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HYPERGOLIC IGNITION AT REDUCED PRESSURES

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AFRPL-TR-64-175

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This technical documentary report has been reviewed and is approved.

Steven J. Tunkel
Manager
Research Engineering Dept.

David J. Mann
Director of Research

FOREWORD

This is the five-month progress report prepared by Thiokol Chemical Corporation, Reaction Motors Division, Denville, New Jersey under Air Force Contract AF04(611)-9946. The work was administered under the direction of Mr. K. Rimer, Rocket Propulsion Laboratory, Edwards Air Force Base.

The Research effort reported herein was conducted during the period 1 May 1964 to 30 September 1964 on RMD Project 5801. The report was prepared by Messrs. A. Corbett, T. Seamans, B. Dawson, and C. Cheetham. Principal investigators of the research effort described are Messrs. B. Dawson and T. Seamans. Other contributors to the program are Dr. M. VanPee and Messrs. C. Cheetham, R. Storms and H. Francis. The Project Leader is Mr. A. D. Corbett, and the Program Manager is Mr. S. J. Tunkel.

ABSTRACT

This report covers the first five months of a ten-month experimental investigation of the ignition of hypergolic propellants at reduced pressures. Unconfined impingement tests are being conducted in a large vacuum chamber in order to define an ignition model for hypergolic propellants and to investigate concepts for reducing ignition delay and resultant pressure spikes. The test setup, experimental program schedule, and concepts for reducing ignition delay are discussed. Results are reported on ignition delay as a function of injection parameters, environmental conditions and concepts such as injector modifications and propellant additives for reducing delay for tests performed with N_2O_4 and IRFNA as oxidizers and hydrazine-type fuels.

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I. INTRODUCTION

With the advent of the many space exploration missions currently in progress or planned, the importance of hypergolic ignition characteristics under vacuum conditions has become of increasing importance. Although hypergolic ignition has been the subject of studies for many years, the effects of space conditions on ignition are relatively unknown. Some propellants which exhibit reliable hypergolic ignition at or near sea level exhibit long ignition delays at vacuum conditions. The unsatisfactory vacuum ignition characteristics of some candidate space propellants present a major limitation to the response capabilities of hypergolic bipropellant reaction controls. Ignition delays encountered during altitude starting severely limit the range and accuracy of pulse-throttled attitude control systems. The extremely high chamber pressure spikes experienced as a result of ignition delay significantly affect the structural integrity of the thrust chambers as well as the accuracy of guidance system sensors.

The present program is a ten-month technical effort to determine and demonstrate the design criteria to minimize hypergolic ignition delay and eliminate the attendant pressure spike upon ignition. This report covers the first five months of the technical program.

The program is being performed in two phases. The first phase consists of a fundamental investigation of hypergolic reactions in a vacuum. The second phase consists of evaluation of the effect of attitude control engine design parameters on ignition delay and the level of pressure spikes in the start transient. The specific objectives of each phase are described as follows:

Phase I consists of:

Item A - The objective of this item is to determine the ignition model for two hypergolic streams impinging in a large vacuum tank and to determine the effect of impingement length, impingement angle, manifold geometry, propellant temperature, injection velocity and ambient pressure on ignition delay. The unconfined impingement tests in the large vacuum tank are intended to eliminate thrust chamber effects on ignition characteristics.

Item B - The purpose of this item is to investigate concepts for reducing ignition delay and resultant pressure spikes. These concepts include additives and/or mixtures to modify propellant properties, injector modifications such as splash plates and unique designs to improve mixing, and valve timing to vary propellant leads.

Phase II consists of:

Design of an attitude control engine on the basis of Phase I results to start with no pressure peak and to maintain a response time of less than 10 milliseconds from signal to 90% Pc. The effect of chamber L*, contraction ratio, design chamber pressure, and propellant leads on the start transient will be evaluated.

The propellants being investigated in the program include:

Oxidizers	Fuels
N_2O_4	Unsymmetrical Dimethylhydrazine
N_2O_4	50% UDMH/50% N_2H_4
H_2O_2	Hybaline A-5
Compound A	Hydrazine
Fluorine (gaseous)	Hydrogen (gaseous)

Emphasis is being placed on the oxidizers and fuels as paired in the above table. However, other potential combinations of oxidizers and fuels also are being evaluated experimentally.

The work covered by this report includes Phase I, Items A and B using N_2O_4 and IRFNA as oxidizers and hydrazine-based fuels including N_2H_4, UDMH, MMH, 50% UDMH/50% N_2H_4 and MHF-5. Scheduled tests with these propellants are 95% completed. The tests will be completed early in the next period, followed by the scheduled tests with the other major propellants indicated above and then by Phase II.

II. SUMMARY

The objective of this program is to establish attitude control engine design criteria which will minimize ignition delay and eliminate pressure spikes in the start transients with hypergolic propellants at reduced pressures. This report covers the first five months of a ten-month experimental program consisting of two phases. The purpose of Phase I is to perform unconfined impingement tests in a vacuum tank in order to define an ignition model for hypergolic propellants and to investigate concepts for reducing ignition delay and resulting pressure spikes. Phase II provides for the evaluation of the design criteria evolved during Phase I in attitude control engines.

This report presents the Phase I results with N_2O_4 and IRFNA as the oxidizers and unsymmetrical dimethyl hydrazine, monomethyl hydrazine and 50% UDMH - 50% N_2H_4 as the fuels. Some comparison tests were made with hydrazine and with MHF-5, a classified mixed hydrazine fuel. Parameters investigated in the unconfined impingement tests included injection velocity, impingement length and angle, manifold feed configuration, propellant temperature and ambient pressure. Because of the large number of parameters to be evaluated, statistical experimental design techniques were used to establish a sixty-run test program to determine the parameters having the strongest influence on ignition characteristics and any interactions which may exist.

Over 400 tests have been made. In no case was it possible to obtain ignition at ambient pressures less than 60 mm Hg in the unconfined tests, at least within the nominal 250 msec duration of each test. However, ignition and stable combustion were obtained in concurrent low-pressure, premixed flame tests at pressures as low as 3 mm Hg. In general, it was found that ambient pressure alone had the most significant effect on ignition characteristics.

All other parameters had little effect on ignition delay although second order effects were obscured to some degree by the wide range of ignition delays encountered at the lower pressures. The wide ranges in delays encountered are undoubtedly due to the unpredictable mixing and concentration of the vapors in the unconfined tests.

Computer analysis and curve fitting of the N_2O_4/UDMH data indicates that the equation

$$\ln \tau_D = 15.5 - 2.6 \ln (P_a)$$

where τ_D is ignition delay and P_a is ambient pressure, best fits

the ignition model. This simple equation accounts for 75.5% of the variations in ignition delay encountered. The percent of variation is defined as the ratio of the "regression sums of squares" of the curve fit to the "total sums of squares" of the data points. A value of 100% (ratio of 1) would indicate that the curve fit has the same sums of squares as the input data points and the two curves coincide. At best, more complicated expressions containing other injector or environmental parameters only account for an additional 2% of the variations.

Injector designs and modifications to improve ignition characteristics which have been evaluated include several splash plate configurations, concentric tube injectors, porous plug injectors, and various spray nozzle injectors. None of these configurations materially improved ignition at the lower pressures and ignition could not be obtained below 60 mm Hg within the nominal test duration of 250 msec. Based on these results, it does not appear that mechanical means short of confining the propellant vapors to generate pressure offer significant improvement in ignition characteristics with this class of propellants.

Propellant additives which have been evaluated include hydrazine nitrate, ammonium perchlorate, and hydrazine diperchlorate in UDMH and NO in N_2O_4. No improvement was obtained. Delays also were longer with N_2H_4 and MHF-5 (although diluted with water) and even small additions (1%) of NO in N_2O_4 appeared to inhibit ignition drastically.

The N_2O_4/hydrazine-type propellant tests will be completed in the immediate future, followed by similar tests with propellants including H_2O_2/Hybaline A-5, Compound A/N_2H_4 and F_2/H_2. Upon completion of the propellant survey, Phase II tests will be conducted.

III. TEST APPARATUS AND INSTRUMENTATION

A. Experimental Facilities

1. Vacuum System

Phase I unconfined impingement tests are being performed in a large vacuum tank so that the effects of confinement in a thrust chamber are eliminated. The vacuum tank is 7 ft. in diameter and 25 ft. long having a volume of approximately 1000 cu. ft. It is fabricated of stainless steel for use with corrosive propellants and products.

Pressure in the tank can be reduced to less than 0.2 mm Hg (0.003 psia) with mechanical pumps. Two pumping systems are used with the vacuum system. One is a Kinney KD 780 pump having a 625 cfm pumping capacity at a pressure of 1 mm Hg. The other is a Roots 6000 system which has a pumping capacity of 3250 cfm at a pressure of 10^{-1} mm Hg. The chamber has ports along both sides for instrumentation and observation.

Pressure rise in the tank during the unconfined impingement tests is negligible. The duration of these tests is 250-500 ms at flow rates corresponding to a thrust level of about 12.5 lbs. During the pre-ignition period, pressure in the tank remains essentially constant and the total rise after the test is generally less than 1 mm Hg. At the expected propellant flow rate of 0.17 lb/sec for the Phase II 50 lb. thrust chamber tests, the rate of pressure rise in the tank will be no more than 0.5 psi/sec after combustion has been established.

Initially, 1 1/4 in. thick pyrex windows were installed in the ports to be used by the schlieren system. However, preliminary tests indicated that the quality of the schliere was unsatisfactory and 3/4 in. thick plate glass was used. Satisfactory test films at approximately 12,000 pictures per second were obtained of inert gases injected through the injector orifices. Schliere due to gas entry can be detected at vacuum chamber pressures down to 5 mm, the lowest pressure tested.

2. Propellant Systems

The oxidizer and fuel propellant systems are shown schematically in Figure 1. Each system consists of a 300 cc stainless steel tank, safety valve, propellant solenoid valve, and associated hand valves and tubing. Each set is mounted on a separate

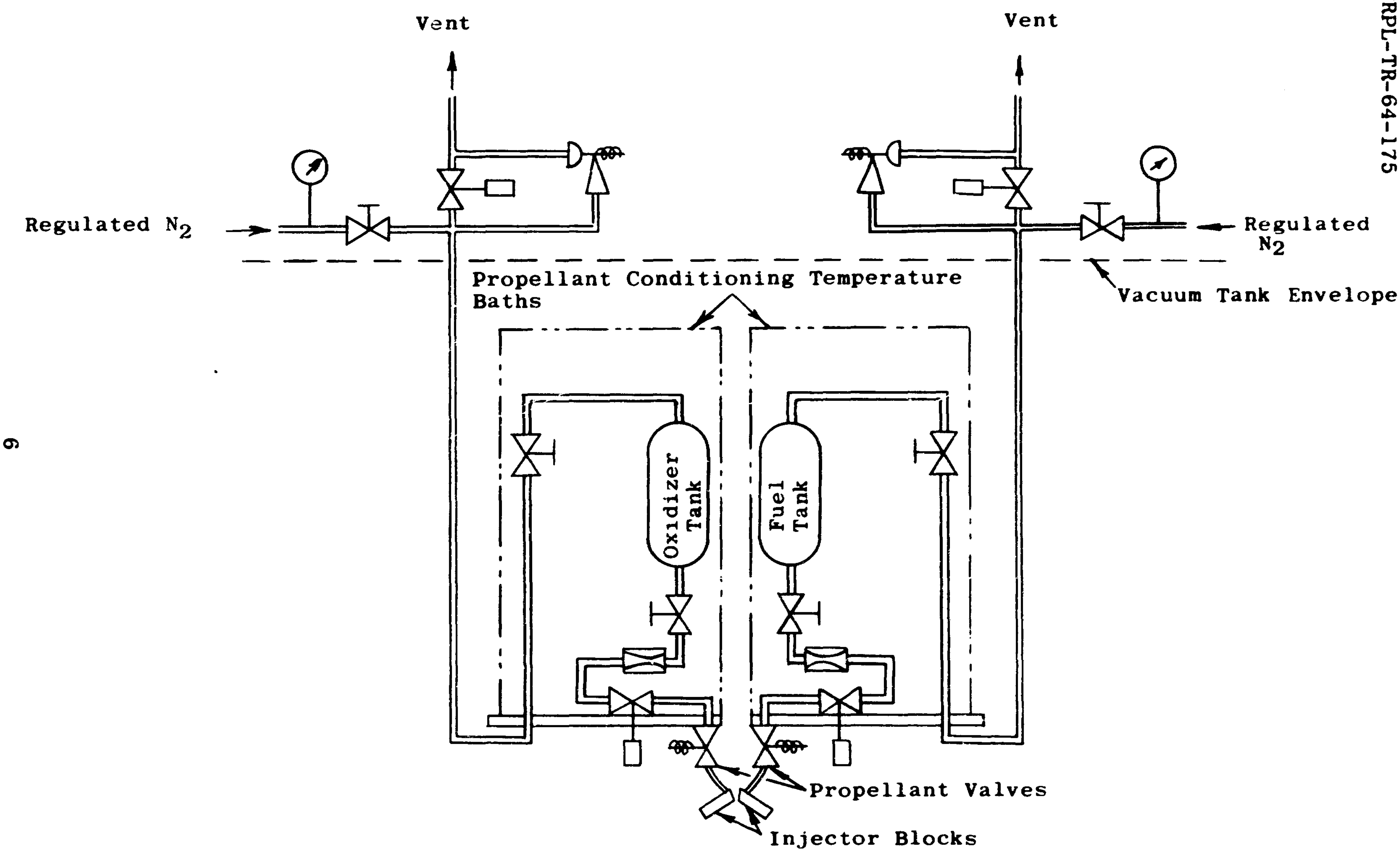

Figure 1. Propellant System Schematic

plate which contains provisions for all necessary external connections such as pressurization, vents and purges so that propellant system conditioning baths can be installed on, or removed from, the mounting plates without disconnecting propellant manifolding. The safety valve actuators and the propellant solenoid valves are located outside the bath for accessibility but are mounted directly on the propellant system mounting plates which serve as bottom closures for the baths so that the propellants are conditioned up to the valve seat.

Figure 2 shows the propellant systems installed in the test mount in the vacuum tank with the conditioning baths removed. In Figure 3, the baths have been installed. One of the solenoid valves for the safety valve actuator is visible in the figures. The propellant solenoid valves are mounted directly below the mounting plate and are not visible.

Separate conditioning baths are used so that propellant temperatures can be controlled individually as desired. The baths contain 1000 watt electrical heaters for the high propellant temperatures. The water bath temperature is monitored remotely and maintained at $+160^{\circ}F$ by automatic temperature controllers. Slurries of ice in water or dry ice in a calcium chloride-water solution are used for the low propellant temperature tests.

During initial tests with N_2O_4 and UDMH, the oxidizer bath was maintained at $+18^{\circ}F$ and the fuel at $-31^{\circ}F$. Respective propellant freezing points are $11.8^{\circ}F$ and $-72^{\circ}F$. However, propellant flows were sluggish at these temperatures and the actual cold tests described in Section IV A were made at oxidizer temperatures of $+32^{\circ}F$ and fuel temperatures of $0^{\circ}F$ in order to obtain reproducible flows.

3. <u>High Response Valve Circuits</u>

Although pulse rate modulation is not required for this program, valves having reproducible, high response characteristics were necessary to minimize any extraneous effects due to this source Since development of special solenoid valves was not within the scope of the work, a circuit was designed and tested to improve the operational characteristics of commercially available solenoid valves. In addition to improving response and reproducibility, another objective of the control circuit was to provide a convenient means of adjusting valve opening times individually so that propellant leads could be adjusted and controlled to determine their effects on ignition characteristics.

