1987

An experimental investigation of the ignition and flammability limits of various hydrocarbon fuels in a two-dimensional solid fuel ramjet.

Wooldridge, Richard Clark

https://hdl.handle.net/10945/22259

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

AN EXPERIMENTAL INVESTIGATION OF THE IGNITION AND FLAMMABILITY LIMITS OF VARIOUS HYDROCARBON FUELS IN A TWO-DIMENSIONAL SOLID FUEL RAMJET

by

Richard Clark Wooldridge

June 1987

Thesis Advisor: David W. Netzer

Approved for public release; distribution is unlimited

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION: UNCLASSIFIED
1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY
2b DECLASSIFICATION / DOWNGRADING SCHEDULE
3 DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited
4 PERFORMING ORGANIZATION REPORT NUMBER(S)
5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION: Naval Postgraduate School
6b OFFICE SYMBOL (If applicable): Code 67
7a NAME OF MONITORING ORGANIZATION: Naval Postgraduate School
6c ADDRESS (City, State, and ZIP Code)
7b ADDRESS (City, State, and ZIP Code)
8a NAME OF FUNDING/SPONSORING ORGANIZATION
8b OFFICE SYMBOL (If applicable)
9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c ADDRESS (City, State, and ZIP Code)
10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO

11 TITLE (Include Security Classification): AN EXPERIMENTAL INVESTIGATION OF THE IGNITION AND FLAMMABILITY LIMITS OF VARIOUS HYDROCARBON FUELS IN A TWO-DIMENSIONAL SOLID FUEL RAMJET
12 PERSONAL AUTHOR(S): Wooldridge, Richard C.
13a TYPE OF REPORT: Master's Thesis
13b TIME COVERED: FROM ______ TO ______
14 DATE OF REPORT (Year, Month, Day): 1987, June
15 PAGE COUNT: 43
16 SUPPLEMENTARY NOTATION

17 COSATI CODES

FIELD	GROUP	SUB-GROUP

18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number): SFRJ, Recirculation Zone, Ignition Limit, Flammability Limit

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

An experimental investigation was conducted to study the effects of inlet step height on ignition and flammability limits and recirculation zone and boundary layer combustion phenomena of various hydrocarbon fuels. A windowed two-dimensional solid fuel ramjet (SFRJ) was utilized. Hydrocarbon fuels were burned under conditions similar to the actual flight conditions proposed for the SFRJ. Effects of inlet step height changes were studied using a variable geometry inlet, an automatic data acquisition system, and high speed motion pictures of the interior of the combustion chamber at the recirculation zone and the boundary layer development region. Data was obtained at a mass flux of 0.2 lbm/in^2-sec at a nominal air inlet temperature of 1000 R with pressures ranging from 100 to 150 psia. The flammability limits were found to be approximately the same or

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS
21 ABSTRACT SECURITY CLASSIFICATION: Unclassified
22a NAME OF RESPONSIBLE INDIVIDUAL: Prof. David. W. Netzer
22b TELEPHONE (Include Area Code): (408) 646-2980
22c OFFICE SYMBOL: Code 67Nt

DD FORM 1473, 84 MAR
83 APR edition may be used until exhausted
All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

#19 - ABSTRACT - (CONTINUED)

slightly less than the ignition limits. Recirculation zone flame stability was dominant in determining flammability limits.

An Experimental Investigation of the Ignition and Flammability Limits of Various Hydrocarbon Fuels in a Two-Dimensional Solid Fuel Ramjet

by

Richard Clark Wooldridge
Lieutenant, United States Navy
B.S., United States Naval Academy, 1980

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 1987

ABSTRACT

An experimental investigation was conducted to study the effects of inlet step height on ignition and flammability limits and recirculation zone and boundary layer combustion phenomena of various hydrocarbon fuels. A windowed two-dimensional solid fuel ramjet (SFRJ) was utilized. Hydrocarbon fuels were burned under conditions similar to the actual flight conditions proposed for the SFRJ. Effects of inlet step height changes were studied using a variable geometry inlet, an automatic data acquisition system, and high speed motion pictures of the interior of the combustion chamber at the recirculation zone and the boundary layer development region. Data was obtained at a mass flux of 0.2 lbm/in^2-sec at a nominal air inlet temperature of 1000 R with pressures ranging from 100 to 150 psia. The flammability limits were found to be approximately the same or slightly less than the ignition limits. Recirculation zone flame stability was dominant in determining flammability limits.

TABLE OF CONTENTS

I. INTRODUCTION -- 9

II. DESCRIPTION OF APPARATUS------------------------- 14

A. TWO-DIMENSIONAL SOLID FUEL RAMJET MOTOR ----- 14

B. AIR SUPPLY, FLOW CONTROL, AND PURGE SYSTEMS -------------------------------------- 18

C. IGNITION SYSTEM ------------------------------ 20

D. DATA ACQUISITION AND CAMERAS --------------- 20

III. EXPERIMENTAL PROCEDURE -------------------------- 23

A. VARIABLE HEIGHT STEP AND SOLID FUEL RAMJET MOTOR --------------------------------- 23

B. HYCAM CAMERA OPERATION --------------------- 24

C. CALIBRATION ---------------------------------- 25

IV. RESULTS AND DISCUSSION -------------------------- 26

A. SOLID FUEL RAMJET MOTOR OPERATION ----------- 26

B. FUEL CHARACTERISTICS ------------------------ 28

V. CONCLUSIONS AND RECOMMENDATIONS ---------------- 39

LIST OF REFERENCES ---------------------------------- 41

INITIAL DISTRIBUTION LIST ---------------------------- 42

LIST OF TABLES

3.1 SUMMARY OF IGNITION/FLAMMABILITY RESULTS --------- 37

LIST OF FIGURES

1.1 Solid Fuel Ramjet Engine ---------------------------- 10

1.2 Flow Field in the Flame Stabilization Region ----- 10

1.3 Flammability Limits for a SFRJ ------------------- 12

2.1 Schematic of the SFRJ Motor ---------------------- 15

2.2 SFRJ Motor Side View with Left Side Removed ------ 16

2.3 SFRJ Variable Height Step Apparatus -------------- 16

2.4 SFRJ Variable Height Step Apparatus -------------- 17

2.5 SFRJ Camera Windows Location --------------------- 17

2.6 SFRJ Block Diagram ------------------------------- 19

2.7 Hycam Cameras ------------------------------------ 22

3.1 Ignition/Flammability Limits of 50% Zecorez 45% R45HT - DDI/5% IDP --------------------------- 30

3.2 Ignition/Flammability Limits of 60% Zecorez 34% R45HT - DDI/6% IDP --------------------------- 31

3.3 Ignition/Flammability Limits of R45HT - DDI ------ 32

3.4 Ignition/Flammability Limits of R45HT - DDI with 5% Teflon ----------------------------------- 33

3.5 Ignition/Flammability Limits of R45HT - DDI with 10% Teflon ---------------------------------- 34

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to Professor David W. Netzer for all his assistance. Special thanks to Mr. Harry Conner, Mr. Don Harvey, and Mr. Pat Hickey, whose special talents proved invaluable in all aspects of this project.

I. INTRODUCTION

Flame stabilization in solid fuel ramjets is provided using a rearward facing step at the grain inlet. This step inlet arrangement results in the formation of two distinct combustion zones (see Figures 1.1 and 1.2). The step serves as the flameholder for the combustion process that occurs in the remainder of the fuel grain. The products and reactants are mixed in the recirculation zone which forms immediately aft of the rearward facing step. The combustion process in this area approaches a well stirred reactor, which considers the composition and all of the thermodynamic properties to be uniform throughout the volume. It is desirable from a pressure loss standpoint that the minimum step height that is capable of sustaining combustion be used. This reduces as much as possible the significant stagnation pressure loss induced by the rearward facing step. [Ref. 1]

The flow reattachment point generally occurs at a distance between seven and eight step heights. The reattachment point moves toward the step inlet with wall mass addition at a constant inlet mass flux. The leading edge of the reattachment zone is quasi-stationary with a fixed inlet step height, regardless of variations in inlet step velocity, provided that the flow remains turbulent. Downstream of the flow reattachment zone along most of the

