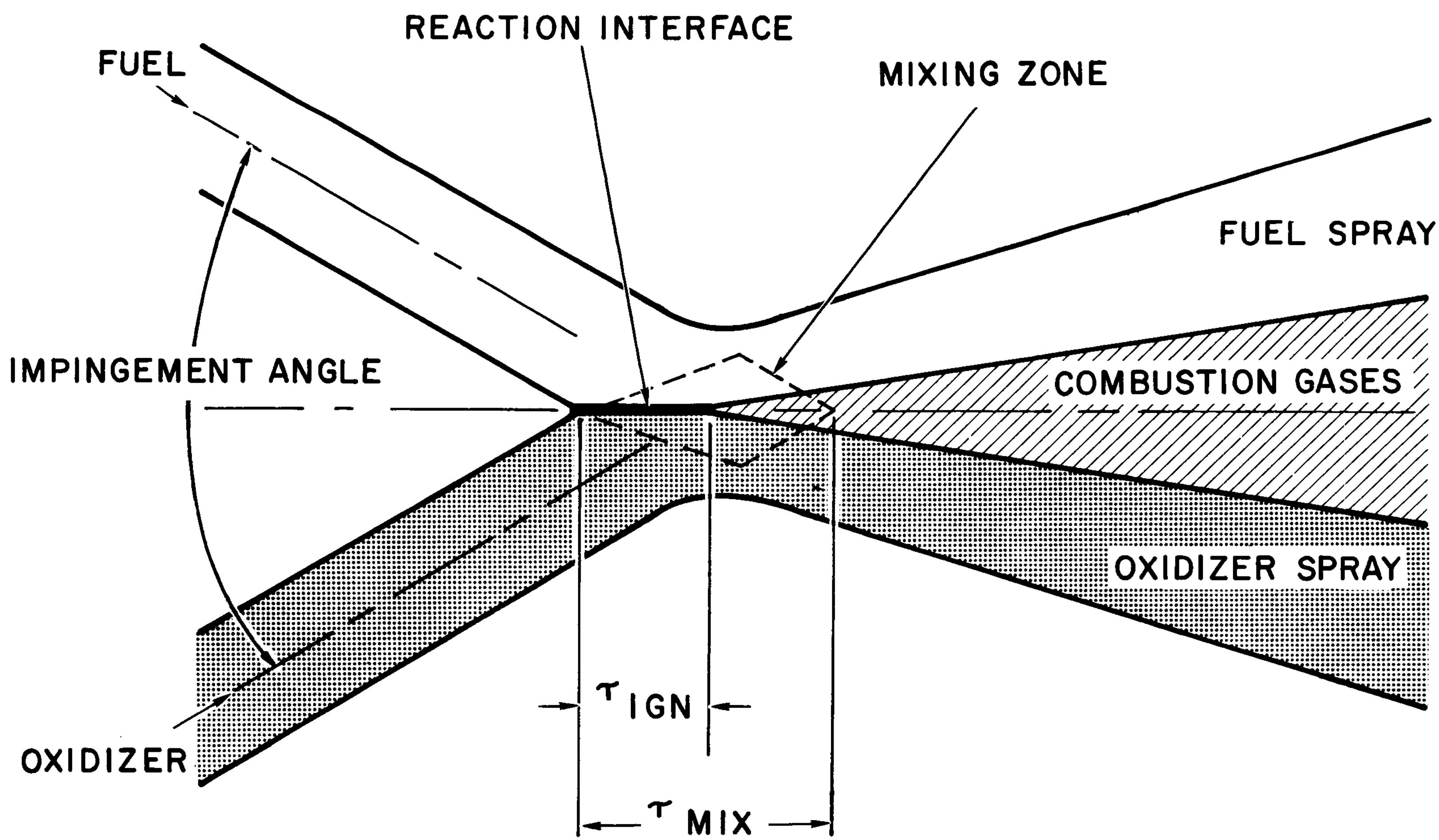


Figure 2. Separation Model for Impinging Hypergolic Streams