A

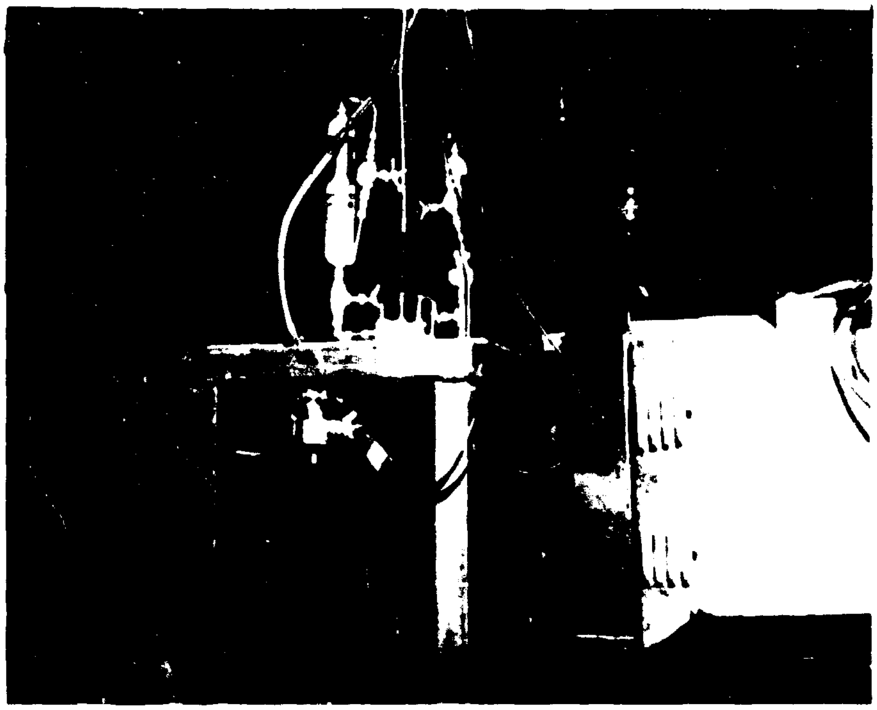

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Figure 2 - Propellant System Installation

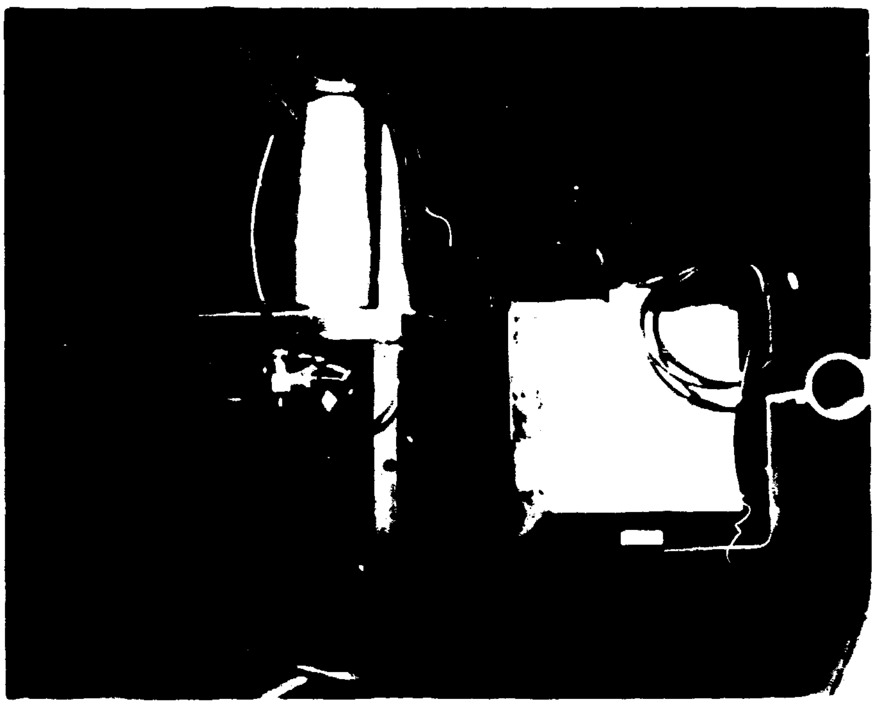

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Figure 3 - Propellant System Installation - Temperature Conditioning Baths Installed

The dual valve timing circuit and power supply schematic are shown in Figure 4. The valves used in the tests to date have been Marotta MV 100 WD Solenoid Valves. These valves have a normal opening time of 24 milliseconds at 24 volts d.c. Valve times as low as 6 msec can be obtained with the circuit and timing is repeatable within 0.5 msec. The potentiometer (R_V) shown in the schematic is used to adjust the propellant leads. Increasing the resistance of the valve circuit increases the opening time of the valve. Timing variations from 0 to 12 msec can be made. To vary which propellant is injected first, the connectors are simply interchanged on the respective propellant valves and the potentiometer adjusted accordingly.

The valve opening time is decreased both by applying a higher voltage across the coil during the time the valve is opening and also by effectively reducing the electrical time constant (τ) of the valve. For example, applying 40 volts across the coil will reduce the normal valve opening time to about 12 msec even though the time constant of the valve is unchanged.

The electrical time constant of the MV 100 WD valves is $\tau = L/R = 21$ msec (63% of final current) where L and R are the coil inductance and resistance, respectively. Coil resistance is 24 ohms. In order to decrease the opening time of the valve, the electrical time constant can be decreased by increasing the resistance R if the forcing voltage is increased to maintain the same current through the valve. In the circuit shown in Figure 4, the time constant is effectively reduced from 21 msec to 10 msec by the two 26 ohm resistors shown. Valve opening current is reached in 6 msec using a driving voltage of 100 v.

The full wave power supply and filter to supply the required voltage also is shown in Figure 4. It is set to provide an open circuit voltage of 150 v.d.c. When the fire switch is closed, the voltage drops to approximately 50 volts due to the current drain through the 10 ohm series resistors and the normal droop in the rectifier output at this current. This voltage drop results in a high initial voltage applied to the valve circuits which drives the current up to the pull-in value very quickly. Steady-state power consumption is distributed throughout the entire circuit and each valve then operates at about 2 ampere

Two valves can be driven simultaneously. The variable resistor, R_V, changes the time constant of the corresponding valve and does not affect that of the other valve. Although increasing the resistance of the variable resistor decreases the electrical time constant further, valve opening time is actually increased in

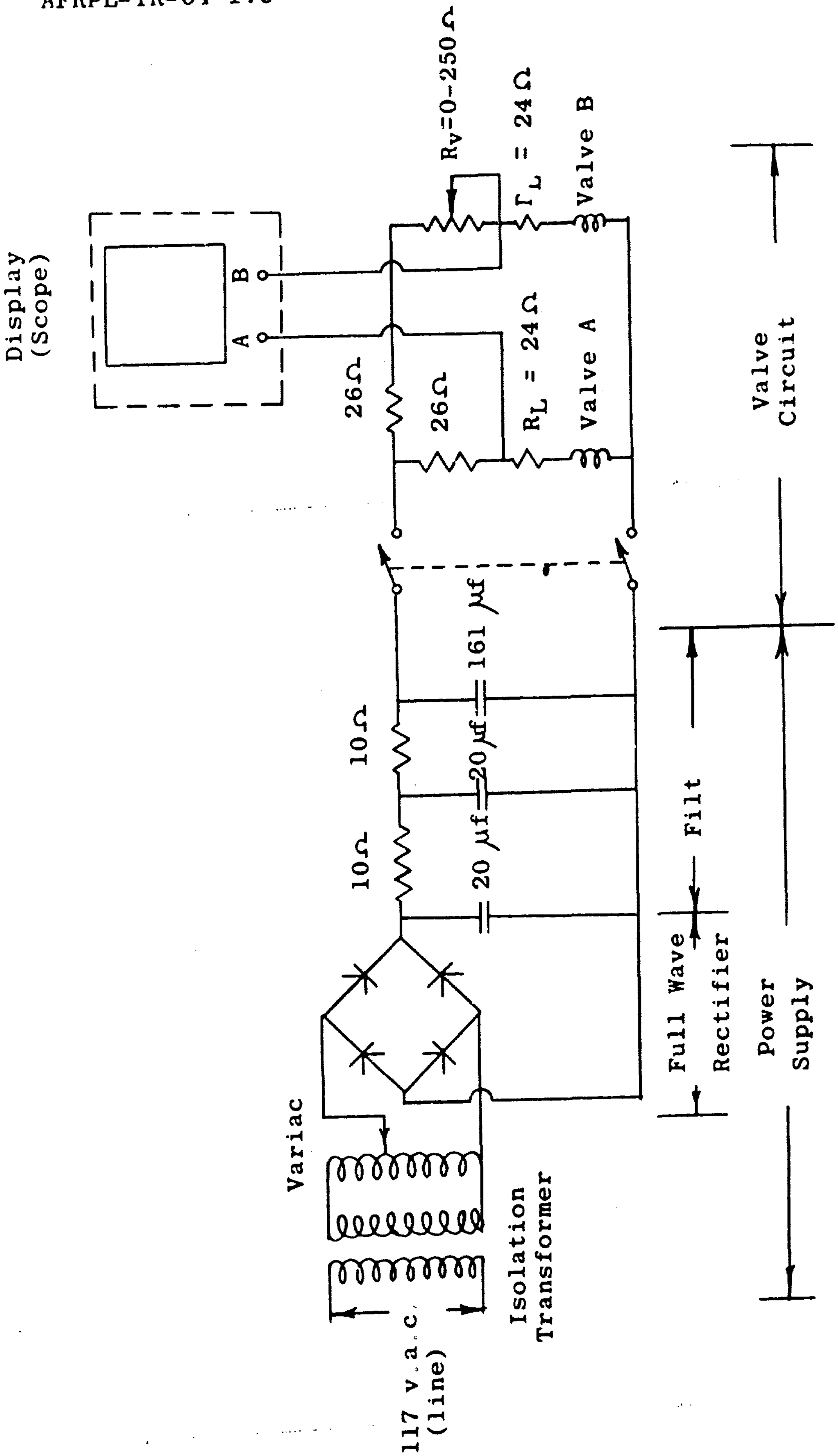

Figure 4. Valve Timing Circuit Schematic

this system. Since the voltage is constant, the final value of the current through the valve is decreased as the variable resistance is increased. The pull-in current, therefore, becomes a larger percentage of the steady state current, increasing the valve opening time.

Solenoid valve current is monitored on a dual beam oscilloscope (see Section III C4) so that valve opening times are accurately recorded and the desired adjustments can be made.

B. Experimental Hardware

The experimental injectors and injector modifications which are discussed below were designed and fabricated for propellant flow rates equivalent to a thrust level of 12.5 pounds. These values were selected on the basis that the single element configurations could be scaled readily to the 50 lb. thrust chamber level specified in Phase II simply by increasing the number of elements used in the actual thrust chamber design. This approach permits evaluation of injector parameters during the unconfined impingement study using essentially the same physical sizes required for the Phase II program, minimizing any possible effects due to dimensional scaling.

The mixture ratios selected for the various propellant combinations are indicated below:

N_2O_4/UDMH	2.0
N_2O_4/50% UDMH-50% N_2H_4	1 6
H_2O_2/Hybaline A5	2.8
Compound A/N_2H_4	2.0
F_2/H_2	10.0

1. Phase I - Item A - Unconfined Impingement Tests

In order to provide an economical method of fabricating a large number of different orifices and facilitate rapid modification of the test setup between runs, a simple injector design consisting of a single oxidizer and a single fuel injector orifice block was used for each injection configuration. Separate blocks having different orifice diameters to obtain the desired injection velocities and to simulate both cross flow and straight tube manifolding were fabricated Cross-sectional views of a direct feed and a cross feed injector block are shown in Figure 5 below.

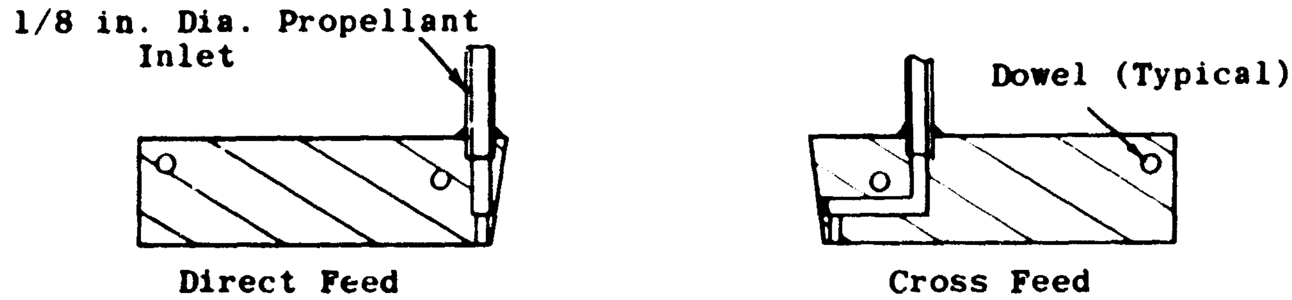

Figure 5. Injector Block Configuration

Typical injector blocks are shown in Figure 6. In the foreground are two direct feed injectors with the inlet line coaxial with the injector orifice. The injector in the right background is typical of the cross feed design. The inlet line is offset 3/8 in. from the injector orifice and connected by a cross-drilled hole. In both injectors to the right of the figure, the orifices are in the opposite face from the inlet lines and are not visible. In both designs the orifices were designed for velocities of 10, 40, 70 and 100 ft/sec with each of the propellants. The L/D of the orifices is 2. The blocks were connected directly to the propellant valves by the 2 in. length of 1/8 in. x 0.020 wall tubing shown.

In order to obtain the desired impingement angles and lengths, the individual injector blocks were mounted on backup plates as shown in Figure 7. A separate backup plate was used for each of the three impingement lengths investigated (1/8, 5/16 and 1/2 in.). Dowel pins, visible in Figure 6, were used for accurate and reproducible orientation of the injector blocks. Each backup plate is drilled for four sets of dowel pins so that angles of 15°, 45°, 60°, and 90° could be obtained while maintaining the impingement length fixed. A typical installation as viewed from the schlieren system port in the vacuum chamber is shown in Figure 8.

2. <u>Phase I - Item B - Injector Designs and Modifications</u>

The purpose of the Item B program is to investigate concepts for reducing ignition delay, based on the results of the Item A tests. The injector modifications designed and fabricated for the concept studies are described below.

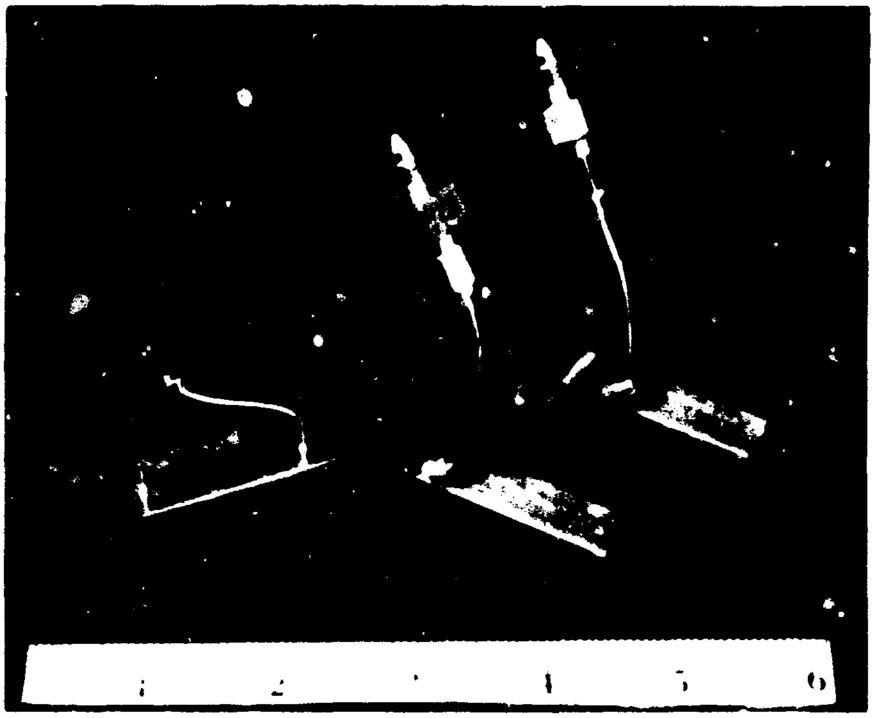

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Figure 6 - Typical Injector Blocks

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Figure 7 - Injector Block Installation On Backup Plate

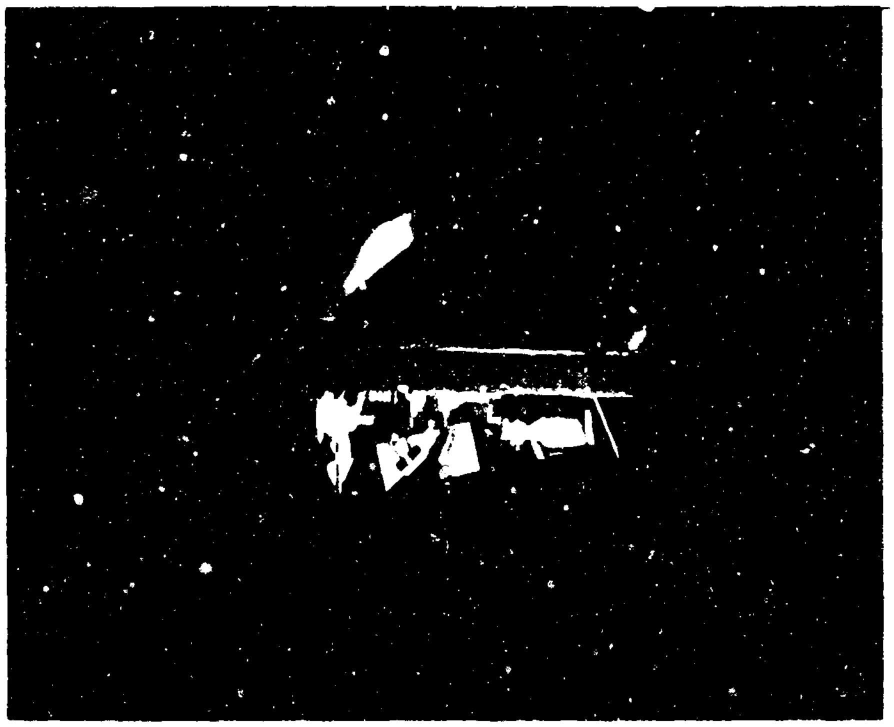

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Figure 8 - Injector Block Assembly Installed in Vacuum Tank

a) Minimum Volume Impinging Stream Injector

Since the results of the Item A tests did not indicate significant effects of the various injection parameters on ignition delay (see Section V), a "standard" minimum volume impinging stream injector was designed and fabricated for evaluation of the various propellant additives and mixtures. As shown in Figure 9, the individual orifice spuds, one for each propellant, were installed directly in the propellant solenoid valves. A mounting bracket maintained an impingement length of 0.25 in. and an impingement angle of 60°. Fuel and oxidizer injection velocities using N_2O_4 and UDMH were 70 ft/sec. The spuds were designed to fill the valve cavity downstream of the poppet. Liquid volume in each injector spud was limited to approximately 0.006 cu. in.

b) Splash Plate Configurations

Several splash plate configurations were fabricated for use with the minimum volume impinging stream injector described above. These are shown in Figure 10. The configurations included: 1) a 1/8 in. diameter stainless steel tube located just below the impingement point of the propellants. The axis of the tube is at right angles to the plane of the impinging streams, 2) a 5/8 in. wide stainless steel plate located just below the impingement point; 3) a 3/16 in. diameter cup mounted on the 5/8 in. wide plate to confine the resulting mixture; and 4) a tube having a 3/16 in. diameter bore located so the impingement point is inside the tube.