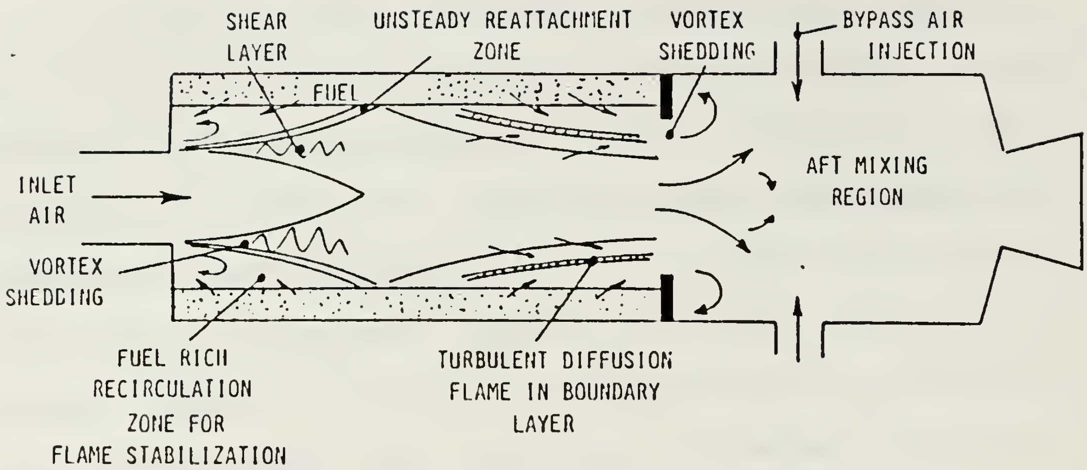


Figure 1.1 Solid Fuel Ramjet Engine [Ref. 2]

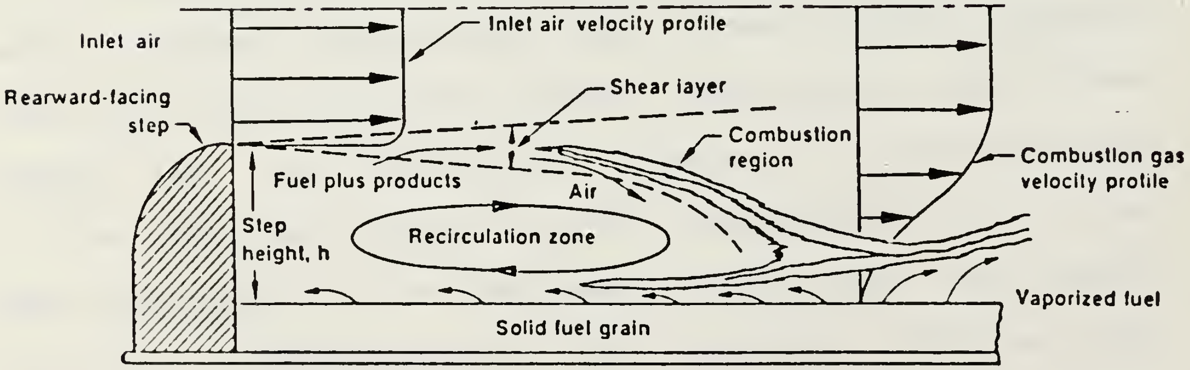


Figure 1.2 Flow Field in the Flame Stabilization Region [Ref. 3]

fuel grain length, a gas-phase diffusion flame, or a "flame sheet," is formed within the highly turbulent boundary layer which develops over the condensed fuel surface. This diffusion flame transfers heat by convection and radiation to the solid fuel surface which causes vaporization and decomposition of the fuel. Fuel vapors diffuse from the decomposing fuel beneath the flame, while oxygen is transported to the flame from the core stream along the combustor centerline. These reactants burn in the gas phase. [Ref. 4]

In order to achieve ignition, a stable, high temperature recirculation zone is required. The rearward facing step height must be large enough to form the required recirculation zone for a given gas velocity in the combustion chamber and a given fuel type. The required size varies according to the range of operating conditions for a particular fuel. [Ref. 5]

There are three parameters that affect the ignition limits for a fuel of given composition (see Figure 1.3); first, the ratio of fuel port area (Ap) to the area of the air injector (Ai), or the ratio of the rearward facing step height to the fuel port diameter. This is the most important factor for initiating ignition. If injector area (Ai) is small compared to the port area (Ap), which corresponds to a larger step height, ignition will be more easily achieved. The larger step height, however, results

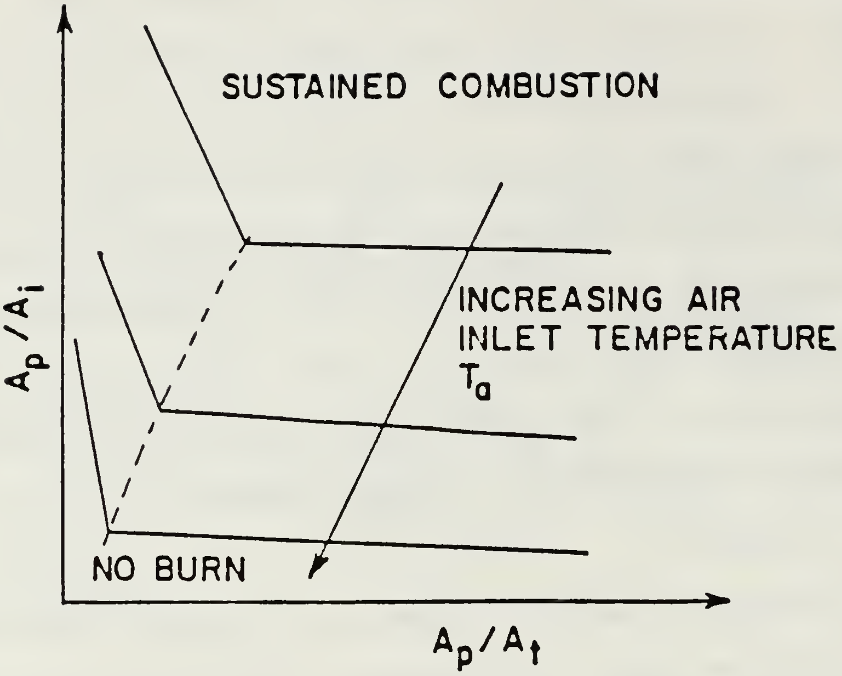


Figure 1.3 Flammability Limits for the SFRJ [Ref. 2]

in increased inlet stagnation pressure losses. Second, the velocity in the fuel grain port is controlled by the ratio of the fuel port area (Ap) to the area of the nozzle throat (At). Blowoff will occur if the flow velocity in the fuel port exceeds some threshold value. Third, as the inlet stagnation temperature increases (i.e., increased flight Mach number or lower altitude) smaller inlet steps are required. [Ref. 6]

The Naval Postgraduate School (NPS) has an ongoing research effort directed at the combustion behavior of solid fuel ramjets under the sponsorship of the Naval Weapons Center China Lake. Much effort has been undertaken to investigate a wide variety of HT-based fuels with special emphasis on the mixing processes in the fuel grain port. In this investigation, the combustion behaviors of several types of fuels were studied under various operating conditions and inlet geometries. It was desired to determine the effect of inlet step height on the ignition and flammability limits of different fuels. In addition, the effects of step height variation on the combustion process within both the recirculation zone and boundary layer development region was studied using high speed photography in a windowed, two-dimensional motor.

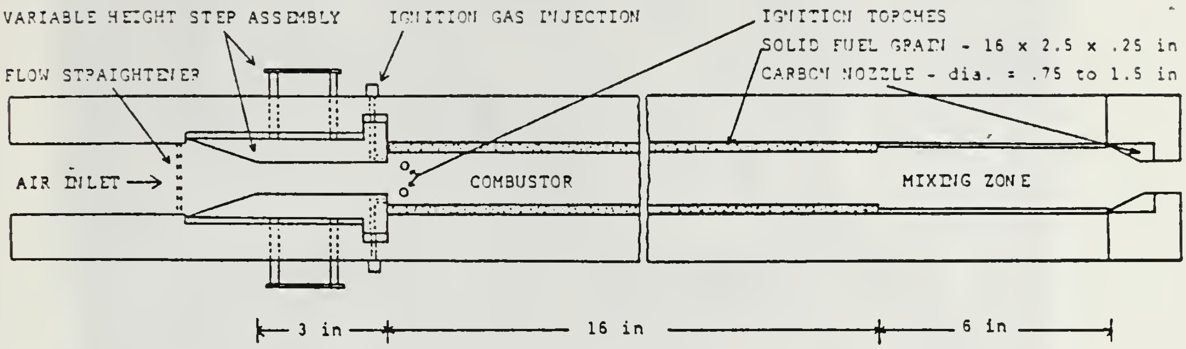
II. DESCRIPTION OF APPARATUS

A. TWO-DIMENSIONAL SOLID FUEL RAMJET MOTOR

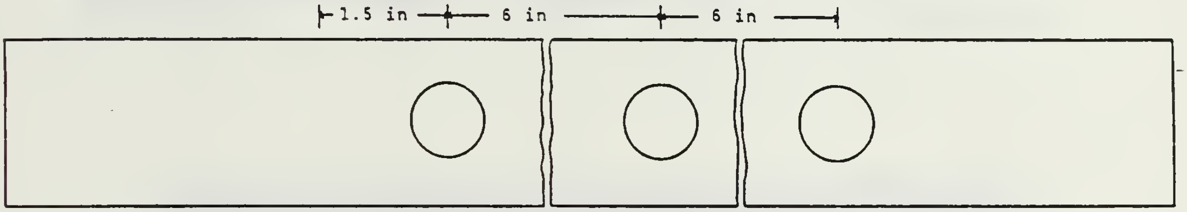
The two dimensional SFRJ consisted of four different sections (see Figures 2.1 and 2.2): (1) the head end, including the air inlet and the variable height, rearward facing step, (2) the main combustion section where the fuel slabs were attached to the top and bottom of the motor with two camera viewing windows on the side walls, (3) an aft mixing chamber located aft of the fuel slabs where further reaction between fuel and air was induced, and (4) the exhaust nozzle.