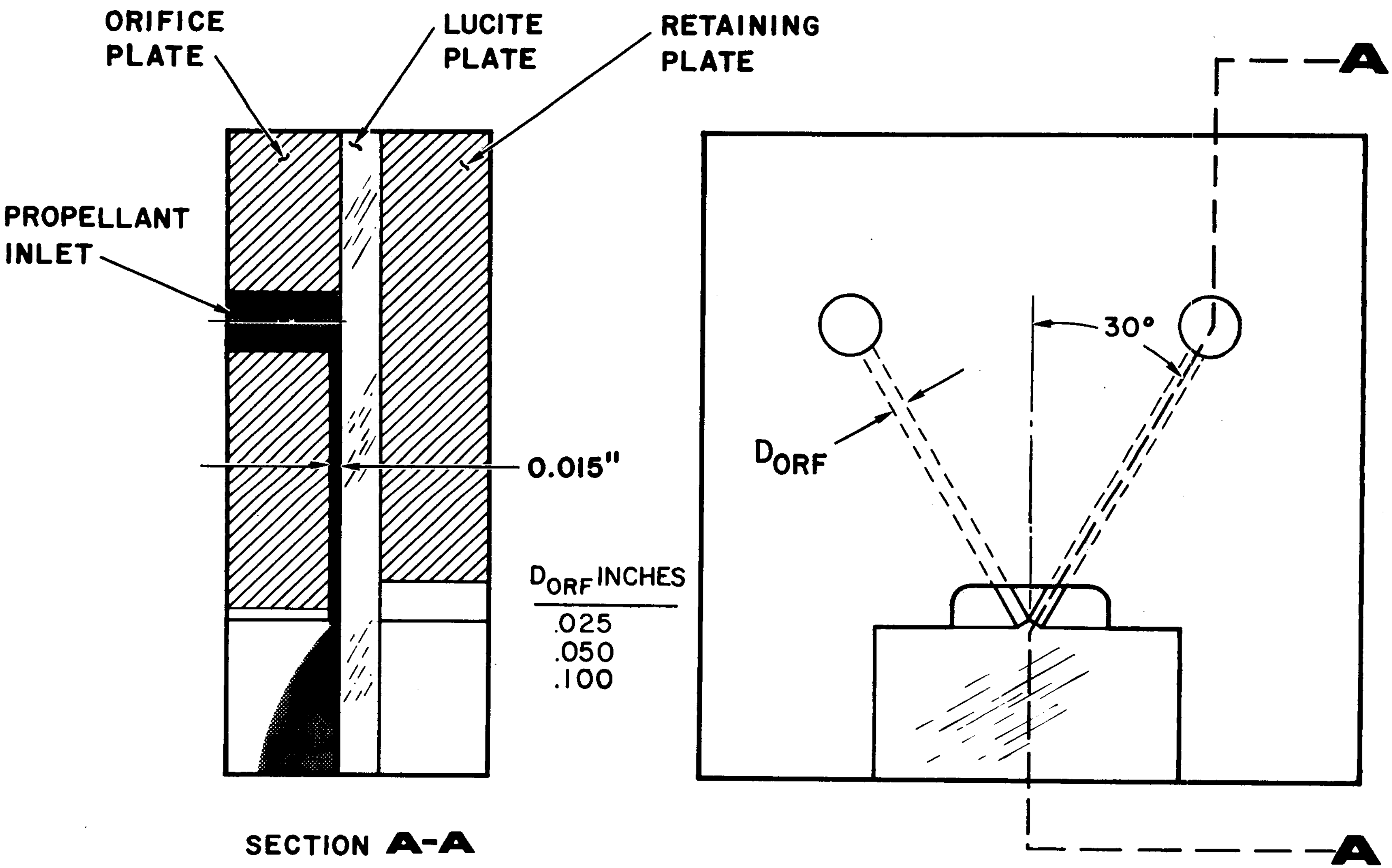


Figure 3. Two-Dimensional Impinging Jet Test Model