c) Concentric Tube Injectors

Two variations of a single-element concentric tube injector were designed and fabricated. In one version the tube ends were coplaner and in the other, the center tube was withdrawn 0.2 in. into the outer tube in order to form a recess for mixing before injection into the chamber. The coplaner configuration is shown in Figure 11. The inner tube was fabricated from a 1/8 in. diameter tube having an 0.02 in. wall thickness. The annular slot between the inner and outer tubes is 0.01 in. Injection velocities with N_2O_4 and UDMH are approximately 10 ft/sec.

d) Porous Plug Injector

The porous plug injector is shown in Figure 12. It consists of stainless steel wire compressed into a plug 0.5 in. in diameter and 0.3 in. long. The plug is contained in a stainless steel housing to which the propellant inlet lines are welded. In the tests discussed in Section V, fuel was injected axially into

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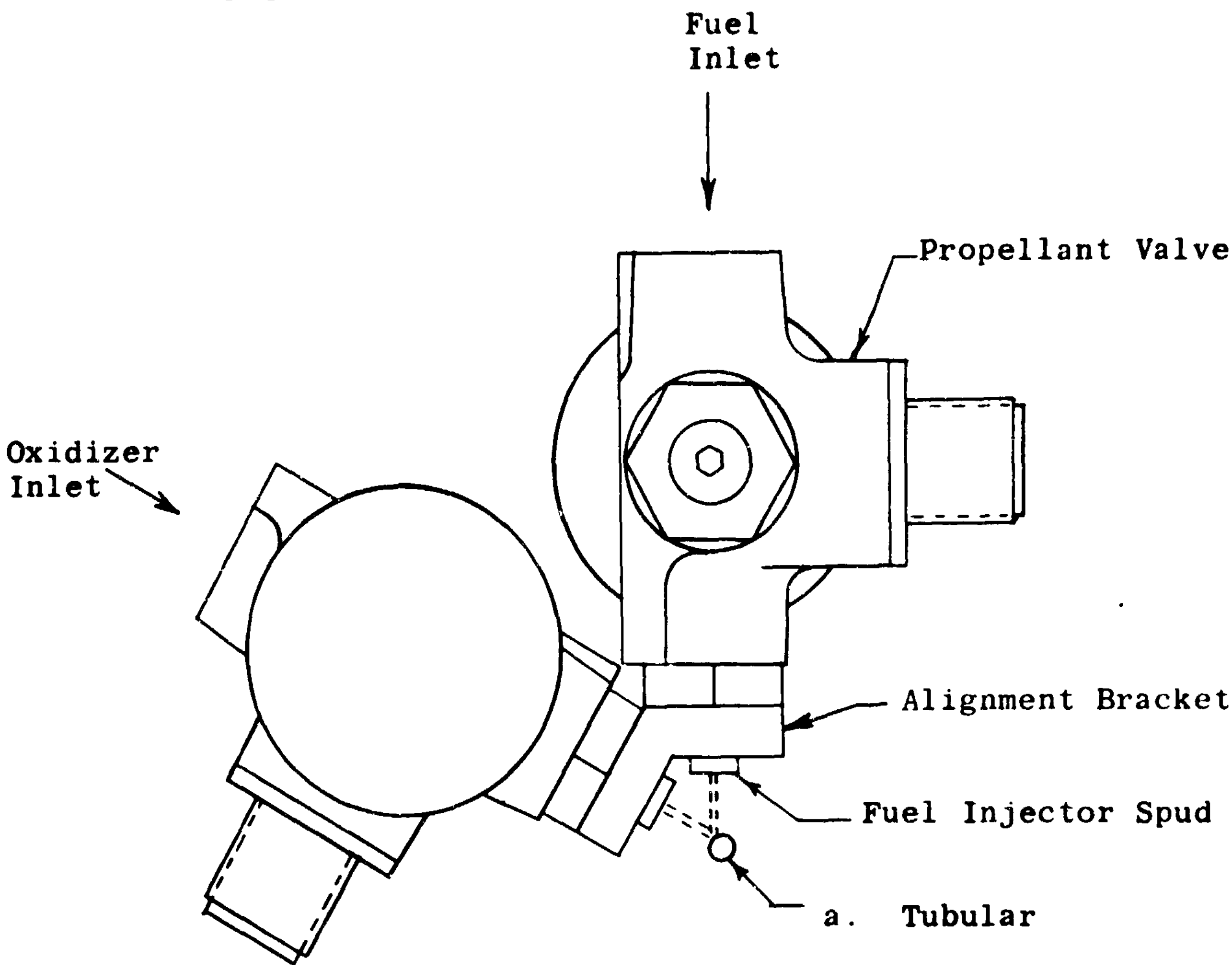
Figure 9 - Minimum Volume Impinging Stream Injector



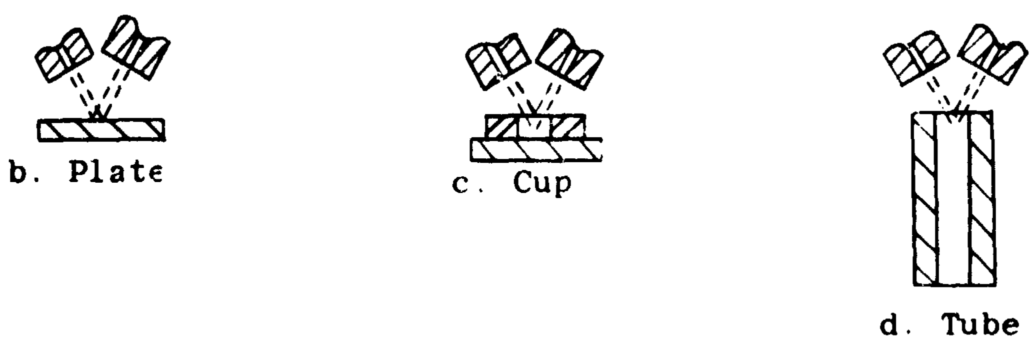


Figure 10. Splash Plate Configurations
with Impinging Injector

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Figure 11 - Concentric Stream Injector

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Figure 12 - Porous Plug Injector

the back center of housing and oxidizer was injected radially into one side of the housing midway along the side of the plug. Injection velocities were approximately 100 ft/sec.

e) Spray Nozzle Injectors

Various combinations of commercial spray nozzles also were tested. These were adapted to fit directly into the propellant valves in order to minimize hold up volumes in the system. One set consisted of Spraying Systems Fulljet 30° full cone (Type 1/8 GG 3001.4) spray nozzles which produced relatively coarse sprays at the test flow rates. Fuel pressure drop was 30 psi and oxidizer pressure drop was 80 psi at the nominal N_2O_4 and UDMH flow rates. The second set of spray nozzles consisted of the 30° spray angle described above for the oxidizer and a 60° full cone Delavan spray nozzle for the fuel. This nozzle had a pressure drop of 580 psi at the nominal fuel flow rate and produced a very fine spray. Both of the above fuel spray nozzles also were used in combination with the single stream oxidizer injector (Figure 9) having an injection velocity of 70 ft/sec. In all of these combinations the centerline impingement angle was 35° and the horizontal distance between the orifices was 0.8 in.

C. Instrumentation

In addition to conventional instrumentation required for propellant pressurization and system monitoring, special instrumentation was employed during the Phase I program to determine ignition delays and monitor local pressure transients during the ignition process. This instrumentation included high speed schlieren movies of the propellant impingement zone, photomultiplier tube to detect ignition, high speed direct photography and high response pressure transducer and recording equipment. The locations of the instrument systems are shown in Figure 13 and are discussed in detail below.

1. Schlieren System

The purpose of the schlieren system was to investigate propellant stream characteristics and determine the time at which the propellants impinged. Not only can the initial time of contact be ascertained by this method but information on vaporization and mixing of the propellants could be obtained. Since it was anticipated that initial injection of the propellants would be in the vapor phase at the lower ambient pressures, direct photography alone would not be adequate for this purpose.

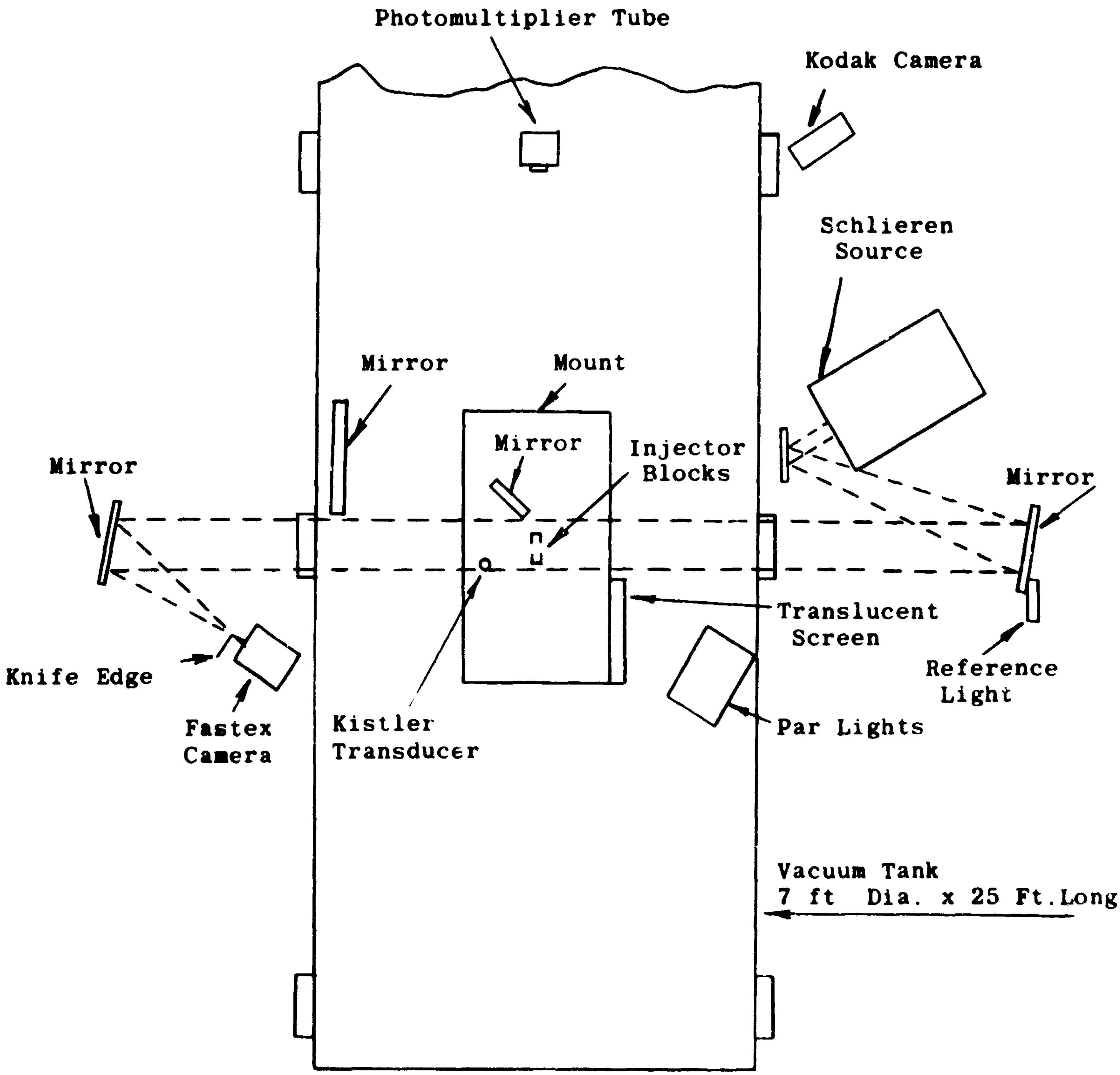

Figure 13. Unconfined Ignition Test Setup

A two-mirror, parallel path schlieren system was used with a Fastax camera as shown in Figure 13 to obtain suitable time resolution. The essential components of the system include a Unertl Model BH6 Normal and Color Schlieren Source, a pair of eight-inch front-surface parabolic mirrors of 64 in. focal length, knife-edge and the Fastax camera capable of up to approximately 16000 pictures per second using split-frame optics. Time resolution at ignition is approximately 6 to 7 frames (12 to 14 pictures) per millisecond.

The schlieren light sources and one parabolic mirror are shown in Figure 14. The second parabolic mirror and the Fastax camera are shown in Figure 15. Also visible in the latter figure is the temperature controller for the propellant bath temperature.

As indicated previously the sensitivity of the schlieren system is satisfactory over the vacuum pressure range of interest using 3/4 in. plate glass windows in the vacuum chamber. Dilute vapors are readily observed issuing from the injector and mixing in the impingement region prior to the appearance of the propellants in the liquid phase. The field of view of the schlieren system is limited to the impingement zone in order to permit maximum resolution of stream characteristics. Since ignition occurs at or near the impingement point at sea level pressure it is readily observed in the high speed movies. Ignitions at reduced pressures, however, occur at some distance below the impingement point, outside the field of view of the schlieren system. The schlieren indication of ignition, therefore, is used to determine ignition delay at sea level where delays are generally less than 1 or 2 msecs while the photomultiplier tube indication is used at reduced pressures where the delays are considerably longer.

Both black-and-white and color films were taken during the course of the test program. Since color did not offer any advantages over black-and-white insofar as analysis was concerned, the majority of the tests were photographed in black-and-white because of the shorter development cycle. Selected runs, however, were photographed in color.

2. Direct Photography

A Kodak camera having a speed of approximately 3000 frames per second was installed for direct photography purposes. Although inadequate alone for vapor injection, it was thought that these pictures might provide additional insight on the vaporization and mixing of the liquid streams and aid in interpretation of the

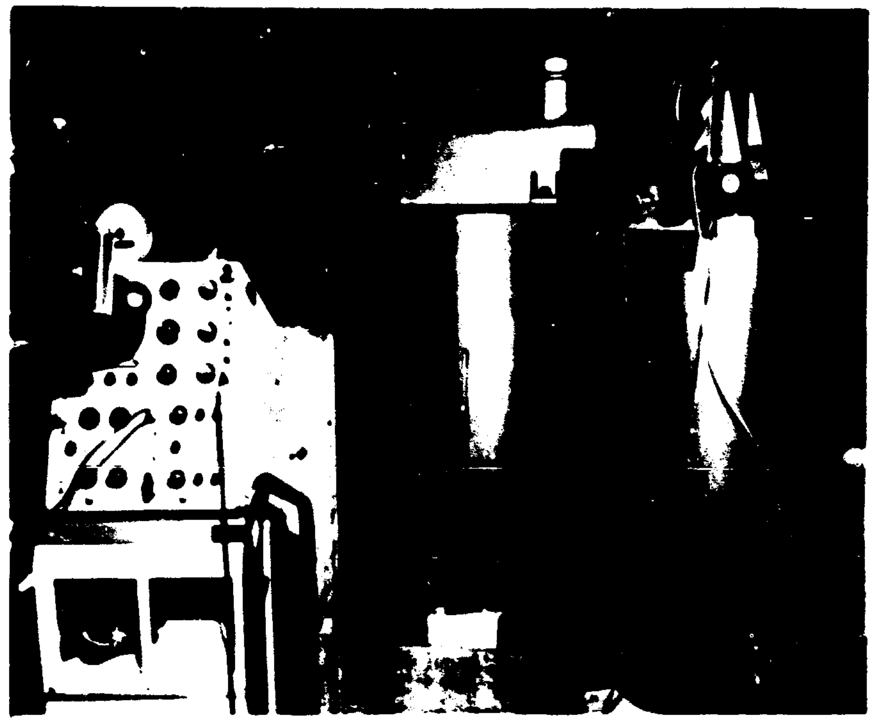

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Figure 14 - Schlieren Light Source and Oscilloscope Setup

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Figure 15 - Schlieren Camera and Propellant Bath Temperature Controller Setup

schlieren films As shown in Figure 12, this camera viewed the impingement zone through a mirror so as not to interfere with the schlieren system. Backlighting through a translucent screen was used. Both color and black-and-white films were taken during the initial tests. However, no additional information was provided by the direct photography films so it was subsequently used for documentation purposes only and data reduction was concentrated on the schlieren system.

3. Ignition Detection

To determine the time at which ignition occurs, a flame detector consisting of an RCA 1P28 photomultiplier tube and an ultraviolet transmitting filter was used Since the photomultiplier tube is sensitive to wavelengths from about 2200 A to 6000 A, a filter was required to block out the visible light from the schlieren source The filter peaks at 3130 A and has a 180 A bandwidth at half-peak transmission. The principle emitter in this spectral region is the (0,0) OH band, an intermediate in the combustion of all propellant combinations tested to date.

The flame detector is located in the vacuum chamber as shown in Figure 13 approximately 6 feet from the injectors with an unobstructed view of the entire mixing zone from the injectors to the bottom of the tank, a distance of about 3 1/2 feet. It is sensitive to ignition regardless of origin therefore, whether it occurs at the impingement point as it does at sea level or whether it occurs well below the impingement point as it does at reduced pressures

The photomultiplier tube is operated at a 900 V potential Its signal is monitored on a Tektronix Type 551 Dual-Beam Oscilloscope and recorded by a fixed-focus Polaroid Camera. Preamplifier gain controls are set for high sensitivity to insure earliest possible sensing of ignition

4. Pressure Instrumentation

In order to detect possible pressure surges accompanying ignitions in the large volume tank, a high-response piezoelectric pressure transducer was used during the unconfined impingement tests. The signal from a Kistler Model 601 pickup having a natural frequency of 150,000 cps in conjunction with a Kistler Charge Amplifier Model 566, was displayed by the second beam of the Tektronix oscilloscope, the first beam of which displayed the flame detector signal. The pressure sensor was located within four inches of the propellant impingement point as shown in Figure 13. Sensitivity of the pressure measuring system permitted detection of a pressure change of as little as 5 mm Hg. However, no indication of pressure surges have been detected in the tests to date.