The head-end consisted of the air inlet, flow straightener, and variable height step. The step was driven by a variable speed, reversible, high torque A.C. motor which could position the step at any desired step height during SFRJ operation (see Figures 2.3 and 2.4). Step height motion was restricted to between 0.12 and 0.36 inches, as referenced to the fuel slab.

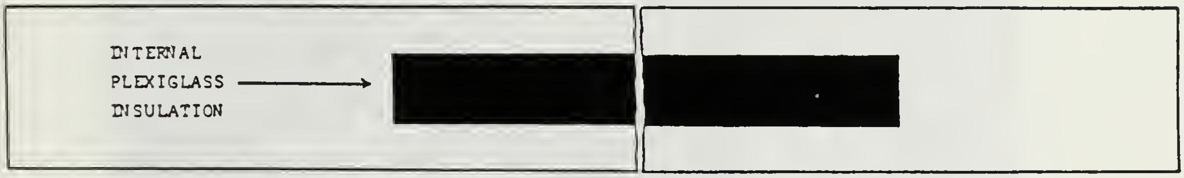
The main combustion section was 2.5 inches wide with 1.0 inches in vertical distance between the fuel slabs. The fuel slabs were 16 inches long, 0.25 inches thick, and 2.5 inches wide. Two Plexiglas viewing windows were used, near the reattachment point and just prior to the aft mixing chamber where the boundary layer was more developed (see