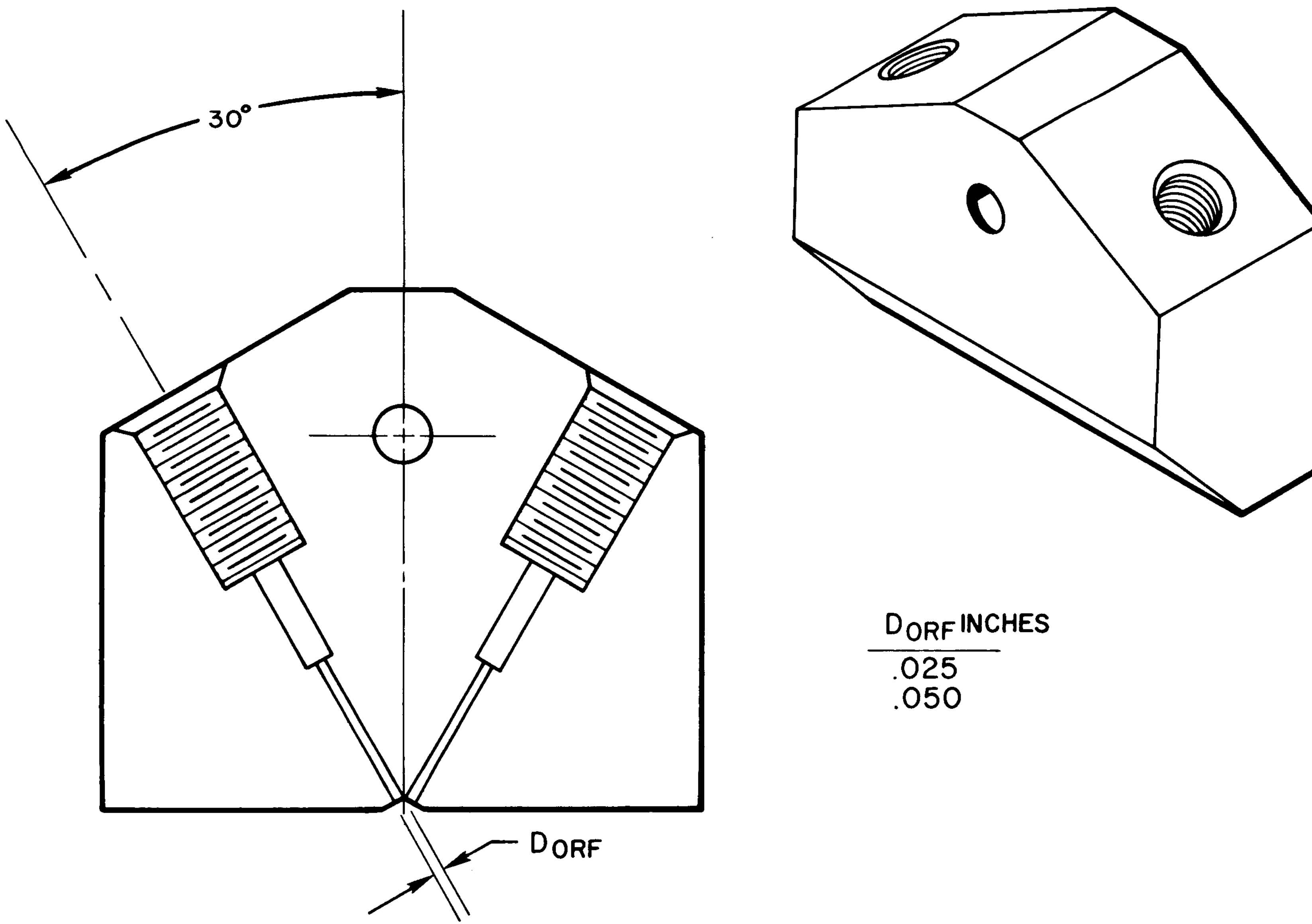


Figure 4. Circular Jet Test Model

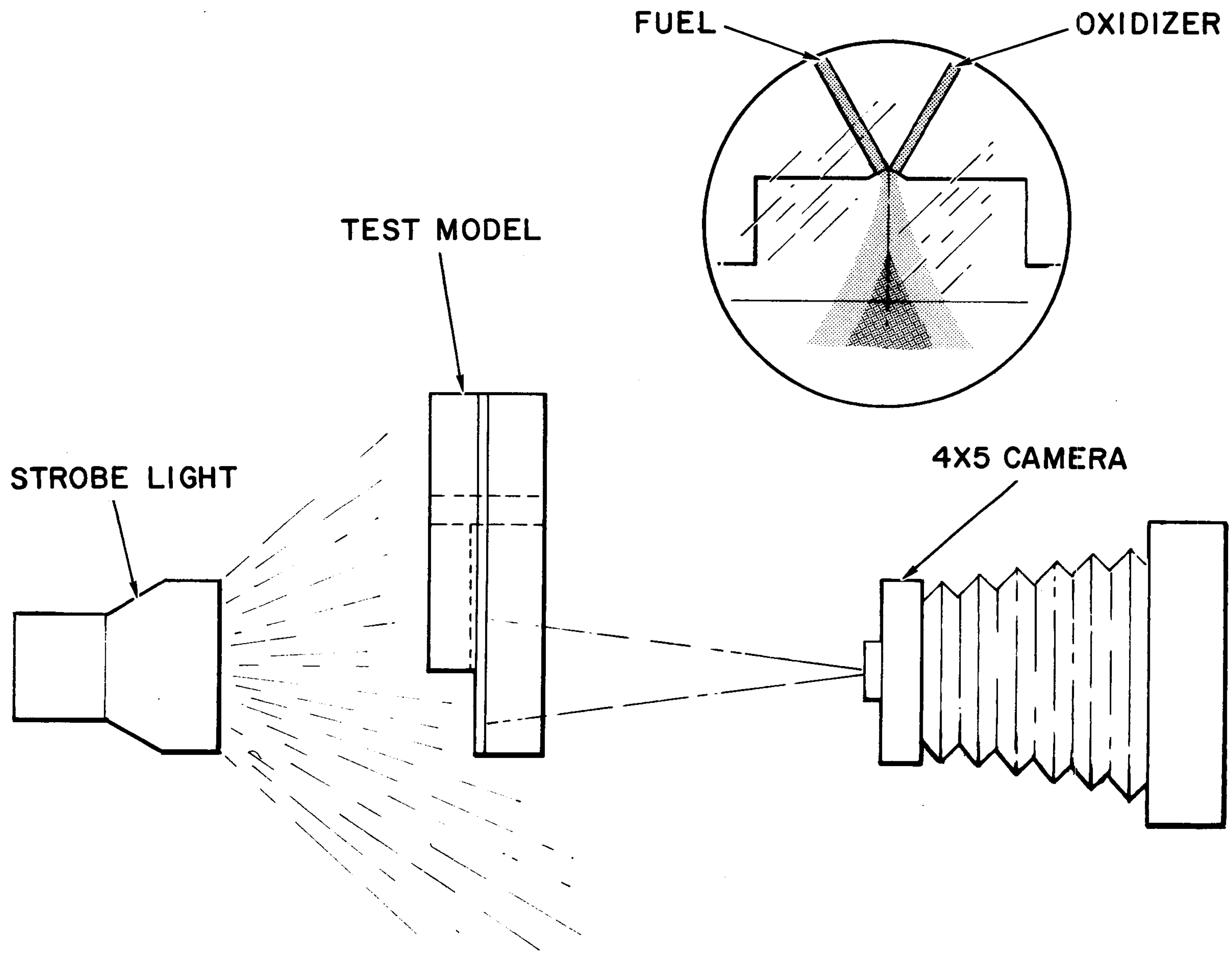