5. Recording Equipment

In addition to the schlieren and direct photography film records, the Tektronix Type 551 Dual-Beam Oscilloscope was the primary means of data acquisition. As indicated previously, the output from the photomultiplier tube to indicate ignition, and pressure in the vacuum chamber to detect any localized pressure surges due to ignition were monitored on the scope and recorded by Polaroid camera. In addition, fuel and oxidizer valve currents to determine valve opening times were recorded on the oscilloscope. The valve currents were superimposed on the oscilloscope beam used to monitor pressure.

A single-flash strobe light mounted outside the vacuum tank was used as a time reference for the cameras and the oscilloscope. The flash, having a duration of 1-2 msec, was detected by the cameras and by the photomultiplier tube and could be used to correlate the various instrumentation time-wise.

The strobe light is shown in Figure 14, attached to the parabolic mirror pedestal. Also visible in the figure is the oscilloscope.

IV. EXPERIMENTAL PROGRAM

A. Phase I, Item A - Unconfined Impingement Tests

The objective of the initial phase of this program is to determine an ignition model for defining the ignition characteristics of hypergolic propellants in unconfined impingement tests at reduced pressures. The specific parameters which are being investigated as part of this work include the effect of impingement length, impingement angle, injection velocity, manifold geometry, propellant temperature, and ambient pressure on ignition delay. The range of parameters that are being investigated are shown below:

Manifold Geometry	Cross flow or straight flow
Impingement Length	1/8, 5/16, 1/2 in.
Impingement Angle	15^{o}, 45^{o}, 60^{o}, 90^{o}
Injection Velocity	10-100 ft/sec (liquids)
Propellant Temperature	~ Freezing point, ambient, and + 160^{o}F
Ambient Pressure	.004-14.7 psia (depending on ignition delay characteristics)

The propellants to be investigated during the course of the program are discussed in Section I.

The simple, single-element injector blocks described in Section IIIB1 were used for the unconfined impingement tests. Because of the extremely large number of possible combinations of injection parameters, environmental conditions and propellant combinations, statistical experimental design techniques were used to establish a rational test program to indicate the variables having the strongest influence on the ignition characteristics and any interactions that may exist between the variables. The basic test schedule encompassing the range of parameters desired, based on the Random Balance Experimental Design approach, is shown in Table I. This 60-run program was coordinated with the injector designs so that impossible or impractical combinations due to geometrical limitations were screened out. The schedule gives equal weight to each of the variables and computer programs are available to analyze the results of the tests.

TABLE I

SCHEDULE OF TESTS

Test No.	Impingement Length (inches)	Impingement Angle (degrees)	Velocity Oxidizer (ft/sec)	Velocity Fuel (ft/sec)	Manifold (Direct) (Cross)	Temp. °F	Press.
1	1/8	90	70	40	D	60	A
2	1/8	90	100	100	D	60	C
3	1/8	90	70	70	C	60	B
4	1/8	45	100	100	C	60	D
5	1/8	60	70	100	C	60	A
6	5/16	90	10	10	C	60	D
7	5/16	60	70	70	D	60	A
8	5/16	90	100	70	C	60	A
9	5/16	60	70	40	C	60	A
10	5/16	45	40	40	D	60	A
11	5/16	15	70	70	D	60	D
12	5/16	15	40	70	D	60	A
13	1/2	90	70	100	D	60	D
14	1/2	60	100	70	D	60	B
15	1/2	45	40	10	D	60	B
16	1/2	45	40	70	C	60	D
17	1/2	45	40	40	C	60	A
18	1/2	45	40	10	C	60	D
19	1/2	45	10	40	C	60	A
20	1/2	15	10	40	D	60	A
21	1/8	90	100	70	C	160	C
22	1/8	90	10	10	D	160	B
23	1/8	90	40	10	D	160	A
24	1/8	60	40	10	D	160	D
25	1/8	60	100	70	D	160	D
26	1/8	45	70	70	D	160	B
27	1/8	45	40	40	C	160	D
28	1/8	45	70	100	C	160	B
29	5/16	90	10	10	C	160	C
30	5/16	90	70	40	D	160	B
31	5/16	60	10	40	D	160	A
32	5/16	60	10	40	C	160	C
33	5/16	45	100	100	C	160	C
34	5/16	45	40	10	C	160	D
35	5/16	15	40	70	C	160	B
36	5/16	15	40	70	D	160	B
37	5/16	15	70	40	D	160	B
38	1/2	90	40	40	D	160	B
39	1/2	90	10	10	C	160	D
40	1/2	15	70	100	C	160	B

TABLE I (Cont'd)

SCHEDULE OF TESTS

Test No.	Impingement Length (inches)	Impingement Angle (degrees)	Velocity Oxidizer (ft/sec)	Velocity Fuel (ft/sec)	Manifold (Direct) (Cross)	Temp. °F	Press.
41	1/8	90	100	70	D	FP	C
42	1/8	90	10	40	C	FP	B
43	1/8	60	40	40	C	FP	A
44	1/8	60	40	10	C	FP	A
45	1/8	60	70	100	C	FP	C
46	1/8	45	100	100	D	FP	A
47	1/8	45	100	100	D	FP	D
48	5/16	60	10	10	C	FP	C
49	5/16	45	100	70	C	FP	C
50	5/16	15	100	100	C	FP	E
51	5/16	15	70	70	D	FP	C
52	1/2	60	70	40	D	FP	D
53	1/2	60	40	70	C	FP	B
54	1/2	60	70	70	C	FP	D
55	1/2	15	70	40	C	FP	C
56	1/2	15	40	40	D	FP	C
57	1/2	15	10	10	D	FP	D
58	1/2	15	10	10	D	FP	C
59	1/2	15	40	70	D	FP	C
60	1/2	15	70	100	D	FP	C

B. Phase I, Item B - Reduction of Ignition Delay

The test program to investigate concepts for reducing ignition delays consists essentially of individual tests at sea level and reduced pressures to determine the effects of each concept. The concepts evaluated to date include injector designs and/or modifications to improve propellant mixing, propellant additives and/or mixtures to modify propellant properties, and valve timing to vary propellant leads.

The injector designs and/or modifications evaluated to date with N_2O_4 and hydrazine-based fuels include:

- splash plates
- concentric tube injectors
- porous plug injector
- spray nozzle injectors

The mechanical details of this design are discussed in Section IIIB2. The propellant mixtures and additives evaluated include:

- N_2O_4 with NO added
- UDMH with hydrazine nitrate added
- UDMH with ammonium perchlorate added
- UDMH with hydrazine diperchlorate added
- MHF-5 (mixed hydrazine fuel)

Unfortunately, solubilities in N_2O_4 are generally low. NO was selected as an additive because of its solubility in N_2O_4 and because it is a commonly used additive to depress the freezing point of N_2O_4. Also, it was observed in the test program that ignition delays with N_2O_4 (and hydrazine-type fuels) were shorter than with IRFNA. One difference between the oxidizers is the higher vapor pressure of N_2O_4. Since NO further increases the vapor pressure of N_2O_4, it afforded a convenient method of investigating this property

The selection of fuel additive was influenced to a large degree by mutual compatibilities. The additives selected are compatible with UDMH and are slightvapor pressure suppressants. This would be desirable if excessive volatility were experienced at low ambient pressures. Reducing vapor pressure would overcome flash vaporization to permit reactions in the liquid phase Actually two conflicting observations were made with the neat propellants. First, ignition in almost every case was preceeded by the appearance of liquids at the injector ports. A lower vapor pressure would permit earlier arrival of liquid propellants But on the other hand, ignition delays were shortest for the hydrazine-based fuels which have the highest vapor pressures, i.e. UDMH of the three such fuels tested with N_2O_4 and IRFNA.

Hybaline was considered as an additive for the hydrazine fuels. However, a substitution reaction is expected but this does not necessarily eliminate Hybaline as a useful additive. The speed of the reaction is not known nor is the reactivity of the resultant specie. These would have had to be determined but time did not permit. However, compatibility studies of Hybaline as an additive do appear to be warranted. Tests with Hybaline A5 and H_2O_2 conducted after this report period gave short ignition delays even at very low ambient pressures.

V. EXPERIMENTAL RESULTS

A. Quenching Diameter Tests

While preparations were being made to conduct the unconfined impingement tests in the large vacuum chamber, a series of experiments with low pressure flames was performed in a smaller vacuum tank. The purp e of these experiments was (1) to obtain minimum pressures for hypergolic ignition of the propellant pairs to indicate the pressure range of interest in the impinging stream tests and (2) to determine the limiting pressures below which stable combustion cannot occur in thrust chambers of typical attitude control motors.

The low pressure flame apparatus in which the propellants were burned is shown in Figure 16 It consists of a burner tube, surrounded by an air or nitrogen shroud, located in the center of a two-foot diameter steel bell jar which is connected to a vacuum pumping system. Oxygen, hydrogen and N_2O_4 gas flows were regulated by throttling valves and calibrated flowrators whereas the liquid fuels (UDMH, MMH, 50% UDMH/50% N_2H_4) were flowrated in the liquid phase and subsequently vaporized in a heated glass spiral. Fuel and oxidizer vapors were premixed in the burner tube which was heated slightly above ambient temperature to prevent condensation.

Premixed flames of H_2, UDMH, MMH and 50% UDMH/50% N_2H_4 were burned at low pressures with both O_2 and N_2O_4 as oxidizers. Flame stability regions, quenching diameter, burning velocities, and pressure ignition limits (in the case of hypergolic combinations) were obtained

Test procedures consisted essentially of evacuating the vacuum chamber to 3 mm Hg or less and then establishing the desired fuel and oxidizer flow rates With these conditions established, the pressure in the chamber was slowly increased until ignition occurred with the hypergolic propellants, defining the limiting pressure for spontaneous ignition at the selected flow rates or stream velocity. Spark ignition was used for the non-hypergols.

With stable combustion established on top of the burner, the pressure in the chamber was increased until the flame struck back into the tube. Pressure in the chamber was then decreased until the flame blew off the tube This procedure was repeated at various propellant flow rates or stream velocities, to establish flame stability regions and pressure ignition limits as described below.

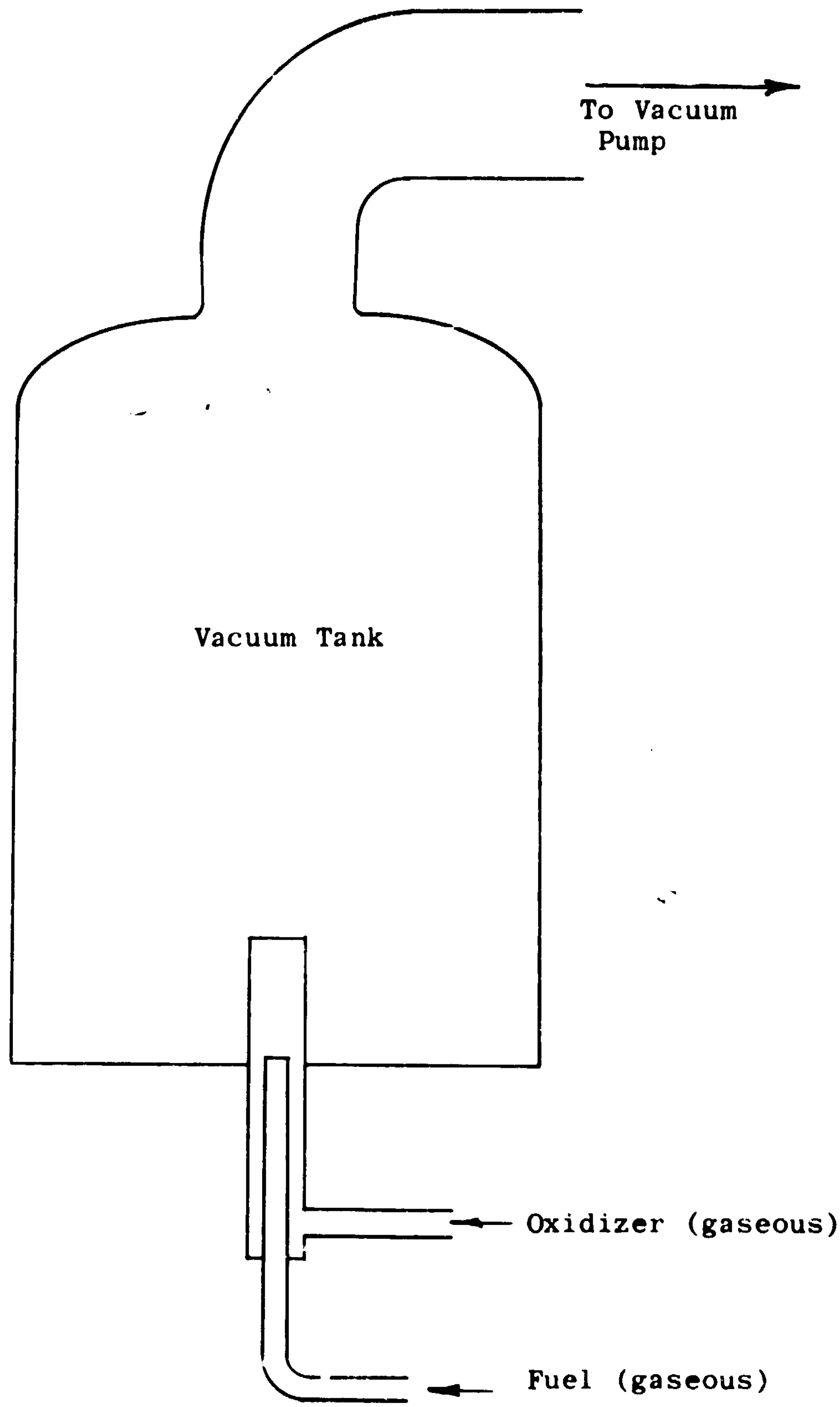

Figure 16. Schematic of Low Pressure Flame Apparatus.

1 Flame Stability Regions and Quenching Diameters

For a given pressure, a flame is stable on top of the burner between two limiting propellant stream velocities. At the upper limit of stream velocity the flame blows off. At the lower limit the flame strikes back into the tube. Blow off and strike back limits are functions of pressure and converge to a single point. At this point the flame is a perfect disc and a slight reduction of stream velocity causes the flame to go out. This is the smallest possible flame which can be burned at a given pressure and its diameter, roughly the diameter of the burner is called the quenching diameter. The quenching diameter is, as a first approximation, inversely proportional to pressure. The larger the diameter, the lower the pressure at which a stable flame can be obtained. Therefore, the determination of the limiting pressure for one burner allows one to derive the limiting pressure for any diameter.

Flame stability diagrams for N_2O_4/UDMH, N_2O_4/MMH and N_2O_4/50% UDMH-50% N_2H_4 are shown in Figures 17-19, respectively. These diagrams were obtained using a burner diameter of 46.6 mm (1.83 in.). The lowest point on each curve represents the limiting pressure at which a stable flame can be obtained with a burner tube of this diameter. Also shown in these figures are the pressure limits for hypergolic ignition for each of the propellant combinations.

Table II summarizes these limiting pressures corresponding to the tube (quenching) diameter of 46.6 mm for the tests using N_2O_4 and with similar tests using O_2 as the oxidizer. Note that the hypergolic combinations with N_2O_4 have a considerably lower limiting pressure than do the same fuels with O_2.

Table III summarizes the quenching diameters at an ambient pressure of 10 mm Hg for the various fuel/oxidizer combinations investigated, based on the above mentioned relationship that the quenching diameter is inversely proportional to pressure.