2-D SFRJ MOTOR SIDE VIEW



WINDOW LOCATIONS
RIGHT SIDE



LEFT SIDE

Figure 2.1 Schematic of the SFRJ Motor

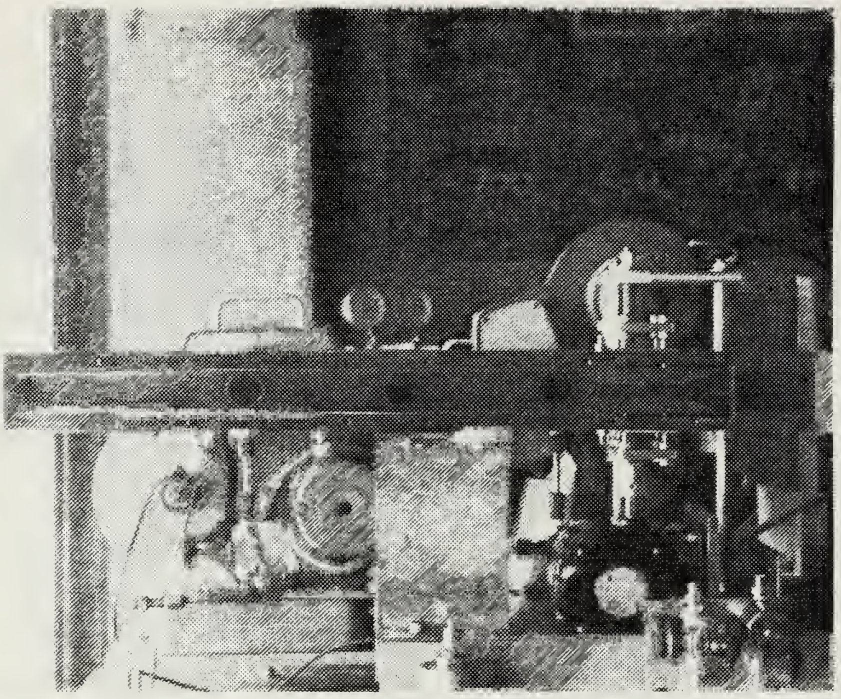


Figure 2.2 SFRJ Motor Side View with Left Side Removed

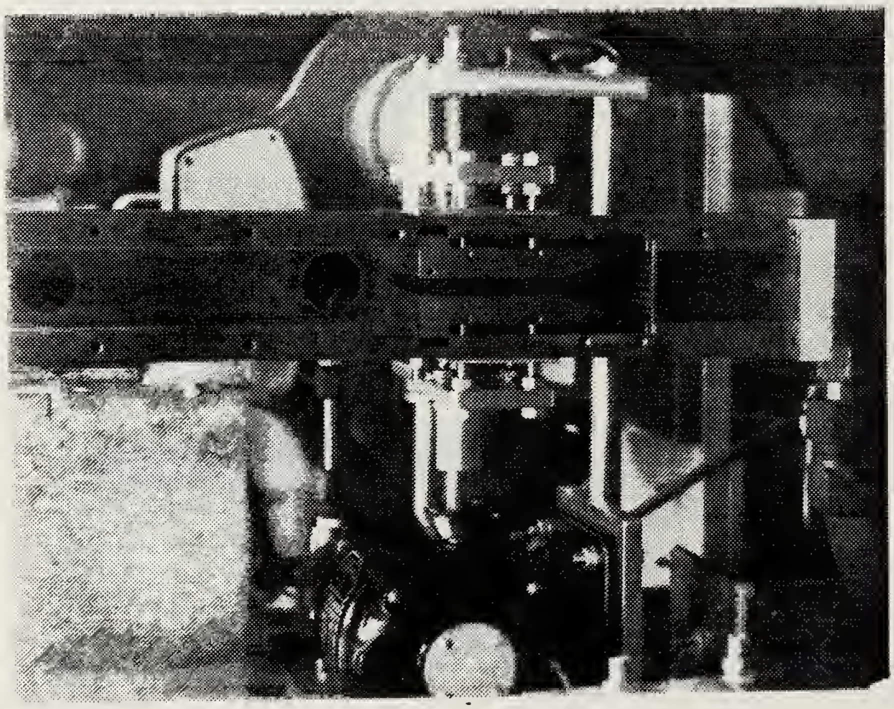


Figure 2.3 SFRJ Variable-Height Step Apparatus

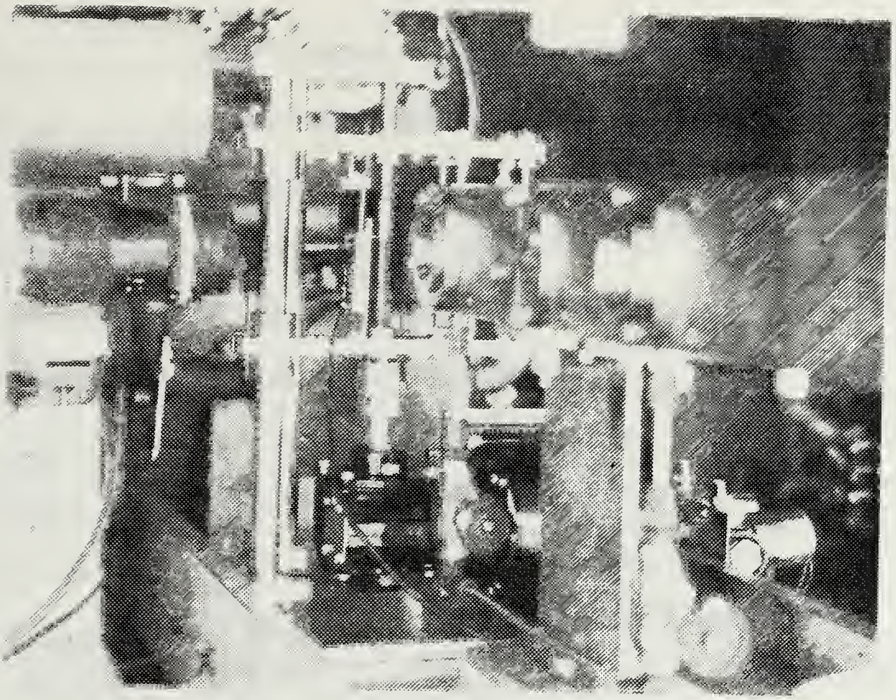


Figure 2.4 SFRJ Variable Height Step Apparatus

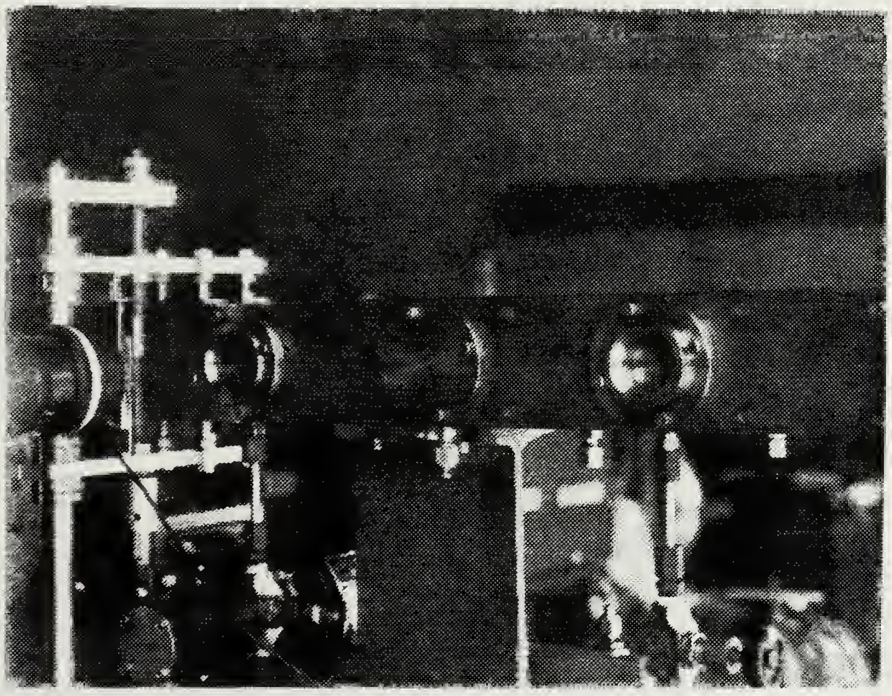


Figure 2.5 SFRJ Camera Windows Location

Figure 2.5). The viewing windows were 0.375 inch Plexiglas with metal shields to prevent fowling or burning of the windows. An air injection system utilizing a sintered bronze ring was used to purge the windows and keep them clear during motor operation. The air flowed through the sintered ring at a rate high enough to keep the windows soot free and yet low enough so as not to interfere with combustion characteristics of the SFRJ. A black Plexiglas slab 16 inches long, 0.25 inches thick, and 1.0 inches wide was sometimes placed on the side opposite the viewing windows to minimize heat loss and enhance combustion characteristics of the SFRJ.

The aft mixing chamber was located immediately after the fuel and was 2.5 inches wide, 6.0 inches long, with 1.25 inches between top and bottom. It was in this region that increased fuel and air mixing took place prior to ejection from the SFRJ.

The exit nozzle section had different carbon nozzles of varying throat diameter which could be installed depending on the required operating pressure inside the combustion chamber.

B. AIR SUPPLY, FLOW CONTROL, AND PURGE SYSTEMS

Air flow was provided to the SFRJ test stand by a 3000 psi air supply (see Figure 2.6). Air could be heated up to 1500 R by means of a vitiated air heater using gaseous methane (CH_4) with oxygen make up to replace that used in

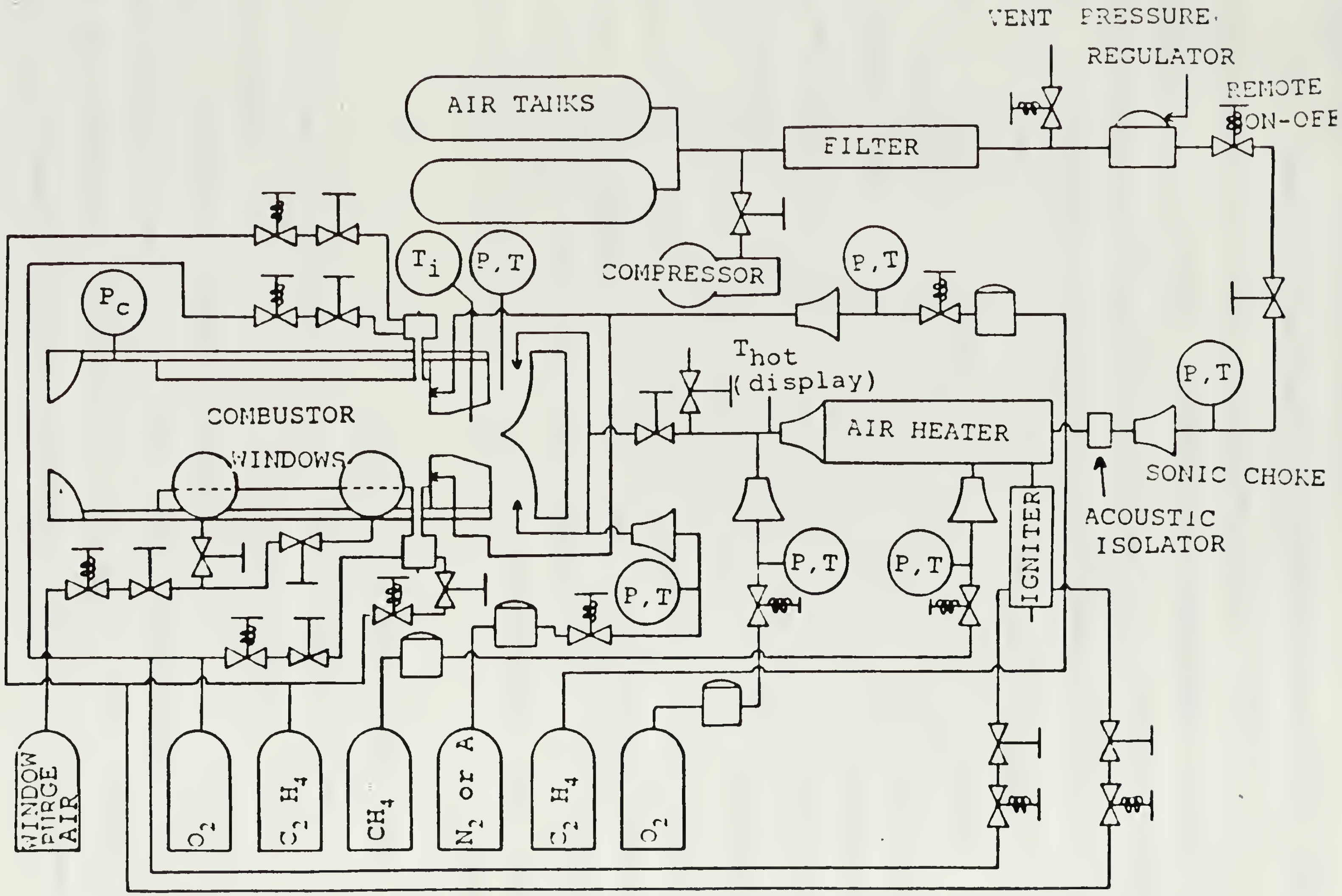


Figure 2.6 SFRJ Block Diagram

the heating process. Both temperature and pressure could be varied to simulate actual flight conditions. Air flow rate was controlled through the use of sonic chokes.

A nitrogen purge system was used to extinguish the combustion process following data acquisition. For several seconds after motor operation, nitrogen was flushed through the combustion chamber to ensure motor shutdown.

C. IGNITION SYSTEM

Ignition of the fuel slabs was accomplished by two ethylene (C_2H_4)-oxygen ignition torches. The torches were located at the upper and lower recirculation zones and directed at the fuel slabs. In addition, ethylene was injected into the recirculation zone from the rearward facing steps to assist in ignition. Once the continued, stable operation of the SFRJ was assured, the ignition torches and ethylene were shut off and the SFRJ allowed to burn. An ignition time of 1.5 seconds was used for most firings.

D. DATA ACQUISITION AND CAMERAS

A Hewlett-Packard 3054A computer based data acquisition and control system, consisting of a HP-9836 computer and 3497A data acquisition and control unit, was used to control many SFRJ operations, obtain temperature and pressure data, and perform data reduction. In addition, a modified IBM PC-AT was used to record combustion chamber pressure and step height data at an increased acquisition rate during fuel flammability limit determination.

High speed pictures of the burning fuel surface and the gas flow field were taken through air purged Plexiglas windows using two Red Lakes Labs 16mm Hycam cameras (see Figure 2.7). 100 feet capacity spools were used throughout the investigation at frame rates between 2000 and 6000 pictures per second. Each camera had a timing light source which was used to expose and annotate the edge of the film. One external timing light per camera supplied 100 Hz pulses. These pulses provided a cross reference with the step height and chamber pressure, since camera activation was recorded simultaneously with the step height and chamber pressure.

