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Final Report

INTERMITTENT DETONATION AS A  
THRUST-PRODUCING MECHANISM

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FOREWORD

The work reported herein was conducted under University of Michigan, Engineering Research Institute Project No. 2318 for the Wright Aeronautical Division of the Curtiss-Wright Corporation. All the work was performed by personnel of the Aircraft Propulsion Laboratory.

## TABLE OF CONTENTS

	Page
FOREWORD	ii
LIST OF FIGURES	iv
ABSTRACT	vi
OBJECTIVE	vii
NOMENCLATURE	viii
ACKNOWLEDGEMENT	x
INTRODUCTION	1
THEORETICAL BACKGROUND	2
EXPERIMENTAL DETERMINATION OF THE IMPULSE FROM A SINGLE DETONATION WAVE	10
CYCLIC DETONATION TUBE	17
RESULTS OF INTERMITTENT DETONATION EXPERIMENTS	22
DISCUSSION	27
CONCLUSIONS	32
REFERENCES	33

## LIST OF FIGURES

	Page
1. Detonation wave in a constant area duct.	2
2. Pressure distribution across a detonation wave.	4
3. Properties of detonation waves.	6
4. Detonation tube.	6
5. Idealized thrust-time history.	8
6. Theoretical thrust and impulse characteristics of intermittent detonation.	9
7. Experimental arrangement.	12
8. Impulse derived from hydrogen-oxygen detonations.	13
9. Impulse derived from acetylene-oxygen detonations.	14
10. Instrumentation for pendulum experiments.	15
11. Acceleration-time graphs of acetylene-oxygen detonations.	16
12. Cyclic detonation tube.	18
13. Photograph of the cyclic detonation tube.	19
14. Experimental arrangement for intermittent detonation tests.	20
15. Oscillograph trace.	23
16. Thrust vs fuel-air ratio for various frequencies.	24
17. Thrust vs fuel-air ratio for various frequencies.	24

18. Thrust vs fuel-air ratio for various frequencies.	25
19. Thrust vs frequency for various air flow rates.	25
20. Specific impulse vs frequency for various air flow rates.	26
21. Temperature ( $T_2$ ) vs fuel-air ratio for various frequencies.	26
22. Temperature ( $T_3$ ) vs fuel-air ratio for various frequencies.	28
23. Temperature ( $T_4$ ) vs fuel-air ratio for various frequencies.	28
24. Temperature vs frequency for constant fuel-air ratio.	29
25. Specific impulse vs fuel-air ratio.	29
26. Specific thrust vs fuel-air ratio.	31
27. Specific impulse vs specific thrust.	31

## ABSTRACT

The feasibility of a reaction device operating on intermittent gaseous detonation waves is considered. The results of a simplified theoretical analysis are presented and discussed.

Preliminary experiments to determine the impulse derived from a single detonation wave are described and analyzed in light of the theoretical results. A few basic parameters, deemed influential to the successful operation of an intermittent detonation engine, were also investigated in these preliminary tests.

A cyclic detonation tube was designed and operated utilizing hydrogen-air mixtures. Measurements of thrust, fuel flow, air flow, and temperatures were effected for a variety of operating conditions. Specific impulses of over 2100 sec were obtained which is in good agreement with the predicted performance.

On the basis of these results and those that could be expected with other fuels, it appears that an intermittent detonation engine offers many advantages for particular applications over conventional reaction devices and that further exploration is warranted.

#### OBJECTIVE

The objective of this project is to investigate the feasibility of operating an engine on intermittent detonation waves.