2 Pressure Ignition Limits

It was found that all the hydrazine fuels ignited spontaneously with N_2O_4 in the test apparatus. Ignition occurred in the vacuum tank above the burner and the flame propagated to the tube. There was, however, a low pressure limit for this spontaneous ignition. These limits are shown in Figure 17-19 for each of the propellant combinations and in Figure 20 for comparison of the propellants. As shown in the figures the lower pressure limit increases only slightly with stream velocity. Rather, it appears to be a function of contact time since ignition occurred further from the burner at the higher stream velocities. However, ignition

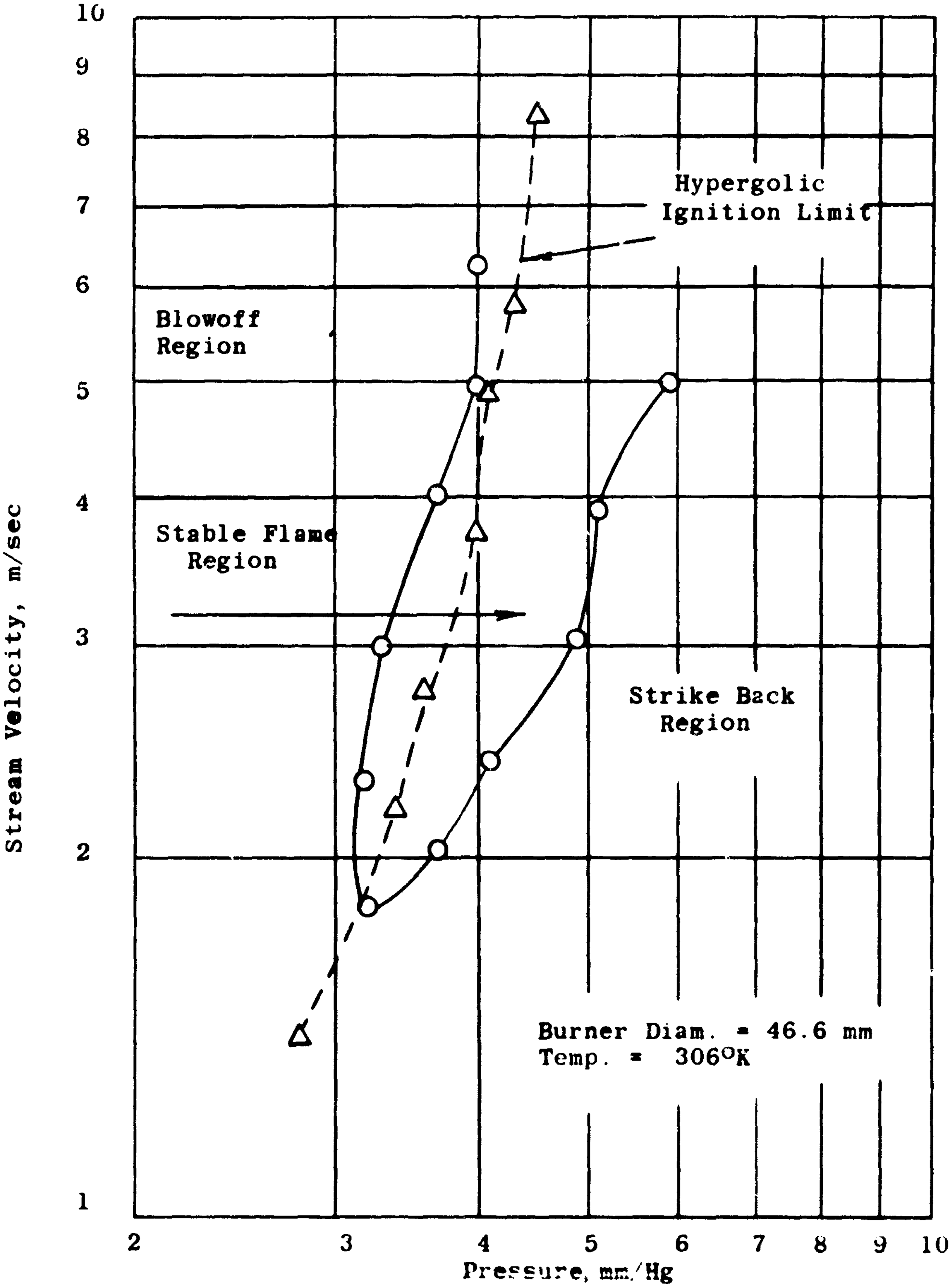

Figure 17. Stability Region of Stoichiometric N_2O_4/UDMH Flame

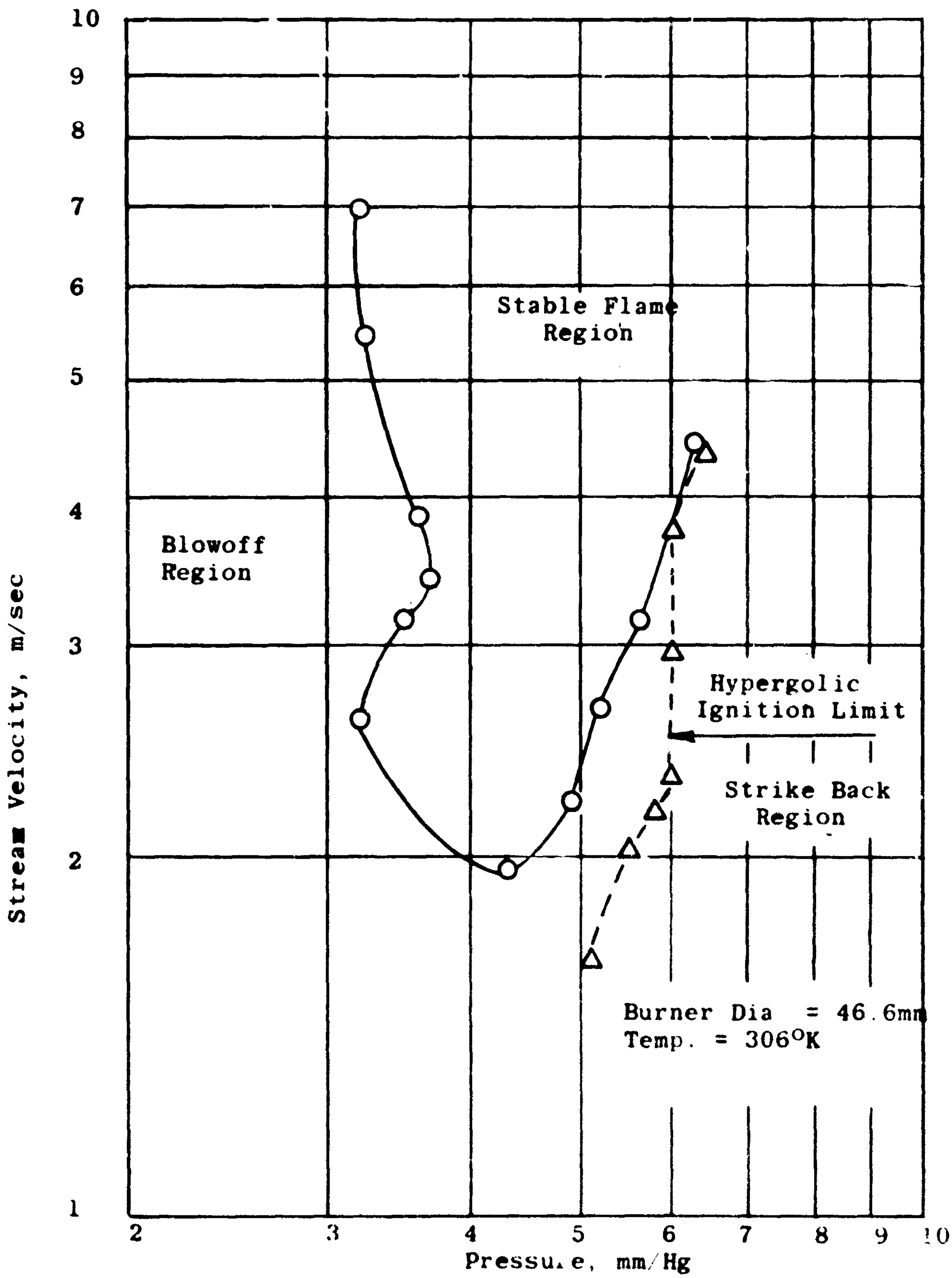

Figure 18. Stability Region of Stoichiometric N_2O_4 - MMH Flame

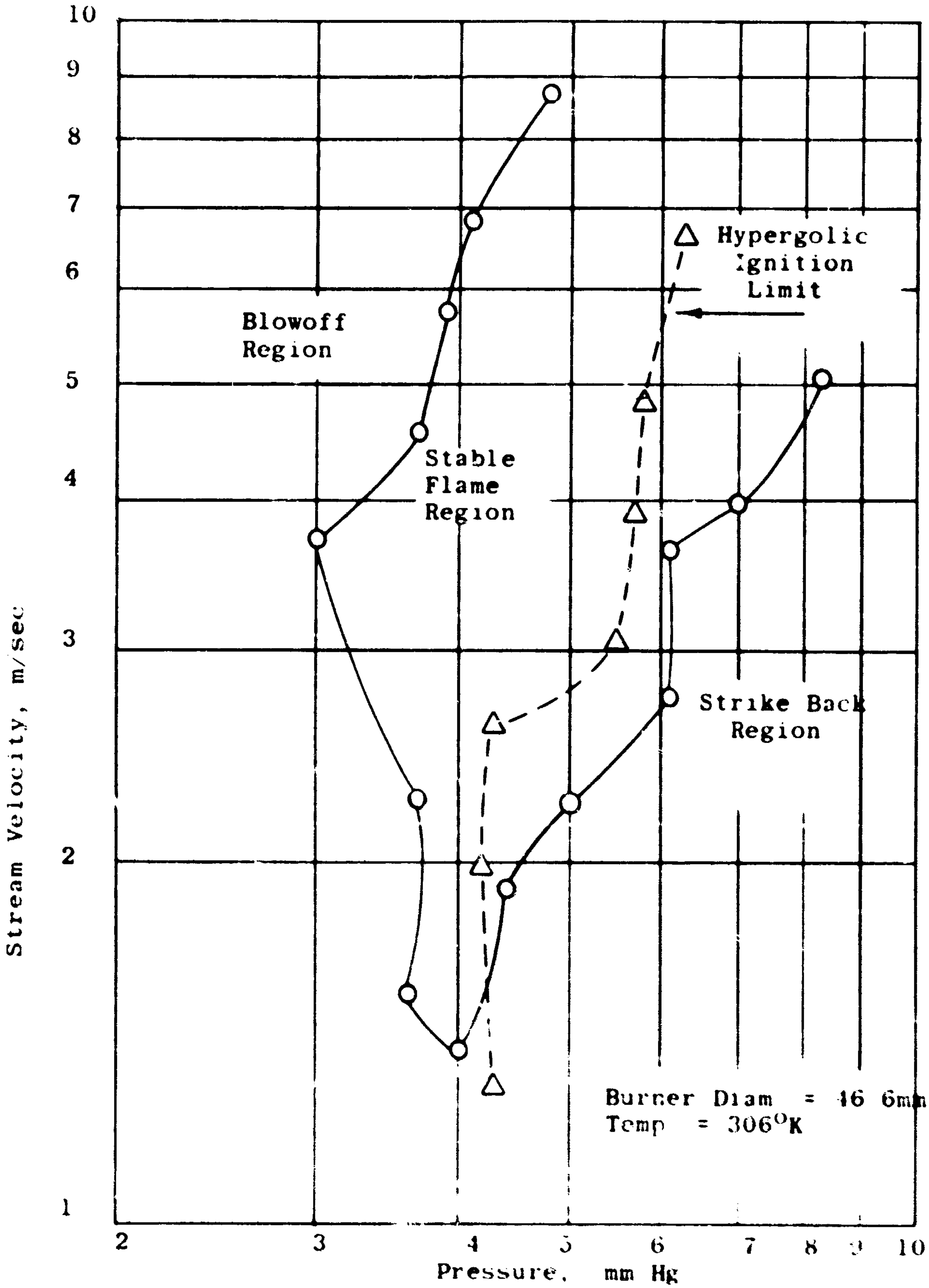

Figure 19 Stability Region of Stoichiometric N_2O_4 - 50% N_2H_4 50% UDMH Flame

TABLE II

LIMITING PRESSURES FOR VARIOUS FUEL OXIDIZER COMBINATIONS WITH 46.6 mm (1.83 in.) BURNER TUBE

Fuel	Oxidizer	
	O_2	N_2O_4
H_2	10 mm Hg	16.0 mm Hg
UDMH	13.5 mm Hg	3.2 mm Hg
MMH	10.0 mm Hg	4.2 mm Hg
50% UDMH/50% N_2H_4	8.0 mm Hg	4.0 mm Hg

TABLE III

QUENCHING DIAMETERS FOR VARIOUS FUEL OXIDIZER COMBINATIONS AT 10 mm Hg PRESSURE

Fuel	Oxidizer	
	O_2	N_2O_4
H_2	46.6 mm	74.5 mm
UDMH	63.0 mm	14.8 mm
MMH	46.6 mm	19.6 mm
50% UDMH/50% N_2H_4	37.7 mm	18.6 mm

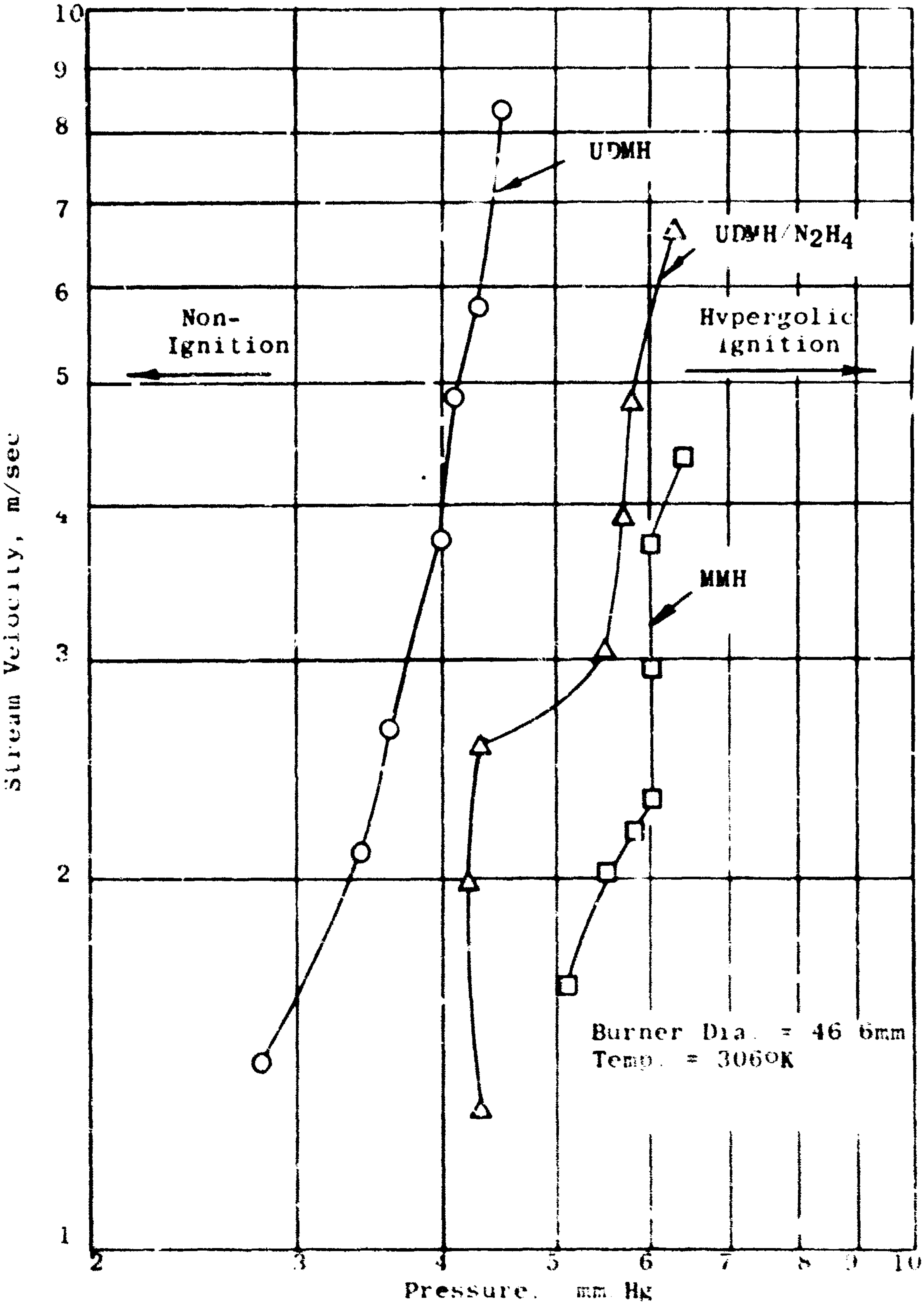

Figure 20. Pressure Limit for Hypergolic Ignition of Hydrazine Based Fuels with N_2O_4

delays are not readily measured in this apparatus.

The limiting pressure for hypergolic ignition was less than 6 mm Hg for the three hydrazine-based fuels tested with N_2O_4 in the low pressure burner apparatus. As will be seen in Section B below, ignitions in the unconfined tests with the same propellants occurred at pressures down to 60 mm Hg. Ignition at lower pressures did not occur. The anomaly between the results of the two types of tests was unexpected and may be due to two principle factors, mixing and contact time.

In the low pressure burner tests, the propellant vapors were premixed in the burner tube. Mixing in this case was quite thorough. The degree of mixing achieved in the unconfined impingement tests could not have been as great.

The contact time for the lowest limiting pressure cases in the burner tests were of the order of one second. Run durations for the unconfined impingement tests were generally one quarter of a second; thus, "effective" contact times for these tests were perhaps somewhat over 250 ms at most. The shorter contact times and less thorough mixing of the propellants together with factors such as the transient nature of local eddies (potential ignition centers) of the resultant stream, and the cooler vapors due to rapid evaporization of the liquid propellants upon issuance from the injectors in the unconfined impinging stream tests lead to markedly higher minimum pressures for hypergolic ignition in the impinging stream tests than in the low pressure burner tests.

3. Burning Velocities

The corresponding burning velocities were determined for UDMH, MMH and 50% UDMH/50% N_2H_4 with N_2O_4 and are shown in Table IV. These velocities were determined at stoichiometric proportions of oxidizer to fuel in each case at the ambient pressures shown in the table.

The burning velocities were calculated as the volumetric gas flow (corrected for a burner temperature of 306°K) divided by the area of the reaction zone. The reaction zone was taken as being the bright inner cone of the flame and was determined by measuring the flame-burner image on a photograph. At the low pressures involved, the luminous boundary of the flame appears somewhat detached from the burner rim. The main source of error in the calculation, therefore, is due to the estimated location of this boundary

TABLE IV

BURNING VELOCITIES OF STOICHIOMETRIC FLAMES

Combination	Ambient Pressure mm Hg	Burning Velocity cm/sec
UDMH/N_2O_4	4.2	115
MMH/N_2O_4	5.5	85
50% UDMH/50% N_2H_4/N_2O_4	5.2	107

B. Phase I, Item A- Unconfined Ignition Tests

Prior to undertaking the experimental program outlined in Table I, a series of about 50 tests was made to check out and calibrate the control circuits and instrumentation systems. These tests were made with N_2O_4 and UDMH, the first propellant combination to be investigated in the test schedule. The tests also served to determine the ambient pressure range over which the tests were to be conducted.

It was found that ignition could be obtained consistently only at pressures over 60 mm Hg. In only one case did ignition occur at 40 mm Hg, but only after a delay of nearly one second which was after the propellant valves had closed. No ignition was obtained during tests at 20 and 2 mm Hg. Based on these tests environmental pressures of 750 mm, 150 mm, 100 mm, and 60 mm Hg were selected for the initial random balance tests. It was determined subsequently that this range was applicable to each of the N_2O_4 or IRFNA and hydrazine-based propellant combinations.