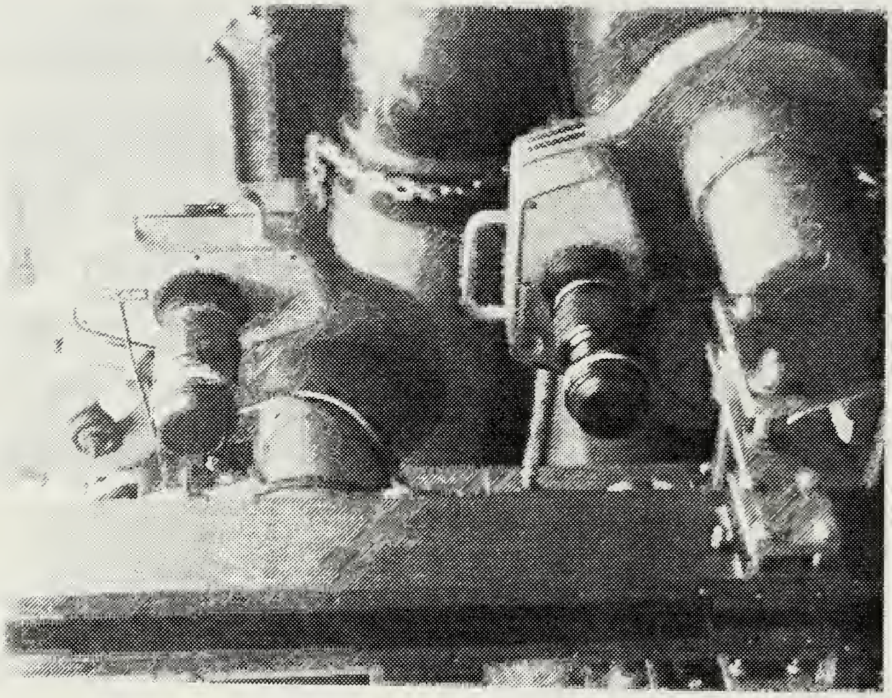


Figure 2.7 Hycam Cameras

III. EXPERIMENTAL PROCEDURE

A. VARIABLE HEIGHT STEP AND SOLID FUEL RAMJET MOTOR

The solid fuel grain was cut to the required size (16 in x 2.5 in x .25 in) and installed in the motor. Several fuel height and port height data readings were physically measured at the recirculation zone and averaged so precise step height data could be obtained. This was done during installation and after each ignition/flammability run. Air was heated to between 950 and 1050 degrees Rankine and supplied to the motor at an air mass flux of 0.2 lbm per second per square inch (air mass flow rate of 0.5 lbm per second). Exit nozzles of .75, .85, .95, 1.125, 1.25, 1.35, and 1.5 inches were available for high and low pressure conditions.

A Hewlett-Packard 3054A computer based data acquisition and control system was used to automatically initiate and control the duration of the following operations: heated air flow through the SFRJ (8 secs), motor igniter time (1.5 secs), motor burn time (5 secs), and purge time (4 secs). The SFRJ was extinguished after 5 seconds by the nitrogen purge system if ignition did take place and the motor failed to flameout due to inlet step operation. Initial step height selection was based on the estimation of the ignition limits of the fuel involved. If the SFRJ failed to ignite, the SFRJ was cooled to ambient temperature, fuel and port height remeasured, and the step height increased until SFRJ ignition/combustion was achieved and the ignition limit identified. After ignition, the inlet step height was decreased at approximately .035 inches per second until SFRJ flameout was achieved, or the motor was extinguished by the Hewlett-Packard control unit. Post run measurements of fuel and port height were then obtained and the fuel grain condition evaluated. If sufficient fuel remained, the process was repeated to verify data obtained thus far. Data acquisition of inlet step height and combustion chamber pressure was at 20 Hz while all other data was acquired at 2 Hz.

B. HYCAM CAMERA OPERATION

High speed pictures of the fuel grain surface just aft of the reattachment point and also just prior to the mixing chamber were taken during SFRJ operation. An F-stop of 5.6 and a frame rate of approximately 2000 pictures per second was used to insure proper exposure and at least 2 seconds of film during the burn sequence. The camera was initiated manually once the SFRJ was operating. 100 Hz timing light pulses annotated all films and camera operating voltage readings were obtained in addition to inlet step height and combustion chamber pressure to coordinate inlet step height and camera operation times.

C. CALIBRATION

All pressure transducers were calibrated as required using the HP-3054A data acquisition and control system. The variable height inlet step mechanism was checked after each run and calibrated every three runs. Mass flow rates and required operating pressures of the air, heater fuel (CH_4), heater oxygen (O_2), and ignition fuel (C_2H_4) were set using the data acquisition and control system.

IV. <u>RESULTS AND DISCUSSION</u>

A. SOLID FUEL RAMJET MOTOR OPERATION

The SFRJ used in this investigation was identical to that used in previous research efforts except for addition of the variable height, inlet step mechanism. Initial efforts concentrated on the development of standardized operating procedures and restrictions in the use of this system. These operating procedures were then interfaced with the experimental procedure so that the desired investigation objectives could be achieved.

In order to determine the effects of the moving inlet step during SFRJ operation, it was necessary to standardize as many of the operating parameters as possible. Air only time (heated air only through the SFRJ) and igniter time were required constants (8 and 1.5 seconds, respectively) since both had profound effects on ignition characteristics. If these times were allowed to become too large, fuel grain ignition was often too easily accomplished. After an ignition attempt or SFRJ operation, it was necessary to run ambient air through the SFRJ to ensure the fuel was at ambient temperature during the start of all ignition/flammability runs. Warmer fuel grains often ignited and operated at step heights lower than normally expected.

During many of the initial series of runs using the variable height step, a step travel rate of approximately 0.09 to 0.1 inches per second was used. In order to minimize the possibility of any transient effects, the step travel rate was slowed to the minimum possible rate. This was discovered to be approximately .035 inches per second or a net step rate of .019 inches per second after correcting for an average fuel regression rate of .016 inches per second. A rate any slower than this sometimes resulted in the flammability limit not being reached during the allotted 5 second burn time.

A smooth, continuous fuel slab extending the length of the combustion chamber provided much more reliable data than did a series of uneven fuel slabs applied in a series. Continuous fuel slabs were not available during the initial runs and smaller slabs often had to be used. The uneven joints in the fuel slabs downstream of the inlet step sometimes contributed to the formation of a second "step." This "step" would serve as a flameholder after the decreasing inlet step had reached the flammability limits of the fuel. Combustion would continue in the aft section of the combustion chamber leading to erroneous results.

Often up to 3 different ignition/flammability runs could be made on a newly installed fuel grain. However, the first and second runs were often more accurate since the fuel surface had become cratered and uneven by the third run.

Fuel height and port height would vary greatly depending on where it was measured. The first run would prove to be the most important when flammability limits needed to be established. Flameouts would rarely occur on anything but a fresh fuel grain. This could be attributed to the range of movement between the step and the fuel grain. The fresh fuel was relatively thick and the inlet step could move a greater distance with respect to the fuel. After the first run, enough of the fuel had been burned so that the flammability limit of the fuel could not be reached before the step had reached its minimum value. Ignition limits could be achieved on both the first and second runs since they were slightly higher than the flammability limits for a given fuel.

B. FUEL CHARACTERISTICS

The following types of fuels were used in the SFRJ. All the fuels contained carbon black unless otherwise noted.

1. R45HT - DDI
2. R45HT - DDI/5% DLX
3. R45HT - DDI/5% Teflon w/o Carbon Black
4. R45HT - DDI/5% Teflon
5. R45HT - DDI/10% Teflon
6. 50% Zecorez/45% R45HT - DDI/5% IDP
7. 60% Zecorez/34% R45HT - DDI/6% IDP

These fuels were selected on the basis of availability without any special emphasis as to desired operating characteristics. Initial attempts were made to acquire hydrocarbon fuels of the same composition but with variations in curing process and/or prepolymer, but they were unavailable at the time of testing.

The step height/port height ratio (H/D) proved to be the most reliable indicator of ignition and flammability limits. All the fuels displayed similar ignition and flameout characteristics. The SFRJ was usually ignited very close to the ignition limits of the given fuel. As the step height was decreased, the chamber pressure would decrease in a two-step fashion. Usually a small pressure drop would immediately occur within or slightly less than the approximate range of the ignition limits. The pressure drop would then increase and remain at a fairly constant rate until a H/D ratio was reached where the pressure would decrease much more rapidly until SFRJ flameout occurred (see Figures 3.1 through 3.5. Flammability limit data was unavailable for fuels (2) and (3) due to equipment malfunction). The exhaust flame could also be seen to diminish in intensity during reduction in the step height. If the step was initially at a H/D ratio higher than the established ignition limits, the chamber pressure would slowly decrease until the ignition region was reached, where a noticeable increase would then occur. At first it was believed that the initial and final pressure