Figure 5. Photographic Setup

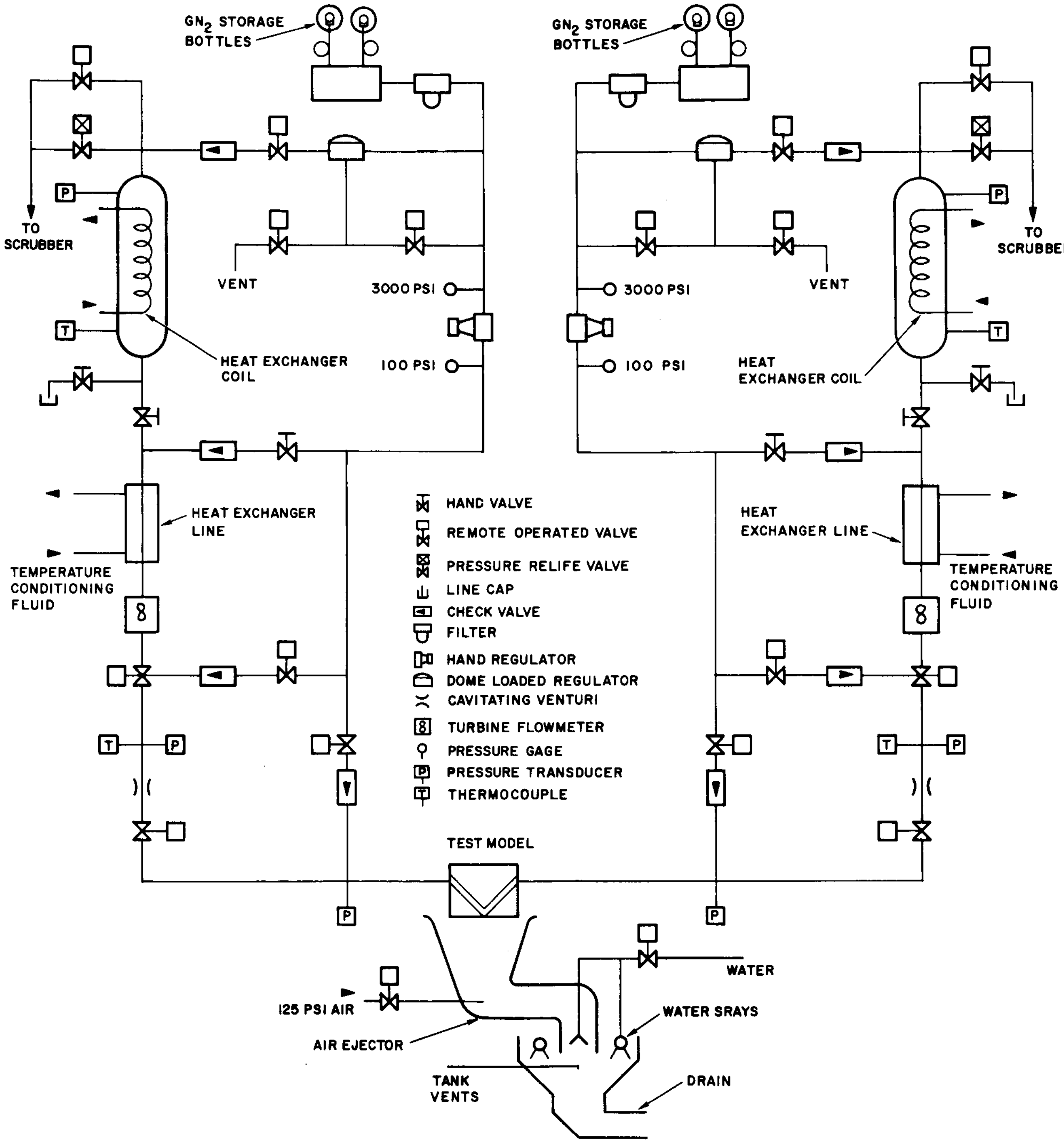
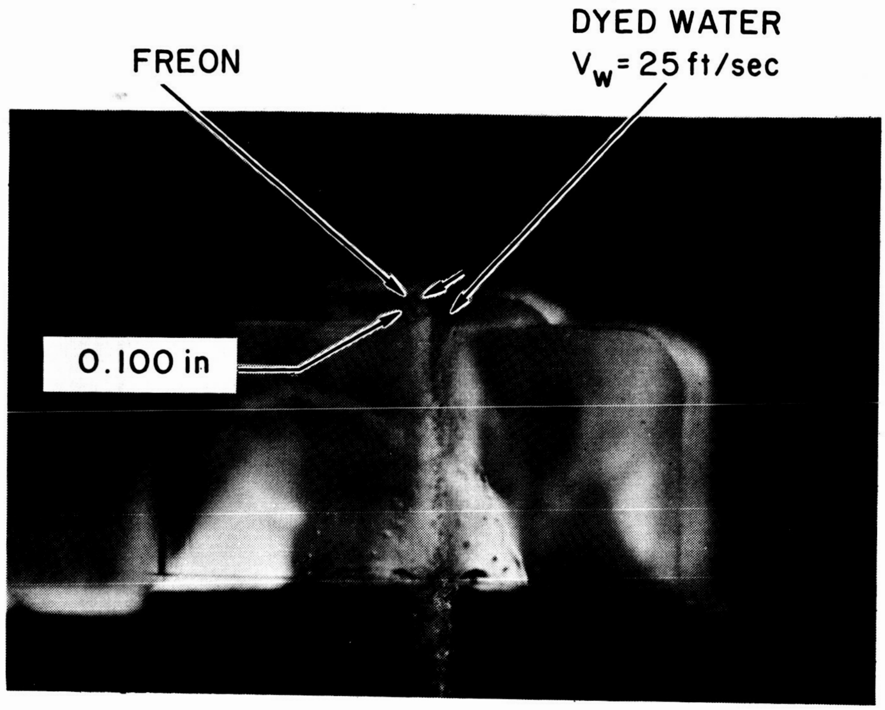