## NOMENCLATURE

a	speed of sound
A	area
f	percent fuel by volume
F	thrust
I	specific impulse, lb thrust/lb fuel per second
L	length
m	molecular weight
M	Mach number
P	pressure
Q	heat release
R	universal gas constant
T	temperature
t	time
$t_D$	time for detonation to traverse length L.
$t_r$	time for rarefaction to traverse length L
$t_f$	time to introduce fresh charge
$t_c$	time for one cycle
V	velocity
$w_f$	weight flow of fuel per unit time
$w_{fc}$	weight of fuel per cycle



$w_O$  weight flow of oxygen per unit time

$w_{Oc}$  weight of oxygen per cycle

$\gamma$  ratio of specific heats

$\rho$  density

Subscripts

1 conditions in unburned gas

2 conditions in burned gas

o stagnation condition or oxygen

3 conditions at plateau behind detonation wave

f fuel

#### ACKNOWLEDGEMENT

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## INTRODUCTION

The advent of jet propulsion has witnessed the successful operation of the turbojet, ramjet, pulse-jet and rocket engines. Each form of reaction device has its inherent characteristics, both advantageous and disadvantageous, which suit it to particular functions. The turbojet achieves the highest fuel economy, yet it is the most demanding in mechanical complexity. In contrast, the ramjet represents the utmost in mechanical simplicity and achieves very high thrusts at supersonic flight velocities. On the debit side, the ramjet lacks static thrust capabilities and has been plagued with serious combustion problems.

The rocket is unique in its ability to operate in a vacuum and is capable of extremely high thrusts. However, the specific impulse is very low, common values being of the order of 250 sec, whereas the turbojet attains values of over 3000 sec. The pulse-jet engine was used in the German V-1 and is currently popular in helicopter applications. It has quite good thrust characteristics at subsonic velocities but is overshadowed by the ramjet for supersonic applications. The efficiency of the pulse-jet is intermediate to the rocket and turbojet. One of the major disadvantages is the problem of valve life. More recently promise has been shown for the valveless pulse-jet. Still in the experimental stage, specific impulses of 2500 sec have been obtained.

In the course of investigations on gaseous detonative combustion<sup>1,2</sup> it occurred to the authors that an engine operating intermittently on detonation waves might afford some advantages. Consequently, a theoretical analysis was made in 1952 in order to investigate the feasibility of such a cycle.<sup>3</sup> These results indicated that, in general, very high specific thrusts (thrust per unit combustion chamber area) could be attained but at the expense of specific impulse. However, in the case of hydrogen-air mixtures the results were the reverse; high specific impulses were indicated but at relatively low specific thrust. It appears that an intermittent detonation engine would offer many advantages. Selection of the proper fuel could materially affect the operating characteristics so that a range of applications is possible. Also the engine would be capable of static thrust as well as efficient operation at supersonic velocities. Hence, it could bridge the gap between the pulse-jet and ramjet. Mechanically, the engine could be extremely simple with few or no rotating parts.

On the basis of this preliminary analysis, the present program was initiated for the purpose of exploring experimentally the possibility and feasibility of an engine operating on intermittent detonative combustion. At the time this work was initiated, no information was available on any previous work on this subject. Subsequently, it was found that Hoffman<sup>4</sup> of Germany had successfully operated an engine on intermittent detonation in 1941. A summary of his work was included in an earlier progress report<sup>5</sup> and will be discussed later along with the results reported herein.

Analytical work relating to this subject has been reported by Biondo, Bollay, and Kendrick.<sup>6,7</sup> In general, their predicted results lay in the intermediate specific impulse and specific thrust ranges. They conclude that a pulsating detonation engine has profitable application to helicopter propulsion.

### THEORETICAL BACKGROUND

As mentioned earlier, theoretical calculations on the performance of a reaction device operating on intermittent detonation waves indicated favorable aspects of such a cycle if it could be realized physically. It is intended to review briefly these results as well as some of the fundamental characteristics of detonation.

A detonation wave is conventionally treated as a shock wave followed by combustion. If we consider a stationary gaseous detonation wave in a constant area duct, the hydrodynamic analysis may be readily formulated and is merely the problem of heat addition to a one-dimensional stream. Referring to Fig. 1, the change in state conditions across the wave may be found by use