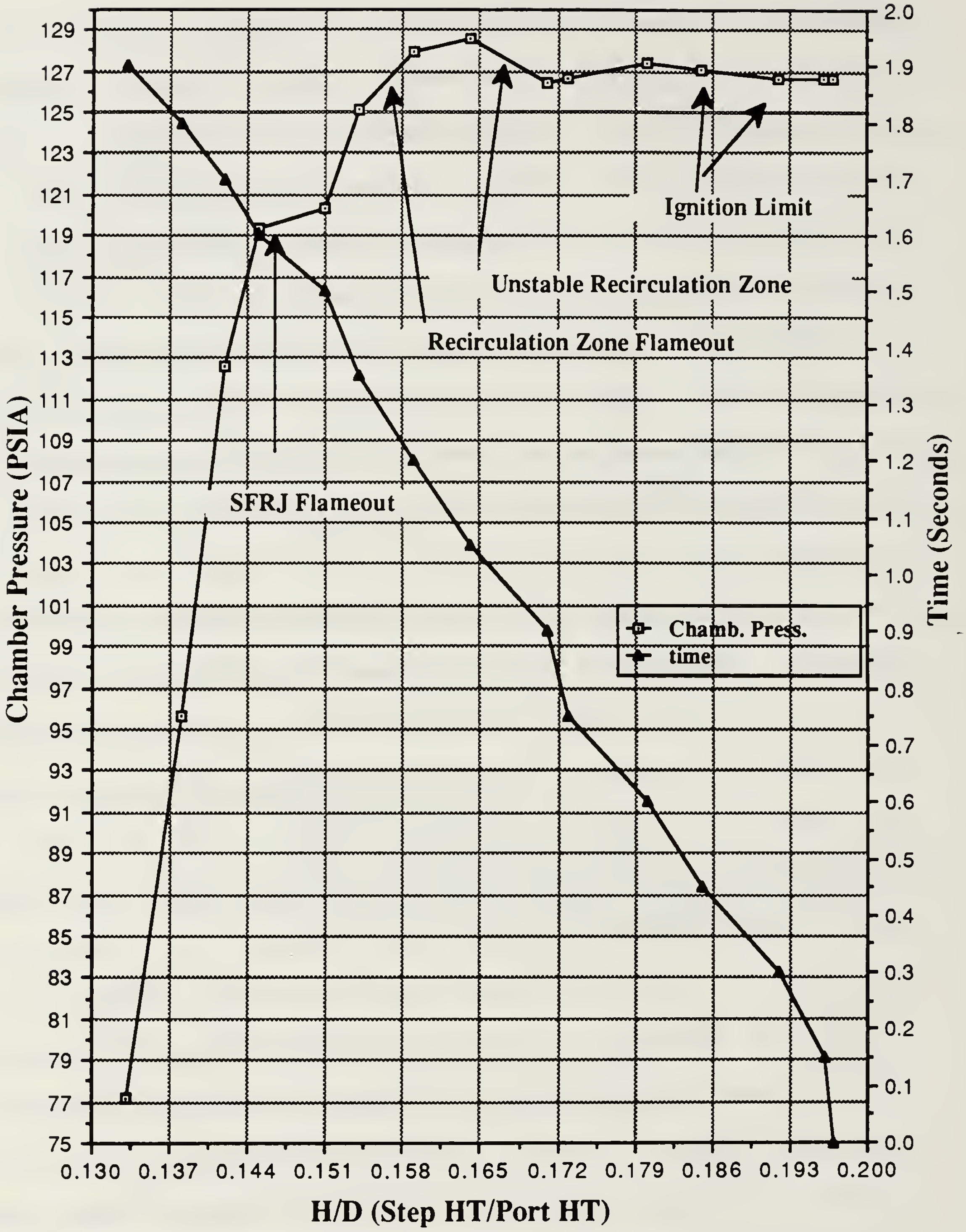


Figure 3.1 Ignition/Flammability Limits of 50% Zecorez / 45% R45HT-DDI / 5% IDP.

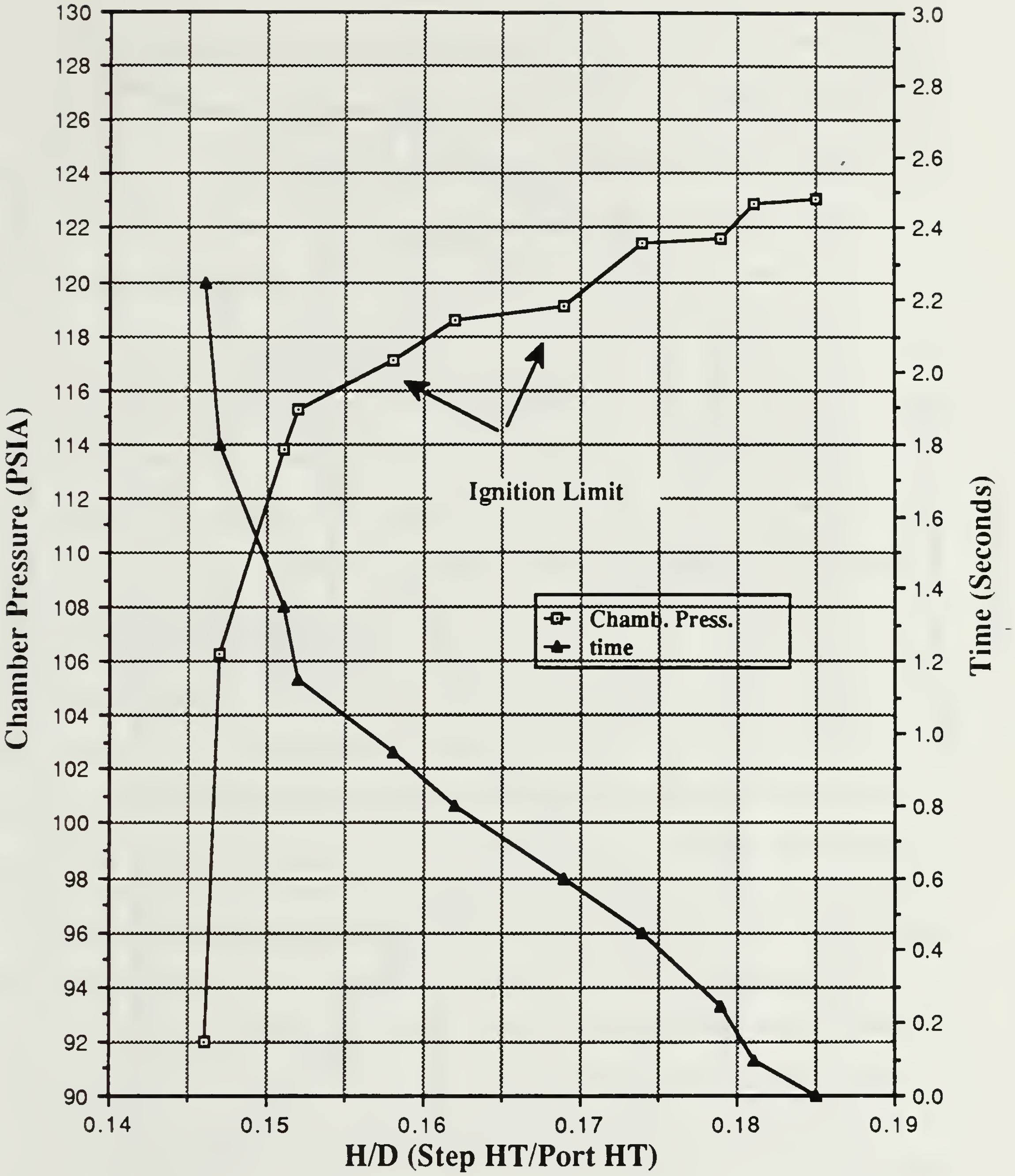


Figure 3.2 Ignition/Flammability Limits of 60% Zecorez / 34% R45HT-DDI / 6% IDP.