Figure 6. Rocket Facility Flow System



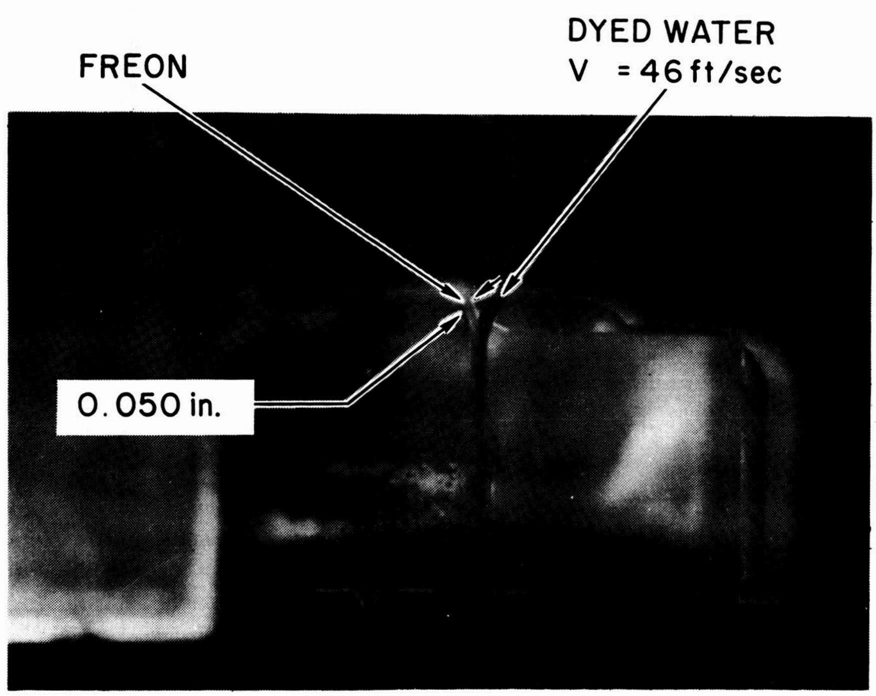


Figure 7. Cold Flow Impingement Tests

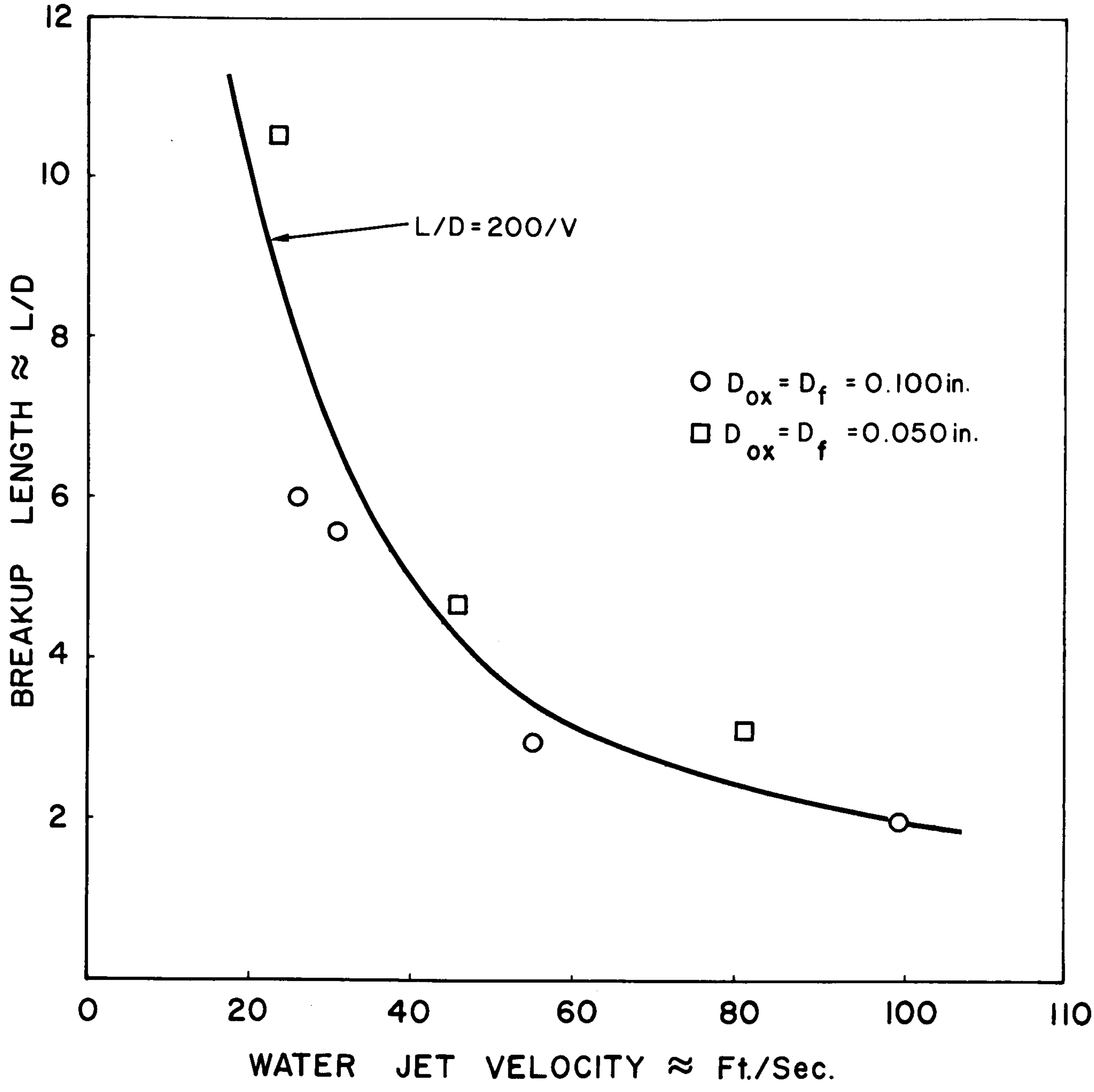


Figure 8. Jet Breakup Length versus Water Jet Velocity for Impinging Jets of Freon and Water.