The schlieren movies of the runs made to date show that at sea level little vaporization of either propellant occurs before impingement. The hypergols, therefore, are mainly in the liquid state when ignition occurs. At reduced pressures, however, the propellants appear at the injector faces as liquids prior to ignition but considerable vaporization occurs before the impingement point is reached. In fact, the vapors are so dense as to obscure a liquid core if such a core exists.

1. N_2O_4/UDMH Tests

Two complete random balance test series were performed with N_2O_4 and UDMH in accordance with the schedule of tests shown in Table I. The first series of tests shown in the table are for tests at optimum mixture ratio. The second series are for tests at a fuel-rich mixture ratio for comparison. In addition, a number of duplicate tests was made for confirmation of results The ignition delays measured with the various configuration and environmental parameter variations are tabulated in Table V, together with corresponding results with other propellant combinations which will be discussed in subsequent sections

TABLE V - UNCONFI

Test No.	Parameters							N
	Pa mmHg	Angle Deg.	Length in.	Ox Vel. ft/sec	Fuel Vel. ft/sec	Feed[a]	Temp.[b]	Run
12	750	15	5/16	40	70	D	A	183
20		15	1/2	10	40	D	A	184
								320
46		45	1/8	100	100	D	C	250
10		45	5/16	40	40	D	A	177
19		45	1/2	10	40	C	A	182
17		45	1/2	40	40	C	A	180
16		45	1/2	40	70	C	A	270
								268
44		60	1/8	40	10	C	C	252
43		60	1/8	40	40	C	C	251
								323
								324
								325
5		60	1/8	70	100	C	A	175
31		60	5/16	10	40	D	H	227
9		60	5/16	70	40	C	A	171
7		60	5/16	70	70	D	A	174
23		90	1/8	40	10	D	H	219
								321
								322
1		90	1/8	70	40	D	A	165
8		90	5/16	100	70	C	A	170
								169
36	150	15	5/16	40	70	D	H	237
35		15	5/16	40	70	C	H	236
37		15	5/16	70	40	D	H	238
50		15	5/16	100	100	C	C	247
40		15	1/2	70	100	C	H	239
26		45	1/8	70	70	D	H	231
28		45	1/8	70	100	C	H	232
15		45	1/2	40	10	D	A	178
16		45	1/2	40	70	C	A	
53		60	1/2	40	70	C	C	256
14		60	1/2	100	70	D	A	173
22		90	1/8	10	10	D	H	218
42		90	1/8	10	40	C	C	259
3		90	1/8	70	70	C	A	167
30		90	5/16	70	40	D	H	223
38		90	1/2	40	40	D	H	222
		60	5/16	10	10	D	A	

NFINED IMPINGEMENT TESTS

N_2O_4-UDMH		N_2O_4-UDMH (low O/F)		N_2O_4-50-50		N_2O_4-MMH		IRFNA-UDMH	
Run	Delay msec	Run	Delay msec	Run	Delay msec	Run	Delay msec	Run	Delay msec
183	.2	57	1.5	213	28	187	.7	285	4.5
				303	.7	196	.1		
184	1.4	62	2	214	1.7	186	.8	275	2.5
320	1.2			215	1.7				
250	0	124	.7						
177	.1	55	.5	212	1.3	188	1.1	284	3
182	1.3	73	.9	210	2.1	190	.6	283	3
				304	2.9				
180	0	71	.5	211	1.3	189	15.5	278	0
						305	1.0		
270	1.5	148	.7	201	1.6	197	.1	286	3.0
268	.2	151	1.2			306	1.6		
252	2.2	133	1.2						
251	15	117	.7						
323	1.6								
324	1.0								
325	1.0								
175	0	68	1.0	216	.2	191	.5	273	1.9
227	.8	85	.9						
171	1	69	.3	209	1.2	192	1.5	282	0
174	0	54	.8	208	.4	193	1.1	281	1.9
219	.1	76	7.6						
321	.1								
322	.1								
165	.1	51	4.5	206	2.1	195	4.5	276	3.7
		52	10.3			316	.6	277	3.1
						317	.6		
170	1	66	.45	207	.9	194	1.2	279	2.2
169	1					161	1.0		
237	8	85	12						
236	11	88	27						
238	12	86	48						
247	53	125	44						
239	11	87	28						
231	15	84	12						
232	18	99	11						
178	16	61	10	298	11	309	11		
		79	20	292	18	198	9	287	∞
								288	>157
256	15	129	12						
173	6	60	9	296	8	312	8.8		
218	24	74	16						
		75	16						
259	13	136	76						
167	22	63	50	294	11	318	3.9	280	∞
								289	∞
223	10	77	>70						
222	11	78	344						
								291	4.4
								292	∞

TABLE V - UNCONFINED IMPINGEMENT

Test No.	Parameters						
	Pa mmHg	Angle Deg.	Length in.	Ox. Vel. ft/sec	Fuel Vel. ft/sec	Feed[a]	Temp.[b]
51	100	15	5/16	70	70	D	C
58		15	1/2	10	40	D	C
56		15	1/2	40	40	D	C
59		15	1/2	40	70	D	C
55		15	1/2	70	40	C	C
60		15	1/2	70	100	D	C
49		45	5/16	100	70	C	C
33		45	5/16	100	100	C	H
16		45	1/2	40	70	C	A
45		60	1/8	70	100	C	C
48		60	5/16	10	10	C	C
32		60	5/16	10	40	C	H
41		90	1/8	100	70	D	C
21		90	1/8	100	70	C	H
2		90	1/8	100	100	D	A
29		90	5/16	10	10	C	H
11	60	15	5/16	70	70	D	A
57		15	1/2	10	10	D	C
27		45	1/8	40	40	C	H
47		45	1/8	100	100	D	C
4		45	1/8	100	100	C	A
34		45	5/16	40	10	C	H
18		45	1/2	40	10	C	A
16		45	1/2	40	70	C	A
24		60	1/8	40	10	D	H
25		60	1/8	100	70	D	H
52		60	1/2	70	40	D	C
54		60	1/2	70	70	C	C
6		90	5/16	10	10	C	A
13		90	1/2	70	100	D	A
39		90	1/2	10	10	C	H

Note:
(a) - Feed
D - direct
C = cross

(b) - Temp.
C - cold (Fuel 0°F, oxidizer,
A = ambient (70°F)
H - +100°F

ENT TESTS (Cont'd)

N_2O_4-UDMH		N_2O_4-UDMH		N_2O_4-50-50		N_2O_4-MMH	
Run	Delay msec	Run	Delay msec	Run	Delay msec	Run	Delay msec
246	82	127	46				
242	42	120	46				
244	54	118	33				
241	14	121	17				
245	61	126	218				
240	14	123	218				
248	17	132	299				
234	∞	100	49				
269	50			203	18	199	40
271	88						
253	15	130	14				
254	11	134	60				
229	∞	102	∞				
258	51	138	24				
217	17	103	46				
166	19	53	45	293	45	319	18.5
220	15	104	∞				
221	18						
185	∞	56	82	302	33.7	307	142
243	63	119	245				
233	68	89	∞				
249	45	128	21				
176	115	67	246	297	114	308	163
235	∞	101	∞				
181	∞	72	∞	300	165	310	171
179	230	70	54	204	35	200	111
				299	83	311	< 300
226	∞	80	∞				
		81	∞				
228	98	82	∞				
255	15	139	50				
257	> 200	137	216				
168	∞	64	∞	301	∞	315	∞
		65	∞				
172	63	58	9	295	23	313	< 22
		59	20			314	44.8
224	25	105	∞				

er, 32°F)

The ignition delay reported in the table and as defined for subsequent discussions is the time interval between entry of the second propellant in the liquid state and the first indication of ignition. At 750 mm Hg pressure in the vacuum chamber, ignition can be detected in the schlieren films as well as by the photomultiplier tube. Since the time resolution is greater (approximately 6-7 frames/ msec) in the schlieren films, ignition delays at 750 mm Hg where the delays are very short were determined from this source. At lower ambient pressures ignition generally occurred outside of the field of view of the schlieren system which was concentrated on the impingement zone for greater resolution of stream characteristics. For these tests the photomultiplier tube indication of ignition was used to determine the ignition delay.

Ignition delays from Table V plotted against the individual parameters for optimum mixture ratio of 2/1 are shown in Figures 21-23. The effects of impingement angle and impingement length over the range of propellant temperatures and ambient pressures discussed previously are shown in Figure 21. The effects of impingement velocity and manifold configuration are shown in Figure 22. In both of these figures, tests at room temperature are plotted on the nominal value of the appropriate injection parameter. Tests at cold temperatures are plotted to the left of the nominal parametric value and tests at high temperatures (+160°F) are plotted to the right in order to differentiate between the propellant temperatures. Ambient pressure level is indicated by the symbols. Figure 23 indicates the effect of ambient pressure on ignition delay.

Visual inspection of the results shown in Table V and in Figures 21-23 does not indicate significant effects which can be other than ambient pressure alone. As indicated in Figure 23, ignition delay times increase substantially as ambient pressure is decreased. At sea level ignition delays are less than 2 msec in all tests regardless of injection or propellant temperature variations. At lower ambient pressures, not only the magnitude but the range of ignition delays increase markedly. However, careful inspection of the results does not indicate clear cut effects due to one parameter or combination of parameters, but rather a random scatter. Both long and short delays can be seen for any one injection condition at the same ambient pressure. It is possible, however, that any second order effects may be obscured by the wide range of ignition delays encountered at the lower ambient pressures with this apparatus.

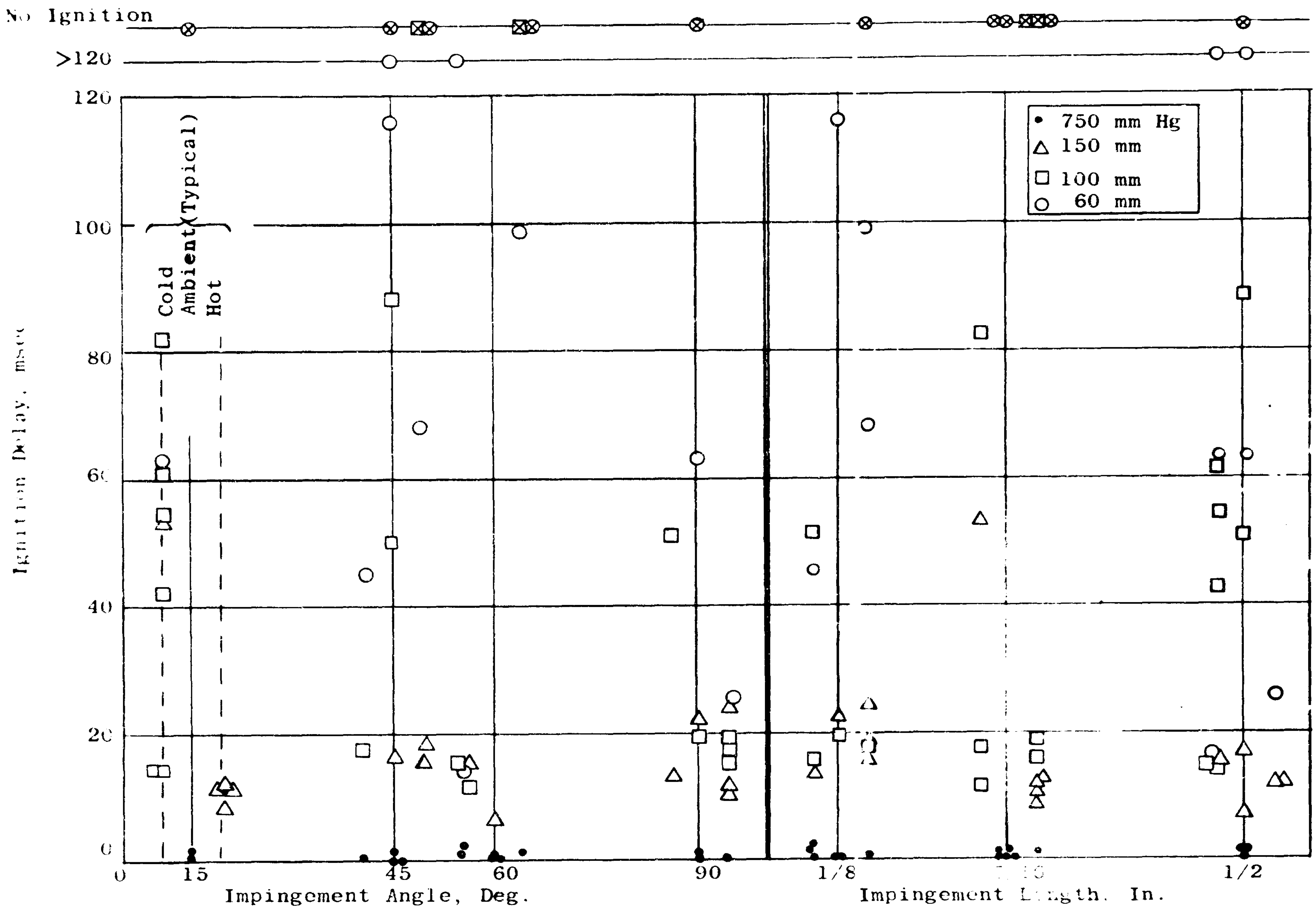

Figure 21. Effect of Impingement Angle and Length on Ignition Delay, N_2O/UDMH

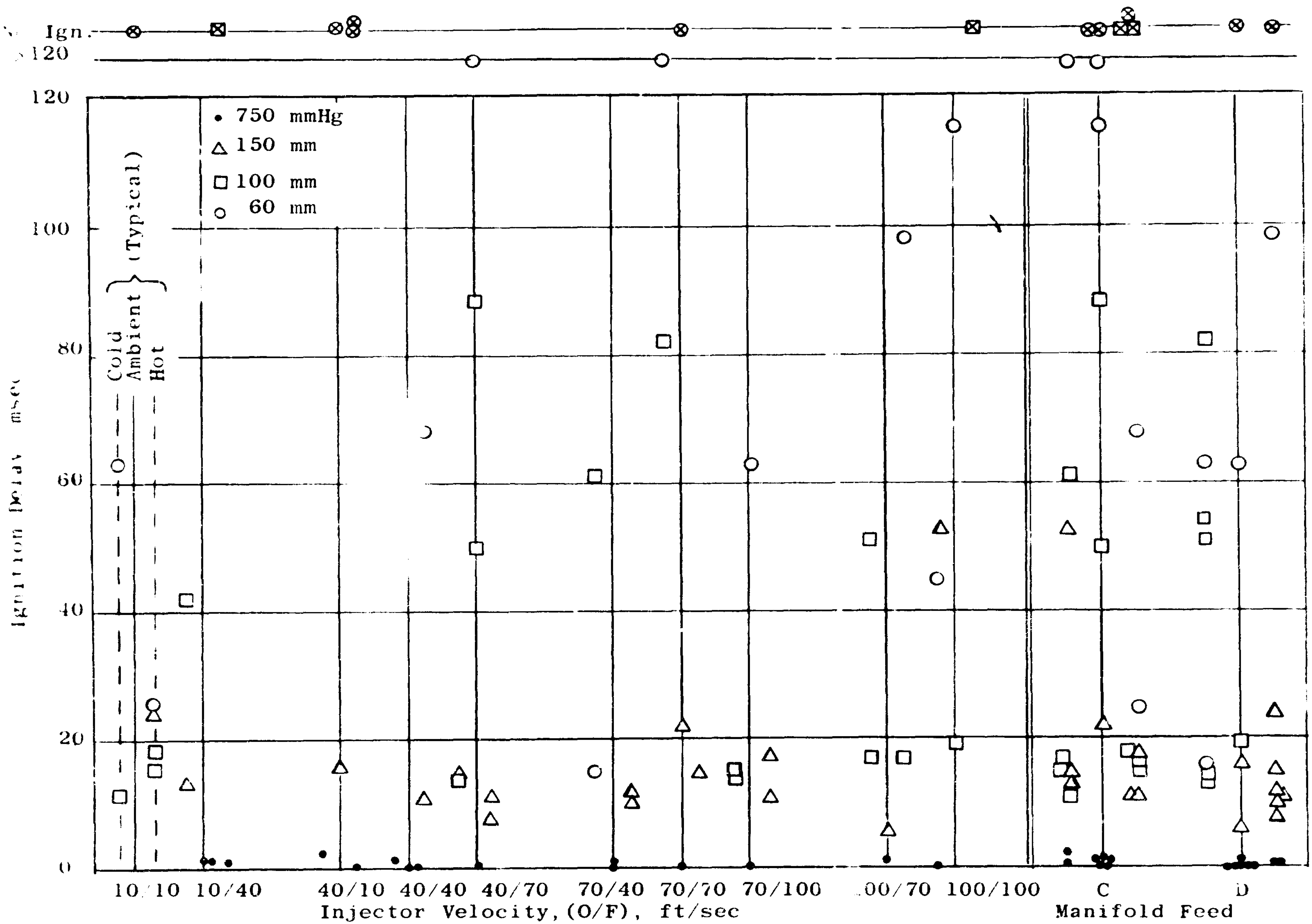

Figure 22 Effect of Injection Velocity and Manifold Feed on Ignition Delay, N_2O_4/UDMH