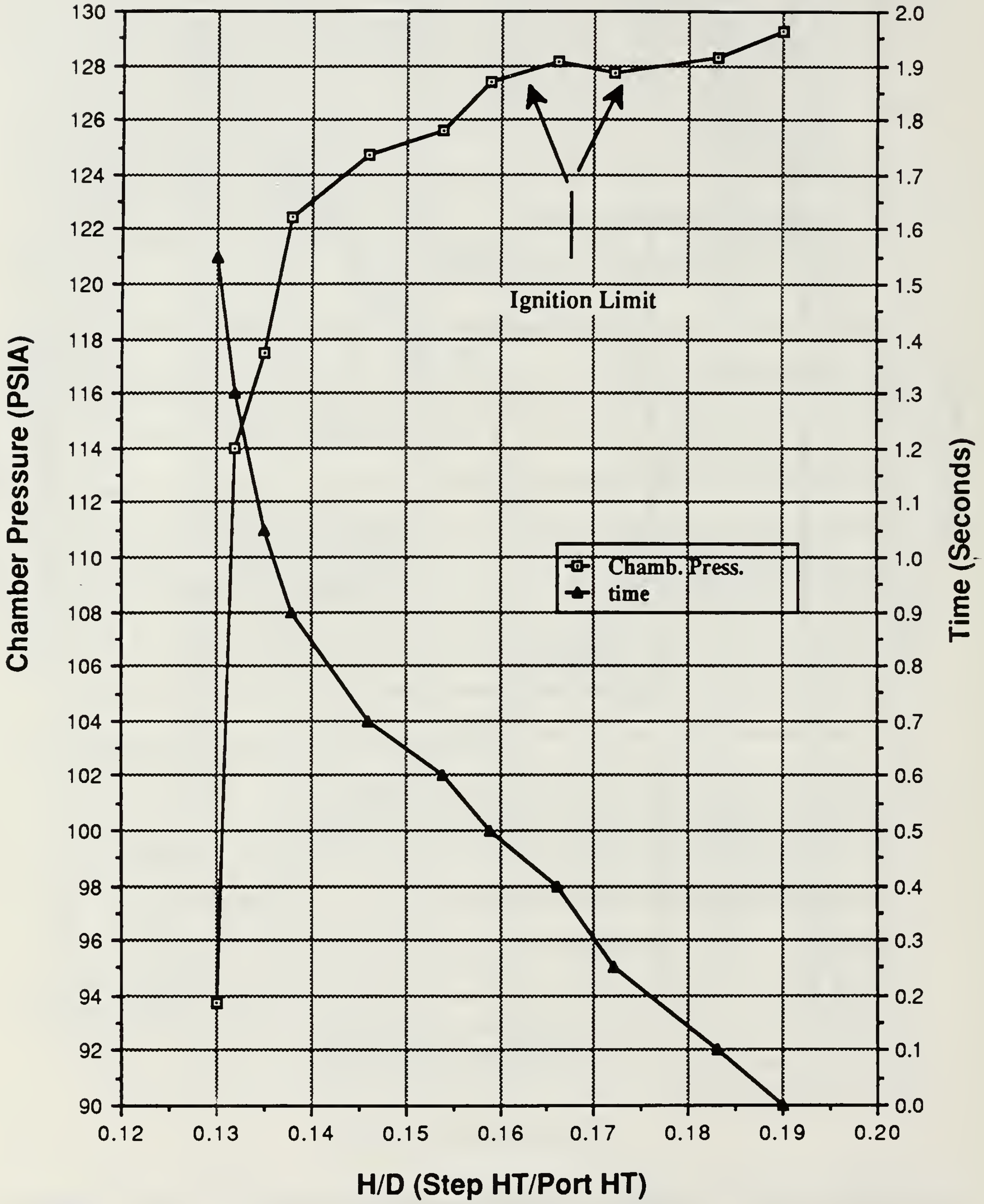


Figure 3.3 Ignition/Flammability Limits of R45HT-DDI.

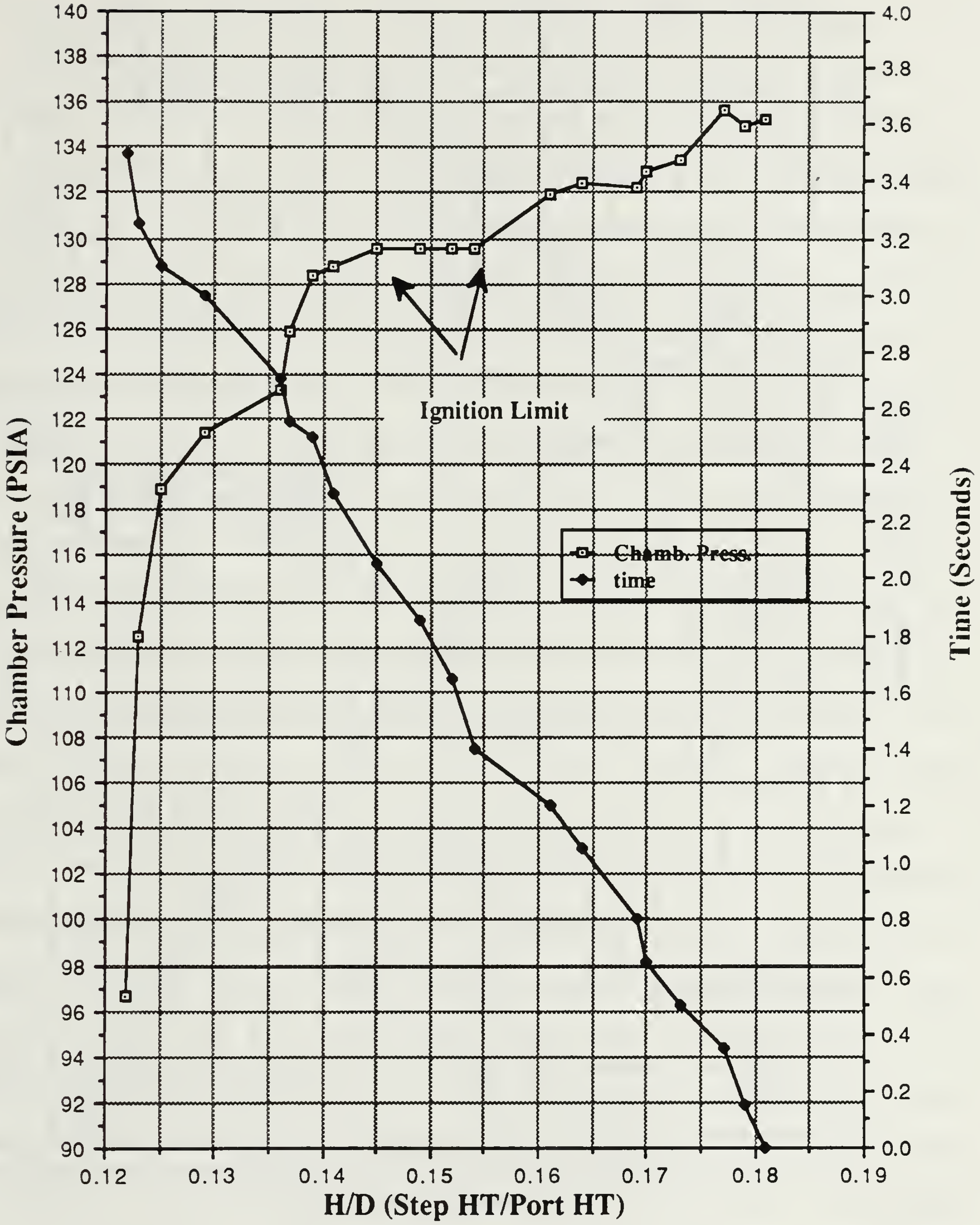


Figure 3.4 Ignition/Flammability Limits of R45HT-DDI / 5% Teflon.