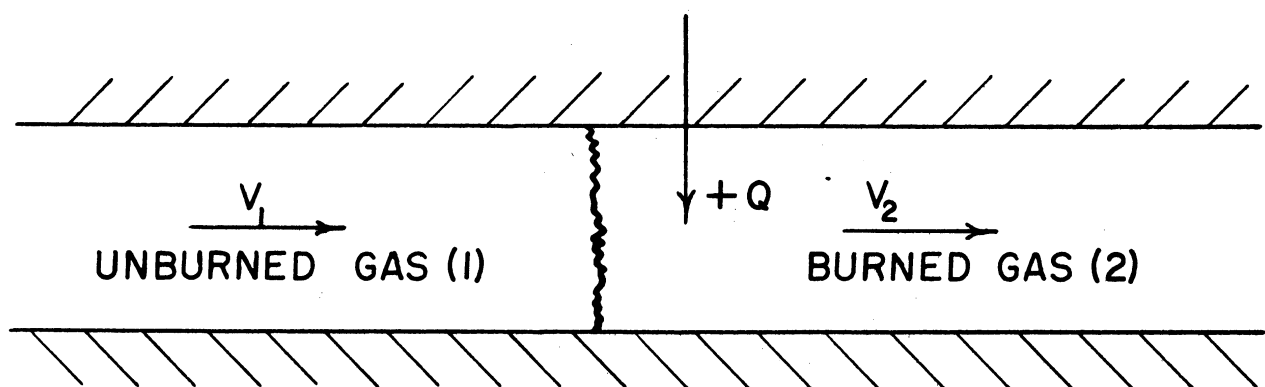


Fig. 1. Detonation wave in a constant area duct.

of the conservation equations. That is

momentum:

$$P_1 + \rho_1 V_1^2 = P_2 + \rho_2 V_2^2 ; \quad (1)$$

mass:

$$\rho_1 V_1 = \rho_2 V_2 ; \quad (2)$$

equation of state:

$$P = \rho \frac{R}{m} T . \quad (3)$$

Rearranging the momentum equation and introducing the equation of state, we may write

$$P_1 \left[ 1 + \frac{V_1^2}{R_1 T_1} \right] = P_2 \left[ 1 + \frac{V_2^2}{R_2 T_2} \right] \text{ or}$$

$$\frac{P_2}{P_1} = \frac{1 + \gamma_1 M_1^2}{1 + \gamma_2 M_2^2} \quad (4)$$

where  $M_1$  will be referred to as the Mach number of detonation. The hydrodynamic analysis predicts that  $M_2$ , the Mach number of the burned gases relative to the front, may be subsonic, sonic, or supersonic. These processes correspond, respectively, to strong detonation, Chapman-Jouguet detonation, and weak detonation. The latter type can be shown to violate entropy considerations while the strong detonation has never been observed in the stable state. It is an experimental fact that the Chapman-Jouguet detonation is the type experienced although under certain conditions it should be possible to generate stable, strong detonations.<sup>1,8</sup> In view of these considerations,  $M_2 = 1$  and the pressure ratio across the detonation wave becomes

$$\frac{P_2}{P_1} = \frac{1 + \gamma_1 M_1^2}{1 + \gamma_2} . \quad (5)$$

Introducing the isentropic relation between static pressure and total pressure, the ratio of stagnation pressures across the wave may be obtained as follows:

$$\frac{P_{02}}{P_{01}} = \frac{P_2 \left[ 1 + \frac{\gamma_2 - 1}{2} M_2^2 \right]^{\frac{\gamma_2}{\gamma_2 - 1}}}{P_1 \left[ 1 + \frac{\gamma_1 - 1}{2} M_1^2 \right]^{\frac{\gamma_1}{\gamma_1 - 1}}}$$

Introducing Equation 5 and also  $M_2 = 1$ ,

$$\frac{P_{02}}{P_{01}} = \frac{1 + \gamma_1 M_1^2}{1 + \gamma_2} \frac{\left(\frac{\gamma_2 + 1}{2}\right)^{\frac{\gamma_2}{\gamma_2 - 1}}}{\left(1 + \frac{\gamma_1 - 1}{2} M_1^2\right)^{\frac{\gamma_1}{\gamma_1 - 1}}} \quad (6)$$

In the case of a flame tube the pressure established behind the detonation wave, as indicated by Equation 5, will be modified by trailing rarefaction waves. Hence, the pressure  $P_2$  will be reduced to a plateau pressure  $P_3$  as shown in Fig. 2. This plateau pressure is related to the peak pressure by a relation derived by Morrison;<sup>1</sup> i.e.,

$$\frac{P_3}{P_1} = \frac{P_2}{P_1} \left[ 1 - \frac{\gamma_2 - 1}{2} M_{2c}^2 \right]^{\frac{2\gamma_2}{\gamma_2 - 1}} \quad (7)$$

where  $M_{2c}$  is the Mach number of the burned gases relative to a fixed point on the flame tube. For Chapman-Jouguet detonation, this is a subsonic Mach number.