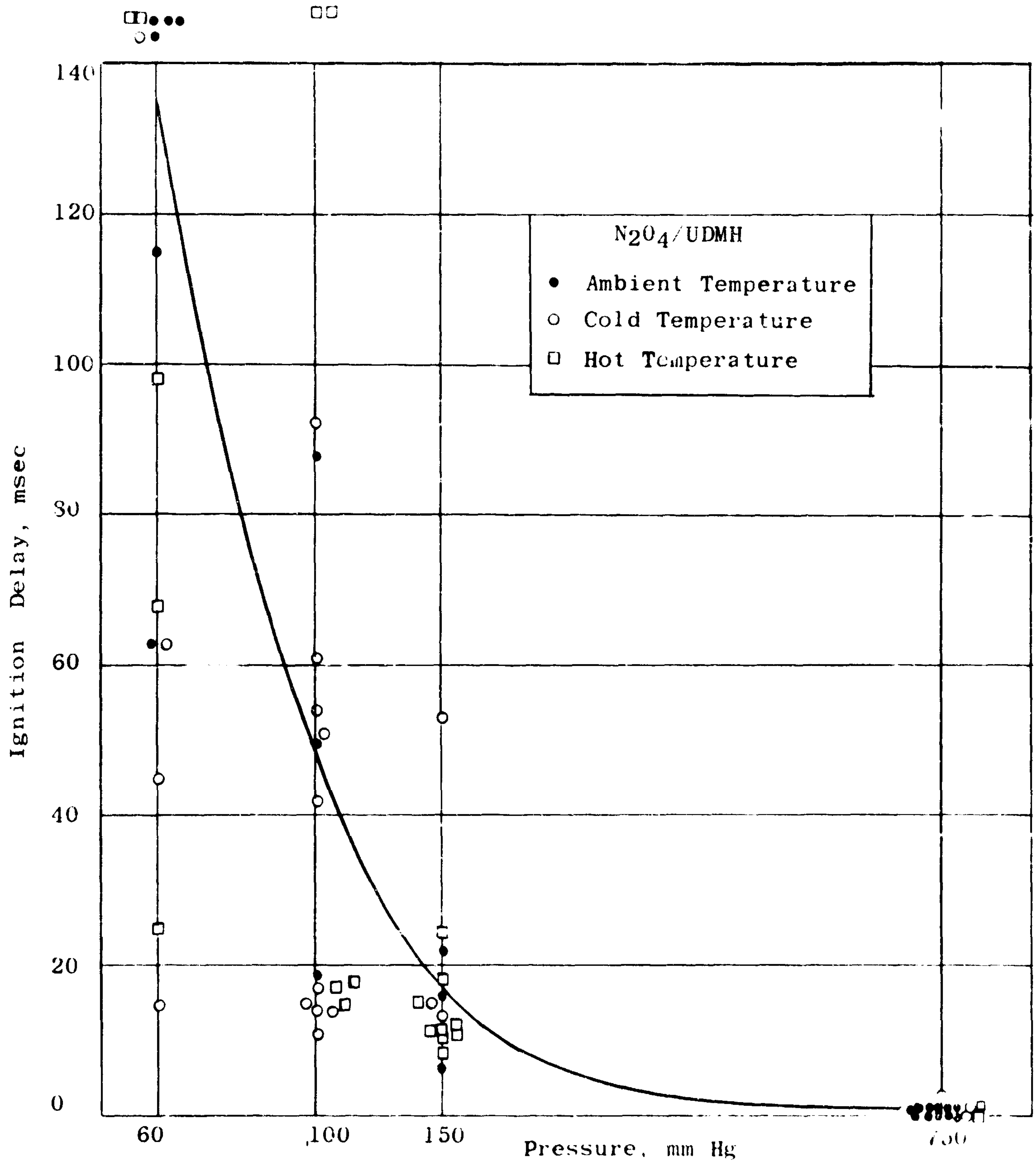

Figure 23. Effect of Ambient Pressure on Ignition Delay, N_2O_4/UDMH

In order to investigate the wide range of ignition delays encountered, a series of tests was made with the same injection configuration (configuration 16 in Table I) to eliminate possible effects of injection parameters. This injector configuration provided an impingement angle of 45° and an impingement length of 1/2 in. The oxidizer and fuel injection velocities are 40 and 70 ft/sec, respectively. The results are tabulated in Table VI. As can be seen, the reproducibility becomes increasingly poorer as ambient pressure is reduced. This trend is attributed to the fact that ignition occurs at or near the point of impingement at sea level but not at lower pressures. Observations indicate that ignition at low pressure may occur several feet away from the impingement point. As a result propellant mixtures and concentrations at the point of ignition are unpredictable in the unconfined impingement tests and can vary substantially from test to test even though the injection conditions, as evidenced by the schlieren films, are reproducible. While it is probable that minor effects of injection parameters are obscured by this scatter, it also is apparent that the parametric variations do not significantly improve ignition characteristics.

A parameter which was not investigated is ambient temperature. It is to be expected that a low environment tends to increase ignition delays by decreasing chemical kinetics.

As indicated previously the random balance schedule of tests shown in Table I was designed to fit the analysis of variance program written for the digital computer. This program considers the effect of factors or parameters up to two at a time and is intended to indicate the most influential factors or combination of factors. A brief explanation of the analysis of variance computer program is given in Appendix I. The N_2O_4/UDMH data presented in Table V which shows ignition delays in response to seven controlled variables with two, three, or four distinct levels of each were analyzed by this program. Computer runs were made under each of the following sets of conditions in an effort to determine significant injector parameters not apparent by visual inspection of the test data. These runs were:

Run I: All factors, all levels using photomultiplier delay data throughout. Factor rankings in order of influence were: ambient pressure, impingement length, fuel velocity.

TABLE VI

REPEATABILITY TESTS

N_2O_4/UDMH

Configuration 16 (Ambient Temperature)

Impingement Angle - 45°

Impingement Length - 1/2 in.

Impingement Velocity - Ox, 40 ft/sec; fuel, 70 ft/sec

Pa mm Hg	Run No.	Delay msec
750	140	0
750	148	0.7
750	151	1.2
150	141	21
150	147	35
150	154	13
100	142	28
100	149	33
100	153	45
60	143	92
60	145	78
60	146	>170
60	150	>170
60	152	230
60	155	408
60	156	112
40	144	∞

Run II: All factors, all levels using schlieren delay data at 750 mm. Factor ranking: ambient pressure, fuel velocity, impingement length.

Run III: Using optimum O/F data, 60 mm Hg level omitted because of wide scatter, and response as ln of ignition delay time. Factor ranking: ambient pressure, propellant temperature, impingement length.

Run IV: Optimum O/F data, 750 mm and 60 mm Hg levels omitted, response as ln of ignition delay time. Factor ranking: ambient pressure alone significant. Manifold feed and fuel velocity may be of minor importance in combination with ambient pressure.

Run V: 60 mm Hg level omitted, response as ln of ignition delay time. Factor ranking: ambient pressure, temperature, pressure in combination with feed, pressure with fuel velocity.

Run VI: Four factors used were pressure, impingement length, fuel velocity and oxidizer velocity. Factor ranking: ambient pressure, fuel velocity and impinge- length.

Run VII: Same factors as Run VI. No-ignition time assigned changed from 1000 msec to 250 msec. Factor ranking: same as Run VI, indicating that the arbitrary time delay assigned to a no-ignition test did not effect factor ranking.

Based on the computer analysis it is evident that ambient pressure alone has the most influential effect on ignition delay in the unconfined impingement tests. The influence of injector parameters and propellant temperatures was slight in comparison to the effect of pressures. Based on computer curve fitting (Appendix I), pressure alone accounted for about 75% of the variations in time delay noted. The addition of the injector parameters to the curve fit only accounted for an additional 2% of the variations. The balance of the variations of time delay cannot be accounted for and is believed to be due to the random nature of the ignition process in the unconfined tests.

The equation best fitting the full data set is:

$$\ln (\tau_D) = +15.5 - 2.6 \ln (P_a)$$

where:

τ_D = Ignition Delay

P_a = Ambient Pressure

This equation accounts for 75.5% of the variations in time delay encountered.

2. N_2O_4 Tests with Other Hydrazine-Type Fuels

The ambient temperature random balance series of tests listed in Table I also was performed with N_2O_4 as the oxidizer and 50% UDMH-50% N_2H_4 and monomethyl hydrazine as the fuels. The results of these tests are shown in Table V. Comparison of these results with the N_2O_4-UDMH tests discussed in the previous section indicates very similar ignition delays for comparable injection and environmental parameters. The overwhelming influence of ambient pressure is evident as in N_2O_4-UDMH tests as well as the increase in scatter at the lower ambient pressures. Based on the results of these tests, there does not appear to be a clear cut advantage of one fuel over the others insofar as the unconfined impingement tests are concerned.

To complete the unconfined impingement comparison of hydrazine-type fuels, a series of tests was made with N_2O_4 and neat N_2H_4 for comparison with the blends. These tests were made with the minimum volume impinging stream injector shown in Figure 9. This injector has an impingement angle of 60° and an impingement length of 1.4 in. The injection velocity is 70 ft/sec for each propellant. At 750 mm Hg, ignition delays were 7.8 to 19.2 msec with N_2H_4 compared with 1 msec or less with UDMH. Combustion appeared rather "rough" by visual comparison with the other hydrazine-type fuels. No ignition was obtained in two tests at 150 mm Hg although ignition delays with the other fuels were relatively short at this pressure. It appears that the higher vapor pressure of the blends improves ignition characteristics. It is also possible of course that the methyl groups of the other hydrazine fuels have an important role in initiating ignition.

3. IRFNA/UDMH Tests

A series of tests was made with inhibited red fuming nitric acid for comparison with N_2O_4. The fuel used in these tests was UDMH. The results are summarized in Table V for comparison. Results indicate that the range of ignition delay at sea level is from 0 to 3.7 msec, approximately twice that obtained with N_2O_4 under similar conditions. However, tests with several injector configurations at 150 mm Hg vacuum tank pressure resulted in no ignition in five out of seven tests and a long delay in one. Sea level delays of 2 msec or less were obtained with two of these injector configurations which resulted in no ignition at 150 mm. As in the case of the N_2O_4/N_2H_4 tests, it appears that propellants having lower vapor pressures have longer ignition delays.

C. Phase I, Item B - Ignition Improvement Concept Evaluation

Concepts for reducing ignition delay which have been investigated to date include: injector types and modifications such as splash plates to improve mixing; propellant mixtures and additions to modify propellant properties; and, valve timing to vary propellant leads. These tests were made with N_2O_4/UDMH. Some additional tests also were made with other hydrazine-type fuels for comparison. Except for tests involving unique injector types, the propellant modification and splash plate tests were made with the minimum volume impinging stream injector (Figure 9). Comparison tests with this injector indicate that ignition delays are comparable with the individual block injectors under similar conditions; therefore, it was used as a standard for the concept evaluation tests.

1. Injector Modifications

a) Splash Plates

Several splash plate configurations were evaluated using the standard impinging stream injector. These include a) a 1/8 in. diameter stainless tube, b) a 5/8 in. wide plate, c) a 3/16 in. diameter cup mounted on the 5/8 in. plate, and d) a tube having a 3/16 in. diameter hole located so the impingement point was within the tube. The first two splash plates were located just below the geometric impingement point. The cup was located so as to confine the resulting mixture as was the latter tube configuration. The results of these tests are shown in Table VII.

TABLE VII

SPLASH PLATE EFFECTS ON IGNITION DELAY
N_2O_4/UDMH

Splash Plate Configuration (Figure 10)	Ignition Delay, msec			
	100 mm Hg Run No.	Delay msec	60 mm Hg Run No.	Delay msec
a) Tube	345	8.5	347	∞
	346	18.3		
b) Plate	348	>89		
	349	35.6		
c) Cup	350	>198		
d) Open Tube	351	>197		

The simple tube, configuration (a), exhibited somewhat shorter ignition delays (8-18 msec) at 100 mm Hg than the other three configurations. However, ignition did not occur at 60 mm Hg. The other three configurations, particularly the latter two, which confined the resultant mixture, had significantly longer delays. This was somewhat surprising since it would appear that any device which promotes local pressure rises should improve ignition because of the obvious pressure dependence of ignition characteristics. Undoubtedly there is an optimum location for each of the splash plate types. However, the completely negative results of these selected tests do not appear to warrant an optimization study at this point.

One test using the simple tubular splash plate, configuration (a), with IRFNA/UDMH resulted in no ignition at the comparatively high pressure of 150 mm Hg.

b) Concentric Tube Injector

As indicated previously, two versions of a concentric tube injector were fabricated and tested. In one, the tube ends were coplaner and in the other, the center tube was withdrawn 0.2 in. into the outer tube. Tests were made both with N_2O_4/N_2H_4 and N_2O_4/UDMH. The propellants were alternated between the inner and outer tubes. Resulting ignition delays are shown in Table VIII. Ignition delays were exceptionally long at 750 mm Hg with each of the configurations and the propellant combinations tested. N_2H_4 actually produced somewhat shorter delays than UDMH in two of the tests at sea level, although still beyond the range obtainable with N_2O_4/UDMH using simple, impinging streams. No ignition was obtained at pressures of 150, 100 and 60 mm Hg with N_2O_4/UDMH using the coplaner configuration with N_2O_4 injected through the inner tube. Further tests with these injector configurations were discontinued because of very poor results.

c) Porous Plug Injector

The ignition characteristics of the porous plug injector shown in Figure 12 were investigated at ambient pressures of 150, 100 and 60 mm Hg. Ignition delays greater than 320 msec at 150 mm Hg and greater than 500 msec at 60 mm Hg were experienced with N_2O_4 and UDMH. At 100 mm Hg the delay was 32.4 msec, more consistent with the impinging stream configurations. It is probable that mixing within the relatively large plug is unpredictable at the relatively low flow rates, leading to the inconsistent results. Further tests at the 50 lb thrust level will be considered during Phase II

TABLE VIII

EFFECT OF CONCENTRIC TUBE INJECTOR ON IGNITION DELAY

Injector Configuration	Ignition Delay, msec							
	750 mm Hg		150 mm Hg		100 mm Hg		60 mm Hg	
	Run No.	Delay msec	Run No.	Delay msec	Run No.	Delay msec	Run No.	Delay msec
a) Fuel Center Tube-Coplaner								
N_2O_4/UDMH	374	>91			375	∞		
N_2O_4/N_2H_4	369	<44						
b) Ox Center Tube Coplaner								
N_2O_4/UDMH	376	~ 66	419	∞	420	∞	421	∞
	418	9						
N_2O_4/N_2H_4	368	9.3						
c) Ox Center Tube Recessed								
N_2O_4/UDMH	377	2						
N_2O_4/N_2H_4	370	<76						
c) Ox Center Tube Recessed, Splash Plate								
N_2O_4/UDMH	378	138						

d) Spray Injectors

Several tests were made with various combinations of spray nozzles using N_2O_4/UDMH Details of the spray nozzle types and configurations are discussed in Section III B2 The ignition delays obtained are tabulated in Table IX Best results were obtained with the 30° fuel spray nozzles in combination with either the 30° spray or single stream oxidizer nozzle, particularly at the lower pressures Although not significantly better than the unconfined impinging stream injectors at pressures of 750 mm and 150 mm Hg, the average delays at 100 mm and 60 mm Hg appear to be somewhat better when compared with the curve shown in Figure 23. It is possible, however, that a larger number of runs might exhibit the same data scatter obtained during the impinging stream tests. No ignition was obtained at 40 mm Hg using the 30° spray nozzle for both the N_2O_4 and the UDMH.

Although the range over which ignition could be obtained was not extended, it does appear that a fuel spray nozzle which promotes vaporization of the fuel to some degree improves ignition characteristics at the lower pressures. There does, however, seem to be an optimum droplet size or degree of vaporization promoted by the injector because the 60° spray fuel injector having a much higher pressure drop and greater degree of atomization resulted in significantly longer ignition delays under the same conditions. Further examination of the fuel spray injector seems warranted in the Phase II tests

Additional injector modifications planned for evaluation include injectors designed with orifices having an L/D of 8 for comparison with the present blocks having an L/D of 2 to determine if increased turbulence will improve mixing. Injectors having injection velocities of about 200 ft/sec with L/D of 2 and 8 also will be investigated

2. Propellant Additives and Mixtures

At this writing tests are in progress to investigate the effect of propellant additives and mixtures on ignition characteristics Quantitative results are not yet available from the schlieren films in every case but some tentative comparisons can be made based on oscillographic and visual observations Actual results and conclusions will be presented in subsequent reports.

TABLE IX

EFFECT OF SPRAY INJECTORS ON IGNITION DELAY - N_2O_4/UDMH

Injector Configuration	Ignition Delay, msec							
	750 mm Hg		150 mm Hg		100 mm Hg		60 mm Hg	
	Run No.	Delay msec	Run No.	Delay msec	Run No.	Delay msec	Run No.	Delay msec
a) 30° ox, 30° Fuel Spray	379 384 388	3 .6 <124	380 385	20.7 23	381 386 389	17.8 14.6 <39	382 387	51.6 96.5
b) 30° ox, 60° Fuel Spray	390	7.3	391	135	392	217		
c) 70 ft/sec ox stream 60° fuel spray			393	97	394	<250		
d) 70 ft/sec ox stream 30° fuel spray	396	1.5	397 395	13 17	398 400	19.1 >380	399	85

One test with configuration (a) resulted in no ignition at 40 mm Hg.

A series of tests was made with N_2O_4 and MHF-5, a classified mixed hydrazine fuel, using the minimum volume impinging stream injector (Figure 9) Ignition delays at 750 mm Hg were 22.6 to 27 4 msec compared with less than 1 msec with UDMH and 7.8 to 19 2 msec with N_2H_4 No ignition was obtained at a pressure of 150 mm Hg Analysis indicated that the MHF-5 contained 30% water which undoubtedly contributed to the unusually long ignition delays encountered. Tests with undiluted MHF-5 will be made later in the program for comparison.

Tests also were made over the 750-60 mm Hg pressure range with the following additives in the UDMH for the reasons discussed in Section IV B

4 gm hydrazine nitrate in 100 cc UDMH
4 gm ammonium perchlorate in 100 cc UDMH
4 1 gm hydrazine diperchlorate in 100 cc UDMH

The results of the tests are tabulated in Table X. These tests also were made with the minimum volume impinging stream injector. Comparison of the results with the neat propellants does not indicate any significant improvement of ignition characteristics at low pressures. In no case was ignition obtained at 60 mm Hg.