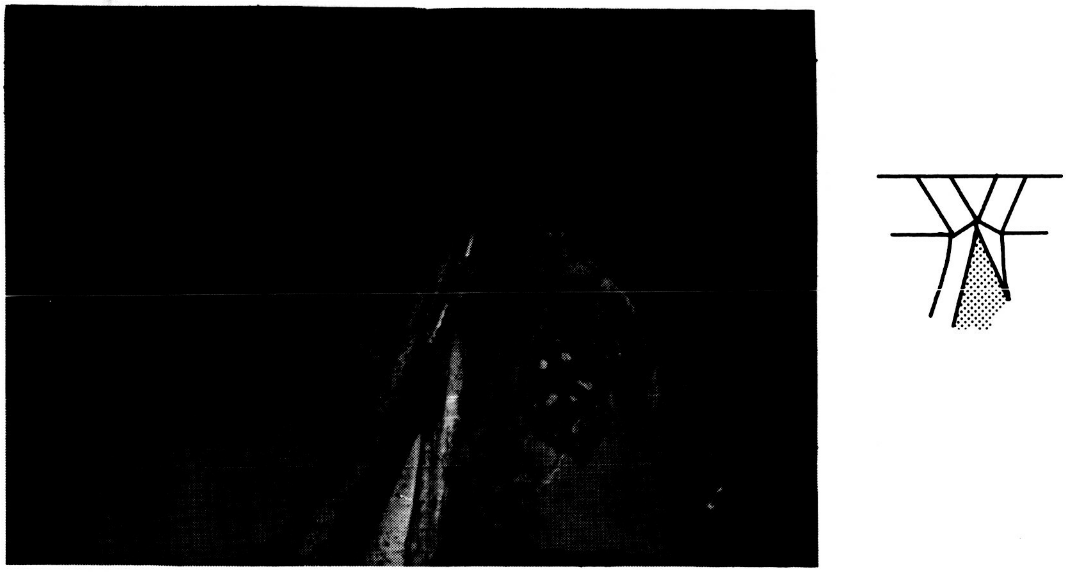


Figure 9. Hydrazine/Nitrogen Tetroxide Impingement at 25°C 25 ft/sec and .100 inch Wide Stream. Regime II-Separation

Figure 10. Dydrazine/Nitrogen Tetroxide Impingement at 25°C 50 ft/sec and .100 inch Wide Stream. Regime II-Separation

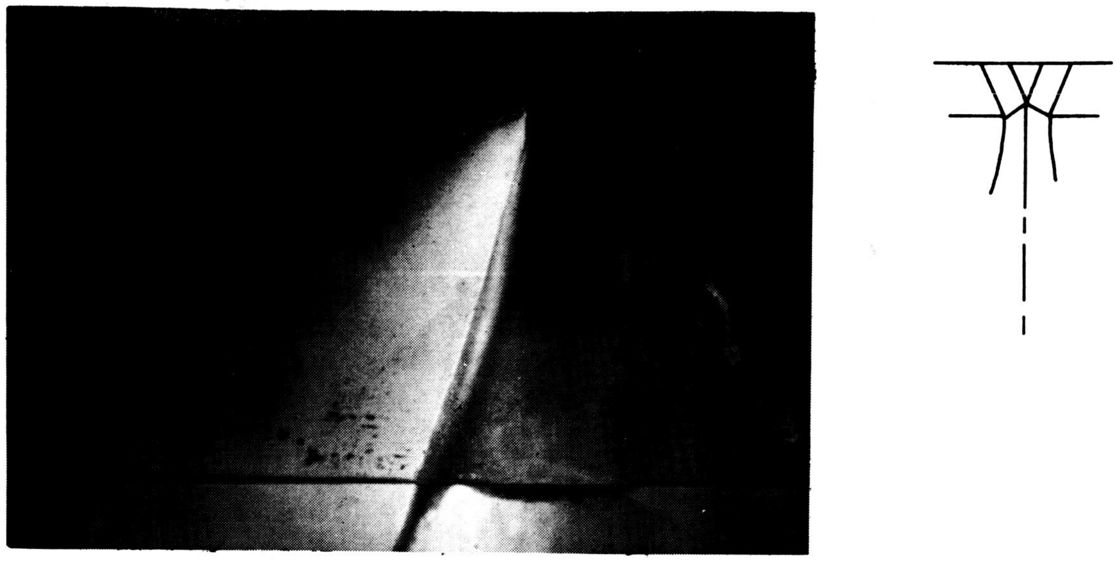


Figure 11. Hydrazine/Nitrogen Tetroxide Impingement 25°C at 100ft/sec and .100 inch Wide Stream. Regime II-Separation