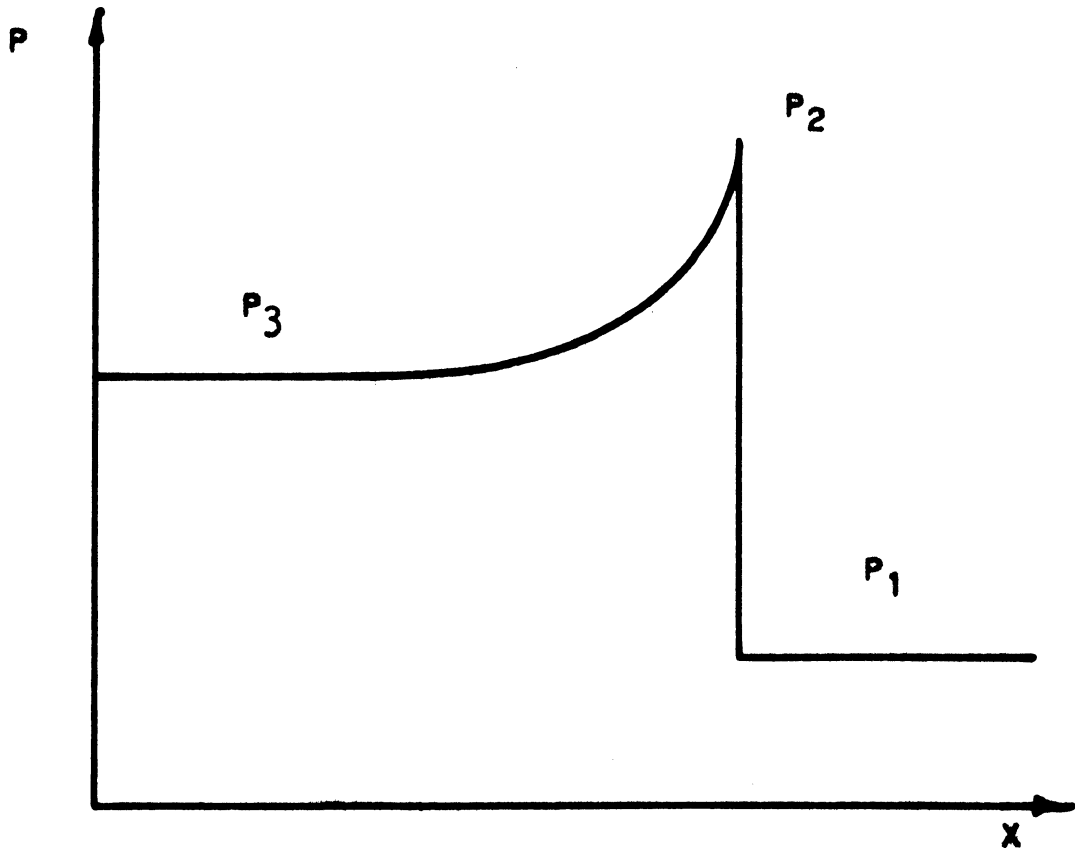


Fig. 2. Pressure distribution across a detonation wave.