Tests have just been made with approximately 1%, 5% and 9% NO added to the N_2O_4 No additives were put in the UDMH during this series. Although schlieren results are not available at this writing, indications are that the NO inhibits ignition The addition of as little as 1% of NO resulted in no ignition at 100 mm Hg. Neither was ignition obtained at this pressure with the higher percents of NO added to the N_2O_4 Quantitative results will be presented in subsequent reports

TABLE X

EFFECT OF ADDITIVES IN UDMH ON IGNITION DELAY

Additive	Ignition Delay, msec							
	750 mm Hg		150 mm Hg		100 mm Hg		60 mm Hg	
	Run No.	Delay msec	Run No.	Delay msec	Run No.	Delay msec	Run No.	Delay msec
a) Hydrazine Nitrate 4 gm/100 cc UDMH	401	4.7	402	12.8	403	55.7	60	∞
			405	<20				
b) Ammonium Perchlorate 4 gm/100 cc UDMH	406	0.9	407	14	408	~ 70	409	∞
			410	15				
c) Hydrazine Diperchlorate 4.1 gm/100 cc UDMH	412	1.2	413	23	414	59	415	∞
			416	16.2				

3. Propellant Leads

Tests were made in which the propellant leads were varied in order to determine the effect on ignition delay. These tests were made at pressures of 750 mm and 100 mm Hg using N_2O_4 and UDMH with injector configuration 16 (Table I). The results of these tests are shown in Table XI.

TABLE XI

EFFECT OF PROPELLANT LEADS ON IGNITION DELAY - N_2O_4/UDMH

Pressure mm Hg	Run No.	Fuel Lead msec	Ignition Delay msec
750	261	-50.2	1.8
	263	-14.6	1.2
	265	-38.3	1.7
	267	- 4.5	1.5
	268	-66.1	1.4
	270	-112.7	1.0
100	262	-22 7	18 6
	264	+35.1	46 8
	266	+30.2	29 7
	269	-23 9	49 9

These tests, including the results of several other tests under similar injection conditions, are shown in Figure 24. At 750 mm Hg no effect on ignition delay is evident from a fuel lead of 41 msec to an oxidizer lead of 113 msec. At 100 mm Hg there also is no apparent effect on ignition delay due to propellant leads alone. Any second order effect is masked by the data scatter encountered at this pressure.

4. Effect of Environmental Composition

As indicated previously, it has been observed that ignition does not occur at the impingement point at low ambient pressures. Since it appeared that diffusion and mixing characteristics of the vapors influenced ignition delays under these conditions and probably accounted for the wide range of ignition delays encountered, a series of tests was made in which the composition of the atmosphere in the vacuum tank was varied to determine the effect of different diffusion rates and heat losses. These tests were made with N_2O_4 and UDMH using the minimum volume impinging stream injector. In order to obtain the desired atmosphere, the vacuum chamber was first evacuated to about 1 mm Hg and then the pressure was increased to the desired level by bleeding in the desired gas or gases.

The first tests were made with a helium atmosphere in order to determine the effect of increased diffusion rates and lower heat losses. In two tests at 100 mm Hg, no ignition was obtained. The test procedure was then repeated with a nitrogen atmosphere at pressures of 100 mm, 150 mm and 750 mm Hg. No ignition occurred in two tests at 100 mm and ignition was delayed 105 msec from valve opening at 150 mm compared with a typical time of 17 msec for similar tests in air at 150 mm. Combustion in the nitrogen atmosphere at 750 mm Hg resulted in an ignition delay of 2.8 msec compared with 0.6 to 1 msec in air at one atmosphere.

Tests were then made at pressures of 100 mm and 60 mm Hg with an oxygen-enriched atmosphere. Air and oxygen were mixed at the bleed point to increase the oxygen content to approximately 30%. The resulting delays were comparable with those in a normal air atmosphere at these pressures.

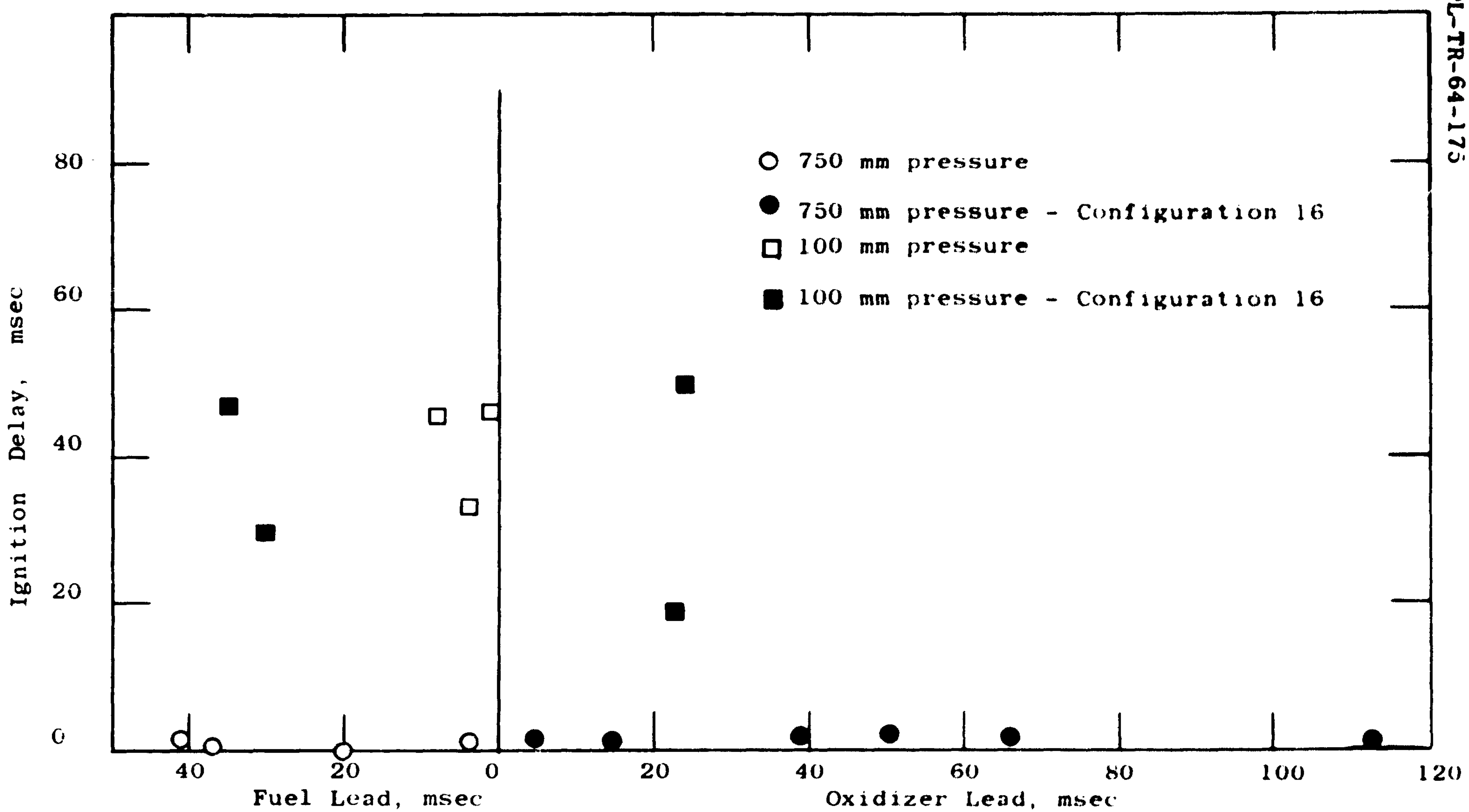

Figure 24. Effect of Propellant Lead on Ignition Delay (N_2O_4-UDMH, Ambient Temperature)

The results of these tests are tabulated in Table XII. It is apparent that the oxygen in air, at least up to normal concentrations, materially improves ignition delays over those in an inert atmosphere in the 750 mm - 60 mm Hg pressure range. Since neither the inert atmosphere nor air simulates the propellant vapor atmosphere in a rocket chamber at ignition under space conditions, it is planned to continue testing in an air atmosphere with the propellant combination. Should any injector modification or propellant mixture materially improve ignition characteristics, selected tests will be made in inert atmospheres.

TABLE XII

IGNITION DELAY OF N_2O_4/UDMH IN VARIOUS ATMOSPHERES

Pa-mm Hg	Enriched Air 70% N_2-30% O_2 Run No.	Enriched Air Delay msec	Air Run No.	Air Delay msec	Nitrogen Run No.	Nitrogen Delay msec	Helium Run No.	Helium Delay msec
750			327	1	356	2.8		
			331	1	357	<14		
			355	.6				
150			328	10.3	344	< 105		
			332	10.2				
100	352	19.5	353	26.6	341	∞	338	∞
			354	21.2	343	∞	339	∞
			336	55				
			340	66.9				
60	360	398	334	387				
			335	395				
			337	∞				
			359	∞				

VI CONCLUSIONS

Based on the results of the investigation to date the following conclusions can be drawn with regard to the N_2O_4 and hydrazine-type propellant combinations

1. Ambient pressure alone has the only significant effect on ignition characteristics of all the injector and environmental parameters investigated in the unconfined impingement tests

2. Although the wide ranges of ignition delays at the lower pressures tends to obscure any second order effects, the injection parameters and injector configurations investigated had little effect on ignition delays. The wide range of ignition delays at the lower pressures is undoubtedly due to marginal ignition as the result of the unpredictable nature of the mixing and concentrations of the propellant vapors in the unconfined tests

3. Similarly, the propellant mixtures and additives tested did not improve ignition characteristics. Ignition delays were longer with N_2H_4 and MHF-5 (although diluted with water), and even small additions of NO in N_2O_4 appeared to inhibit ignition drastically

4. It does not appear that the propellant additives tested or mechanical modifications short of confining the propellant mixture to generate pressure offer significant means of improving ignition delays with this class of propellants. It must be noted, however, that the scope of effort with any one propellant combination during this program does not permit evaluation of all potential additives nor optimization of injector modifications or configurations

5. More basic studies are required to determine the reasons for the high limiting pressure for ignition in the unconfined impingement tests (60 mm Hg) as opposed to the limiting pressure in the quenching diameter tests (3 to 5 mm Hg). Perhaps of more immediate significance however is the need to determine the controlling steps in the ignition process. Only then can sound corrective actions be taken to shorten ignition delays by the intelligent choice of additives to accomplish specific kinetic purposes

VII. FUTURE PLANS AND RECOMMENDATIONS

Immediate program plans include the completion of Phase I tests with N_2O_4 and the hydrazine-type fuels. Upon completion of these tests, the required system changes will be made and the Phase I tests (Items A and B) using hydrogen peroxide and Hybaline A-5 will be performed in accordance with the format discussed in this report. Phase I tests with the balance of the propellant combinations will then be conducted followed by the Phase II thrust chamber tests.

Because of the negative results obtained to date insofar as ignition improvement is concerned, several recommendations appear to be in order. These include

1. A more basic investigation of the vacuum ignition and combustion processes is recommended in order to define the nature of the phenomena and determine potential methods of improving characteristics.

2. Based on the results of this study and the current program, perform an intensive evaluation of these methods of improving ignition characteristics with selected propellant combinations. It appears rather incongruous at this point that all potential additives or modifications should have no effect on ignition characteristics if not actually inhibit ignition. Yet this is the conclusion which must be drawn, at least with the N_2O_4/hydrazine-type propellants, on the basis of the results at this writing. In spite of careful screening of the possible additives and injector configurations, the large number of propellants to be considered in the current program does not permit exhaustive evaluation of all potential modifications.

APPENDIX

APPENDIX I

DESCRIPTION OF THE ANALYSIS OF VARIANCE COMPUTER PROGRAM

The data presented in Table V shows ignition delays in milliseconds in response to 7 controlled variables with 2, 3 or 4 distinct levels of each. There is a random choice of variable combinations such that each variable appears randomly through its range of levels with each of the other six variables. The random balance table of tests was designed to fit the analysis of variance program for the digital computer where factors are considered up to two at a time. This program is intended to indicate the most influential factors. Figure 25 shows a typical printout from the computer program. The factors of importance are indicated by a high 'percentage' figure and a high 'F-ratio' based on the 'degree of freedom' for that factor. Other calculations performed are the 'sum of squares' and 'mean squares'.

The sum of squares is calculated by subtracting the average (or a curve fit value) of each level from the average for the total experiment; squaring each difference and adding.

The 'mean squares' is obtained by dividing the 'sum of squares' by the number of 'degrees of freedom', DF, which is taken as one less than the number of levels. For example, a 3 level system could plot as a straight line function or a curved line of 3 points (a quadratic). The factor is said to have 2 degrees of freedom. The 'mean squares' column has more significance than the 'sum of squares' since it is less dependent on the number of levels for that set of factors. The 'percent' column is an indication of the amount of response variation due to the associated factor. The 'F ratio' is the ratio of the 'mean square' to the 'mean square' of the remainder. It is an indication of the experimental error as well as the degree of curve fit made based on levels of factors (not values of factors).

Suitable values of F ratio (given in references on statistics) are listed below in Table XIII according to the degrees of freedom in the remainder and also in the function.

FACTORS 1 x 2 (Run 2)

Average Responses

Level	Factor 1 Pressure		Factor 2 Angle	
1	1.4480	02	4.5107	01
2	5.9333	01	7.4479	01
3	1.6333	01	5.7667	01
4	6.4118	-01	3.3700	01

Analysis of Variance Table

Source of Variance	Sums of Squares		DF	Mean Squares		Percent	F Ratio	
Regression on Factor J1	1.9386	05	3	6.4621	04	46.53	1.58	01
Regression on Both	2.0318	05	6	3.3864	04	48.77	8.29	00
Difference Due to Adding Factor J2 to Factor J1	9.3211	03	3	3.1070	03	2.24	7.61	-01
Factors and Interactions	2.1652	05	15	1.4435	04	51.97	3.53	00
Difference Due to Adding Interaction	1.3339	04	9	1.4821	03	3.20	3.63	-01
Remainder	2.0011	05	49	4.0839	03	48.03	1.00	00
Total	4.1663	05	64	6.5099	03	10.00	1.59	00

Figure 25 - Typical Printout From Analysis of Variance Program

TABLE XIII

SIGNIFICANT F-RATIO VALUES

Remainder DF	Function DF	Significant F Ratio
40	1	2.84
	2	2.44
	3	2.23
	4	2.09
	9	1.79

The 'F Ratio' should be as large as possible to indicate any significance of the 'percent' or 'mean squares'. The values given in Table XIIIrepresent the minimum values. If the 'F ratio' is not greater than the minimum then a large sum of squares or a large mean square has little significance.

The following is a list of the 'sources of the variations' and a brief explanation of the significance of each in the analysis:

1. Regression of factor J_1---------------------- (J_1)

   Describes the correlation of the first factor, J_1, listed on the particular printout page to the response (time delay).

2. Regression of both ------------------------ (J_1+J_2)

   Indicates the correlation of both J_1 and J_2, together with the time delay. The form of the curve fit is:

$$\Upsilon = a_o + a_1 x + a_2 x^2 - \ldots$$
$$+ c_1 y + c_2 y^2 - \ldots$$

3. Difference due to adding factor J_2 to factor J_1---(J_2 on J_1)

Indicates the influence of factor J_2 on the response when J_1 is also present.

4. Factors and interactions-------------------- ($J_1+J_1xJ_2+J_2$)

Indicates the importance of factors J_1 and J_2 with the interactions (product terms).

The interaction terms are added to the curve fit as follows:

$$\Upsilon = a_o + a_1x + a_2x^2 + \ldots + c_1y + c_2y^2 + \ldots + b_{11}xy + b_{12}xy^2 + \ldots + b_{21}x^2y + b_{22}x^2y^2 + \ldots + \ldots$$

5. Difference due to adding interaction----------- (J_1xJ_2)

Gives the effects of the product of J_1xJ_2 alone on the response.

6. Remainder---------------------------------- ($J_1+J_1xJ_2+J_2$)

The difference between the 'total' and the 'factors and interactions' is a measure of the data scatter from the 'factors and interactions' curve fit.

7. Total-- (Σ)

This is a measure of the total scatter of data from the average response for the entire experiment.

Curve Fitting

The following curve fits were made with the digital computer using the factors indicated by the 'analysis of variance' program. The curve fits are made by minimizing the sum of squares for the equation form programmed.

1. P_a* vs. τ_D.

   $\ln \tau_D = 15.5 - 2.6 \ln (P_a)$

   75.5% of variations are accounted for in this curve fit.

2. P_a*, Temp., Feed and Length vs. τ_D.

   $\ln (\tau_D) = 15.7 - 2.44 \ln (P_a) - 1.27 (T)$

   $+ .34 (T)^2 - .58 (\text{Feed}) + .67 (L) - .1 (L)^2.$

   77% of the variations of τ_D are accounted for in this equation. This is not a significant improvement over P_a vs. τ_D alone in equation 1.

3. P_a, L and V_{fuel} vs. τ_D.

   $\ln (\tau_D) = 15.97 - 2.6 \ln (P_a)$

   $+ .5 (L) - .002 (V_f).$

   74% variations are accounted for in this curve fit based on a full data set.

Based on curve fits obtained, the following conclusions can be drawn.

1. Pressure alone is the most significant factor.

2. The addition of other factors to the curve fit program provides only minor improvements of about 2% to that obtained with pressure alone as the variable.

3. Approximately 25% of the variations of time delay cannot be accounted for in the curve fitting program. This is undoubtedly due to the wide range of ignition delay experienced at the lower vapor pressures.

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1. Fuel and Rocket Propellants
2. Space Propulsion
3. Injectors
4. Combustion Chambers
5. Ignition-Hypergolic, Space

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