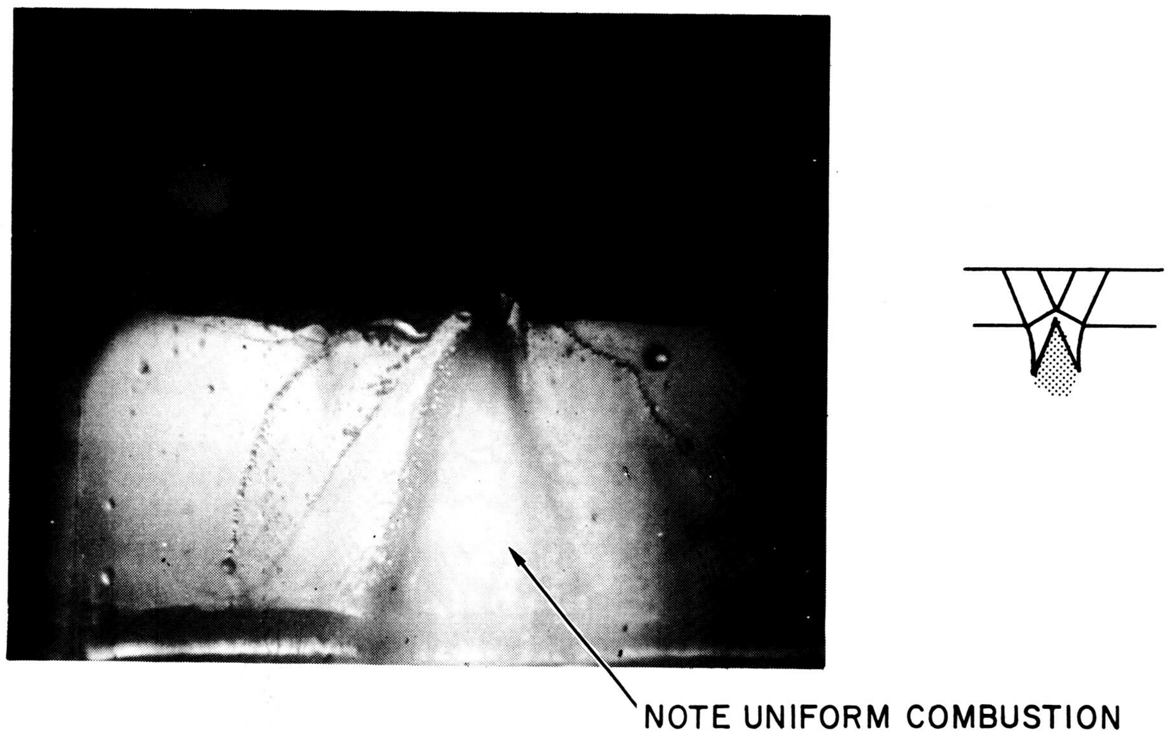


Figure 12. Mixing and Uniform Spray Combustion of N_2O_4/N_2H_4 at 14°C. at 50 ft/sec and .050 inch Wide Stream. Regime I-Mixing