The density ratio across a detonation wave may be obtained by combining Equations 1 and 2 to give

$$(\rho_1 V_1)^2 = (\rho_2 V_2)^2 = \frac{P_1 - P_2}{\frac{1}{\rho_2} - \frac{1}{\rho_1}} \text{ or}$$

$$\gamma_1 M_1^2 = \frac{\left(1 - \frac{P_2}{P_1}\right)}{\left(\frac{\rho_1}{\rho_2} - 1\right)},$$

which yields

$$\frac{\rho_1}{\rho_2} = \frac{1 - \frac{P_2}{P_1}}{\gamma_1 M_1^2} + 1. \quad (8)$$

The state equation may be written in the form

$$\frac{T_2}{T_1} = \frac{P_2}{P_1} \cdot \frac{m_2}{m_1} \cdot \frac{\rho_1}{\rho_2}. \quad (9)$$

Introducing Equations 5 and 8 and simplifying, the temperature ratio becomes;

$$\frac{T_2}{T_1} = \frac{m_2}{m_1} \cdot \frac{\gamma_2}{\gamma_1} \cdot \frac{1}{M_1^2} \left[ \frac{1 + \gamma_1 M_1^2}{1 + \gamma_2} \right]^2. \quad (10)$$

As can be seen from the relations derived, the fundamental parameter in expressing the changes across a detonation wave is the Mach number of detonation. Consequently, a general range of the pressures and temperatures involved may be obtained by plotting the ratios against the Mach number of detonation if simplifications are made as to the changes in  $\gamma$  and molecular weight. Such a plot is shown in Fig. 3 wherein it was assumed that  $\gamma_1 = 1.4$ ,  $\gamma_2 = 1.15$ , and  $m_2/m_1 = 1.0$ . Typical values of the Mach number of detonation range from about 3.0 to 10.

The above characteristics are, of course, influential in the thrust-producing ability of intermittent detonation waves. Let us consider a detonation tube of uniform cross-sectional area  $A$  and length  $L$  (Fig. 4). A spark plug is located at the closed end while the other end is open. The intermittent detonation cycle visualized is as follows:

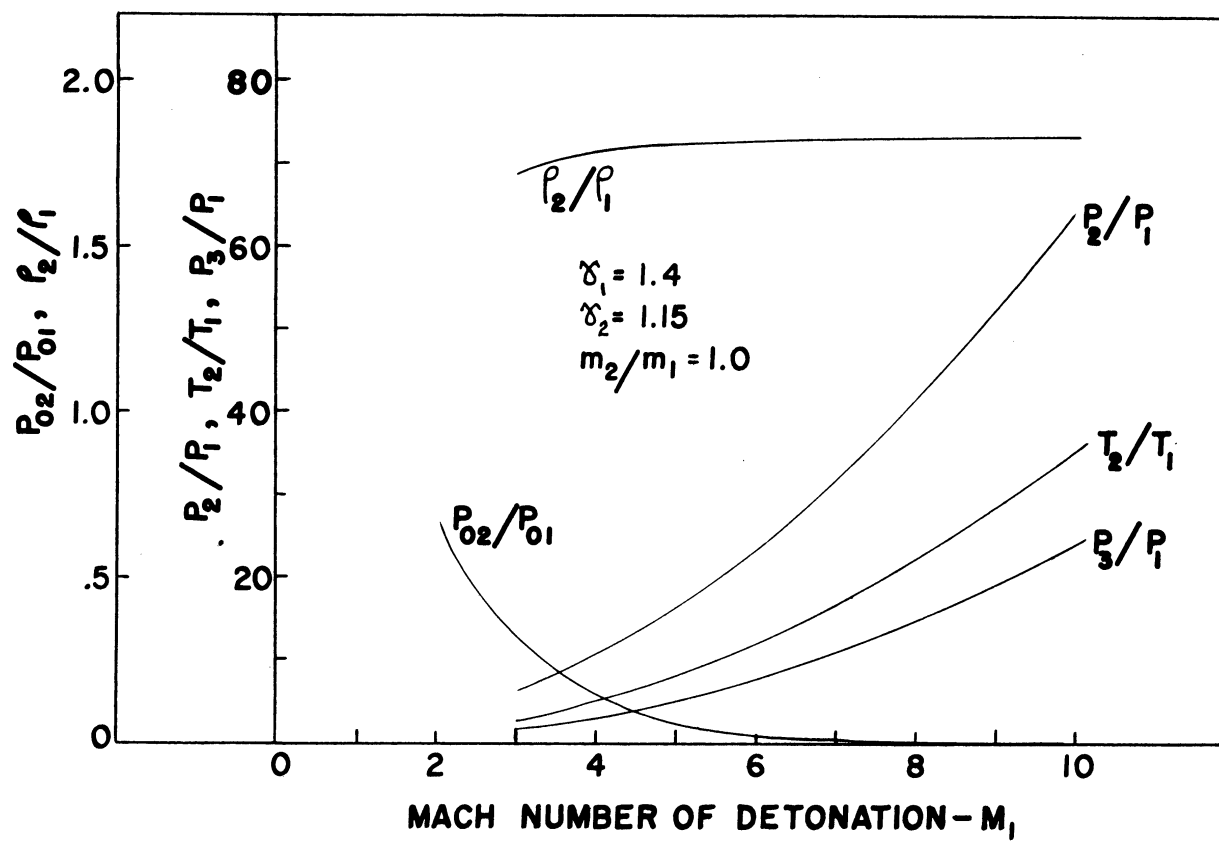


Fig. 3. Properties of detonation waves.

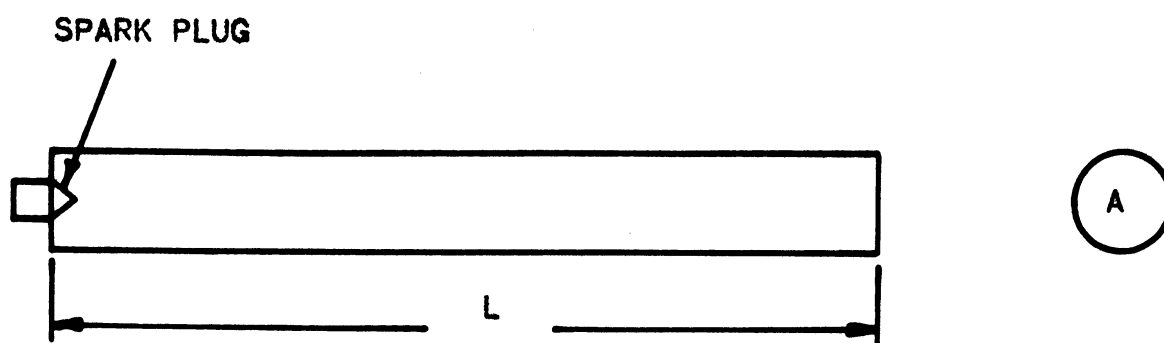


Fig. 4. Detonation tube.



1. introduction of the gaseous detonable mixture,
2. initiation of a flame front at the closed end by energization of the spark plug,
3. development of a detonation wave from the flame front,
4. reflection of rarefaction waves as the detonation wave reaches the open end of the tube,
5. gradual exhausting of the burned gases as the rarefaction waves move upstream and reflect from the closed end as a further rarefaction; eventually, the tube reaches sub-atmospheric pressures so that compression waves are reflected from the open end, and
6. introduction of the fresh charge for the next cycle.

A detailed analysis of this unsteady-flow thermodynamic cycle would be exceedingly complex and lengthy. Furthermore, there would still be ambiguity in that the mathematical description of the transition of flame front to detonation cannot be formulated. Accordingly, a number of simplifying assumptions were made in the original analysis in order to readily obtain an engineering evaluation of an intermittent detonation engine. These assumptions were:

1. Chapman-Jouguet detonation is established immediately at the closed end of the tube.
2. The rarefaction wave returns as a discontinuity and at sonic velocity corresponding to state  $\gamma$ .
3. This original rarefaction wave reduces the pressure level of the tube to atmospheric pressure so that all subsequent reflections are neglected.
4. Introduction of the fresh charge takes place at atmospheric pressure.
5. No valving or frictional losses are involved.