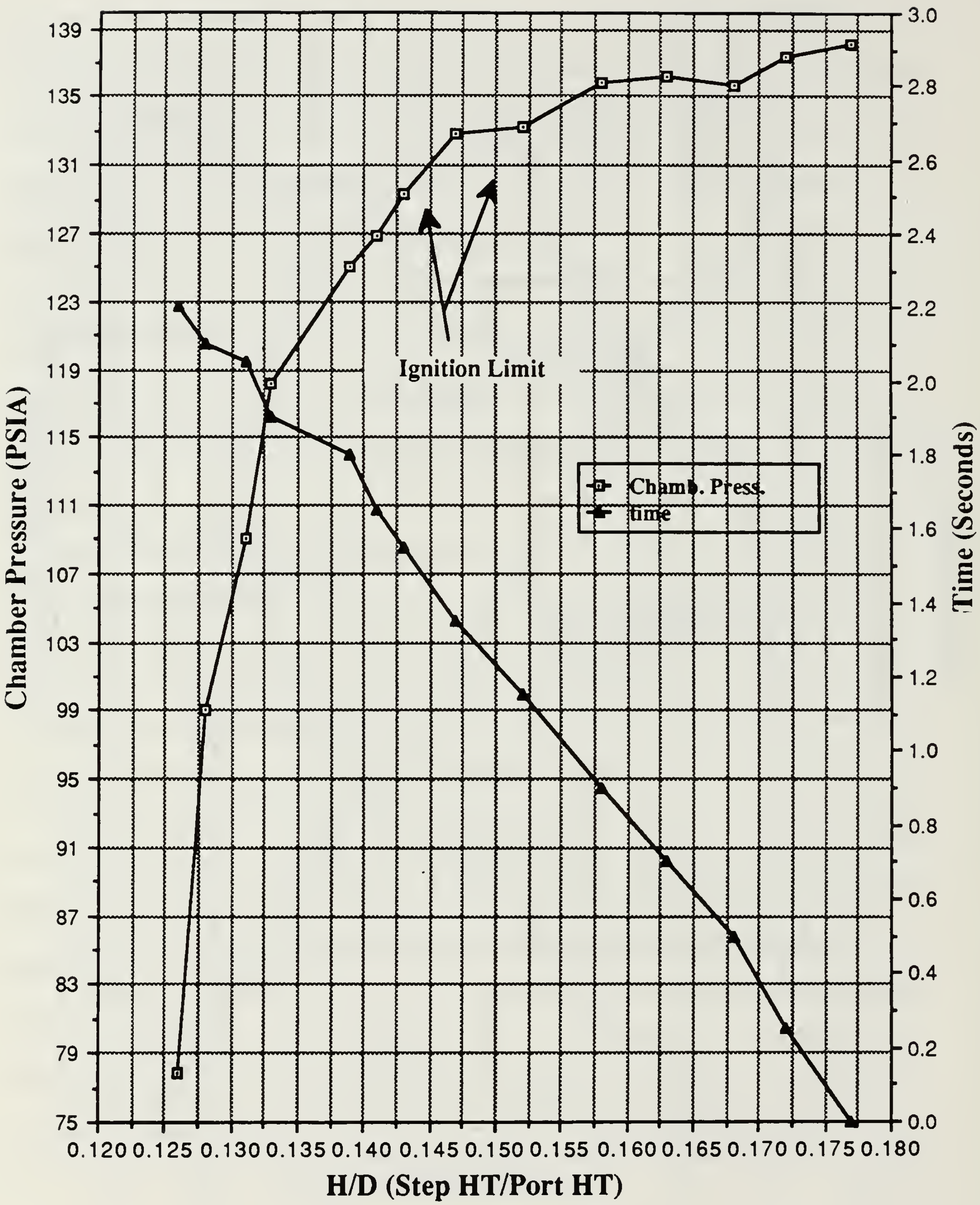


Figure 3.5 Ignition/Flammability Limits of R45HT-DDI / 10% Teflon.

drops were separate, unrelated phenomena. However, films from the HYCAM cameras indicated the second drop was a direct result of the first. During SFRJ operation with the inlet step at a fixed position, a bright and stable flame could be observed just aft of the recirculation zone and in the boundary layer. The fuel surface appeared to be flowing at a very slow rate in the direction of flow with little or no particulate matter in the flame region. The flames would exist continuously as the step height was decreased until at a certain point where the flames near the reattachment zone would begin to extinguish and reignite in an oscillatory manner (see Figure 3.1). The size and intensity of the oscillatory flame would decrease until it disappeared all together, indicating flameout of the recirculation zone. By comparing the data printouts of the chamber pressure and camera voltage with the timing light pulses on the films, it was determined that the first small pressure disturbance started with the beginning of the oscillatory flame in the recirculation zone and ended with recirculation zone flameout. The pressure drop rate would then increase and remain fairly constant as the flameout effects from the recirculation zone proceeded aft through the boundary layer region. The films from the boundary layer camera indicated that flameout in this region did not coincide with the recirculation zone flameout, but rather consistently occurred approximately .35 to .50 seconds later. Flameout in this region occurred rather abruptly without the slow decay observed in the other region, but a heavy concentration of solid fuel particles could be seen just prior to flameout. As the boundary layer region flamed out, the second sudden pressure drop could be observed (Figure 3.1). Therefore, while the H/D data for the various types of fuels (see Table 3.1) indicated SFRJ flameout usually much lower than the ignition limits, the actual flammability limit was reached when the recirculation zone flamed out during the first pressure drop, close to the ignition limit range. At that point, the rearward facing step had lost its flameholding characteristics and SFRJ flameout occurred shortly thereafter. The time delay between recirculation zone and boundary layer flameout appeared to be a boundary layer/fuel burning rate surface phenomena since the axial flow velocities through the center of the motor were so high that flameout by that means would be almost instantaneous. The longer flameout times were observed for the Teflon derivative fuels (Figures 3.4 and 3.5), where the oxidizer enriched surface regions reduced the rate of chamber pressure decrease and increased fuel resistance to flame blowoff.

The fuels which contained the most oxidizer (10% and 5% Teflon), together with carbon black, displayed the lowest ignition/flammability limits or smallest step height requirements (Table 3.1). However, the 5% Teflon fuel

TABLE 3.1

SUMMARY OF RESULTS

	H/D Ratio	
Fuel Type	Ignition Limit	SFRJ Flameout
R45HT - DDI	.165-.177	.143
R45HT - DDI 5% Teflon No Carbon Black	.175-.183	*
R45HT - DDI 5% Teflon	.146-.155	.129-.135
R45HT - DDI 10% Teflon	.145-.148	.130-.136
R45HT - DDI 5% DLX	.150-.157	*
50% Zecorez 45% R45HT - DDI 5% IDP	.187-.193	.145-.152
60% Zecorez 34% R45HT - DDI 6% IDP	.160-.169	.152-.155

NOTES: (1) * denotes data unavailable due to equipment malfunction.

(2) Flameout data is for flameout of the entire combustor.

(3) Data represents the net results from 33 SFRJ tests. All tests were made under the following operating conditions:

Mass Flux: 0.194-0.203 lbm/in^2/sec
Air Mass Flow Rate: 0.49-0.51 lbm/sec
Air Inlet Temperature: 920-960 degrees Rankine
Operating Chamber Pressure: 128-140 psia
Nozzle Throat Diameter: 0.75 inches
Pre-ignition Air Time: 8.0 seconds
Ignition Time: 1.5 seconds
Burn Time: 4.0 seconds

without carbon black had among the largest step requirements, second only to the fuel containing 50% Zecorez. By comparing the R45HT - DDI with its 5% Teflon derivative fuels with and w/o carbon black, it can be seen that the presence of carbon black reduced the ignition/flammability limits more than the addition of 5% Teflon. By increasing the amount of Zecorez from 50% to 60%, the ignition/flammability limits were reduced from .187-.193 to .160-.169.

V. CONCLUSIONS AND RECOMMENDATIONS

The two-dimensional windowed motor with variable inlet step height proved to be a good diagnostic device for studying the ignition and flammability characteristics of the solid fueled ramjet.

The major results of this initial investigation were as follows:

(1) As H/D is reduced, the flameout process begins as an oscillatory ignition/extinguishment behavior in the recirculation zone. This is followed by a weakening flame and, finally, to extinguishment of the recirculation zone. Flameout along the fuel surface occurred at a rate between 2 and 3 ft/sec.

(2) As H/D was decreased (before the ignition limits were reached), chamber pressure (and therefore fuel regression rate) decreased (except for the 50% Zecorez fuel). This behavior may provide a method for some thrust modulation of the SFRJ.

(3) In most cases the ignition limits occurred at nearly the same H/D where oscillatory recirculation zone combustion behavior began during step height transient tests.

(4) Addition of oxidizer to the fuels reduced the required H/D, as expected.

(5) Increasing the amount of Zecorez in the Zecorez/R45HT mixtures changed the H/D requirements from greater than to less than that required for pure R45HT.

(6) The removal of carbon black significantly increased the H/D requirements. This indicates that ignition/flammability limits are strongly influenced by surface pyrolysis processes.

Some of the testing was hampered due to the limited quantity of fuels. Often only one sample of each fuel type was available to determine both ignition and flammability limits. More fuel samples would permit the verification of existing data while providing the opportunity for testing under a variety of operating conditions. Testing under high G conditions (mass flux of 0.5 lbm/in^2), lower operating pressures, and different air inlet temperatures would provide greater insight into the ignition/flammability limits of the fuels.

LIST OF REFERENCES

1. Binn, B.A., A Comparison of Solid Fuel Ramjet Flow Characteristics and Combustion Behavior, M.S. Thesis, Naval Postgraduate School, Monterey, California, December 1979.

2. Netzer, D.W., "Overview of Ramjet and Ducted Rocket Engines for Tactical Missiles," Naval Postgraduate School, Monterey, California.

3. Chemical Systems Division/United Technologies, "Solid Fuel Ramjets."

4. Gany, A. and Netzer, D.W., "Combustion Studies of Metallized Fuels for Solid Fuel Ramjets," Naval Postgraduate School Report, NPS 67-84-012, October 1984.

5. Chemical Systems Division, United Technologies, "The Pocket Ramjet Reader," 1978.

6. Karadimitris, Adonis, The Effects of Metallized Fuel Composition on the Combustion Characteristics of Solid Fuel Ramjets, M.S. Thesis, Naval Postgraduate School, Monterey, California, December 1986.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Technical Information Center Cameron Station Alexandria, Virginia 22304-6145	2
2.	Library, Code 0142 Naval Postgraduate School Monterey, California 93943-5002	2
3.	Department Chairman, Code 67 Department of Aeronautics Naval Postgraduate School Monterey, California 93943-5000	1
4.	Professor D.W. Netzer, Code 67Nt Department of Aeronautics Naval Postgraduate School Monterey, California 93943-5000	2
5.	Lt. Richard C. Wooldridge Faireconron Four NAS Patuxent River, Maryland 20670	2

Thesis
W84375 Wooldridge
c.1 An experimental investigation of the ignition and flammability limits of various hydrocarbon fuels in a two-dimensional solid fuel ramjet.