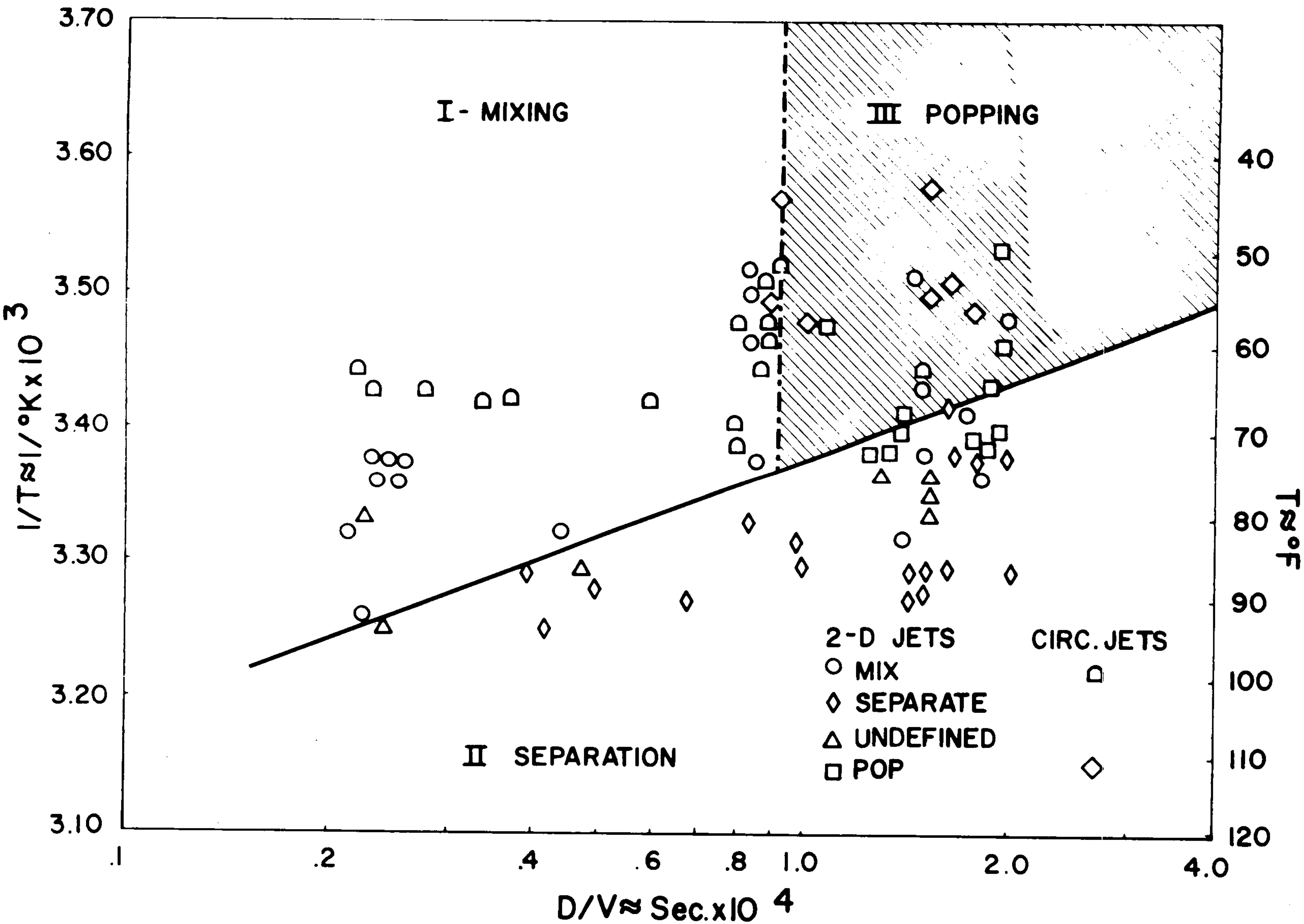


Figure 13. Impinging Jet Separation Data for N_2O_4/N_2H_4 Streams

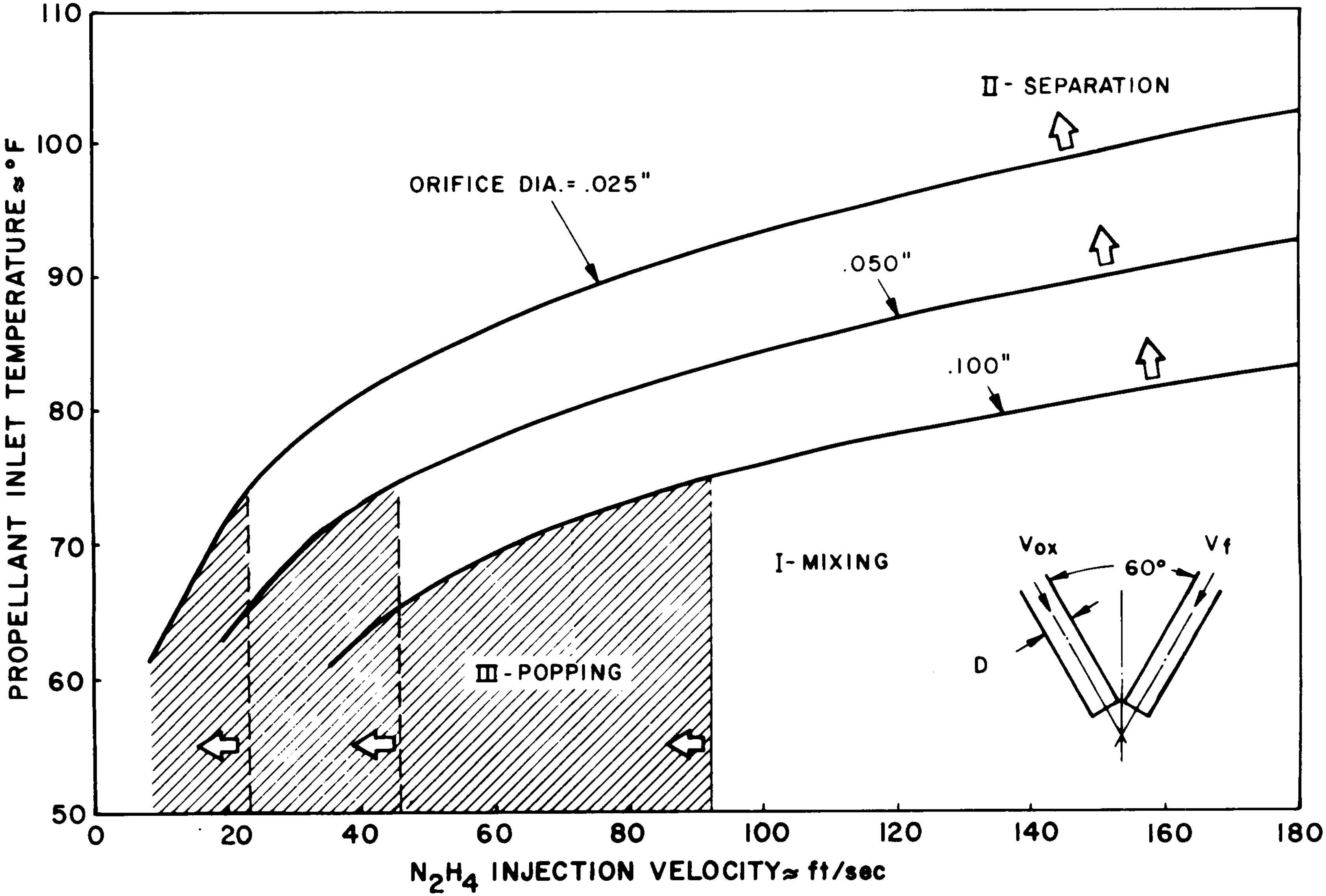


Figure 14. Jet Separation Limits for Impinging N_2O_4/N_2H_4 Streams Propellant Inlet Temperature vs N_2H_4 Injection Velocity

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