In view of these simplifying assumptions a thrust-time history would appear as shown in Fig. 5. The average thrust may be evaluated by:

$$F_{avg} = \frac{\int_0^{t_c} F dt}{t_c} = \frac{F(t_D + t_r)}{t_D + t_r + t_f} \text{ or}$$

$$F_{avg} = \frac{F}{\frac{t_c}{t_D + t_r}} \quad (11)$$

Noting that

$$F = (P_3 - P_1)A = AP_1 \left( \frac{P_3}{P_1} - 1 \right), \quad (12)$$

the equations derived earlier may be used to obtain the equation for average thrust as

$$F_{avg} = AP_1 \left\{ \frac{1+\gamma_1 M_1^2}{1+\gamma_2} \left[ 1 - \frac{\gamma_2-1}{2} M_{2c}^2 \right]^{\frac{2\gamma_2}{\gamma_2-1}} - 1 \right\} \left( \frac{t_D+t_r}{t_c} \right). \quad (13)$$

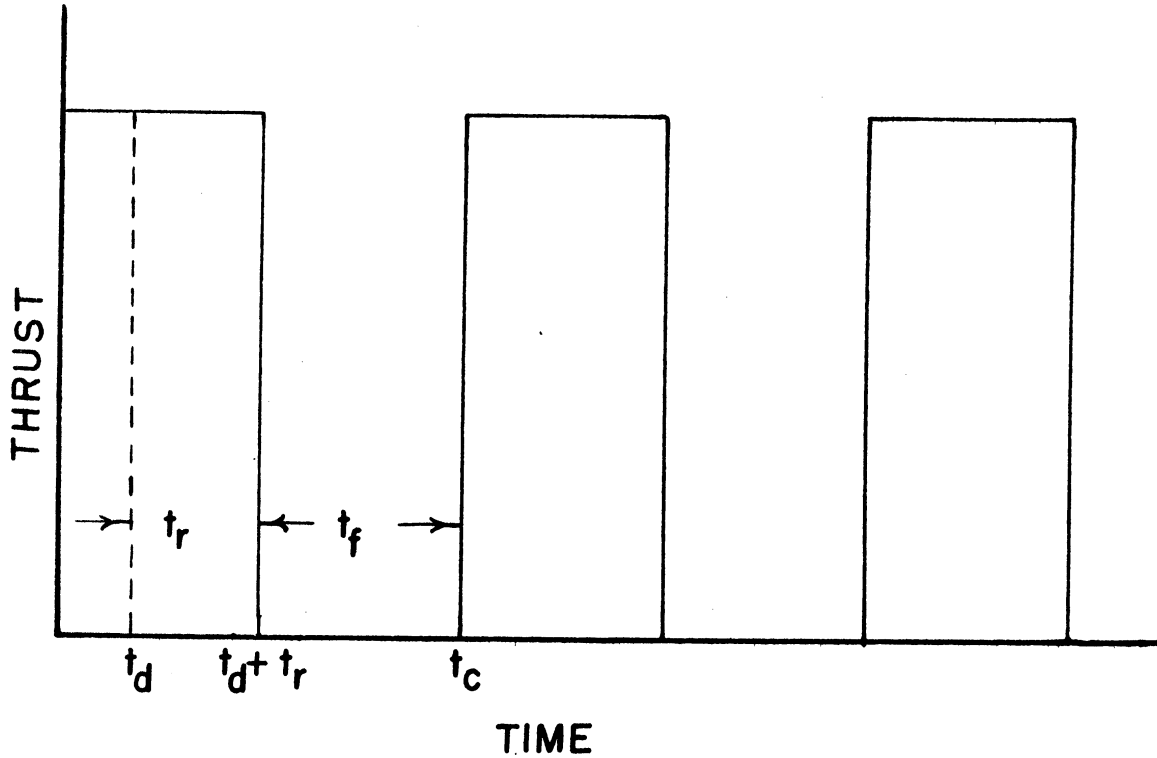


Fig. 5. Idealized thrust-time history.

In order to circumvent the tube geometry and the uncertainty in the term

$$\frac{t_c}{t_D + t_r},$$

a modified thrust term may be utilized for purposes of calculation, i.e.,

$$\frac{F_{avg}}{A} \left( \frac{t_c}{t_D+t_r} \right).$$

Reference 3 shows the results of these calculations for a number of gaseous mixtures. Particular assumptions made in the calculations were that  $P_1 = 14.7$  psia,  $T_1 = 528^\circ R$ , and  $\gamma_2 = 1.15$ . Experimental values of the velocity and Mach number of detonation were utilized. The theoretical results for acetylene-oxygen and hydrogen-air mixtures are reproduced in Fig. 6.

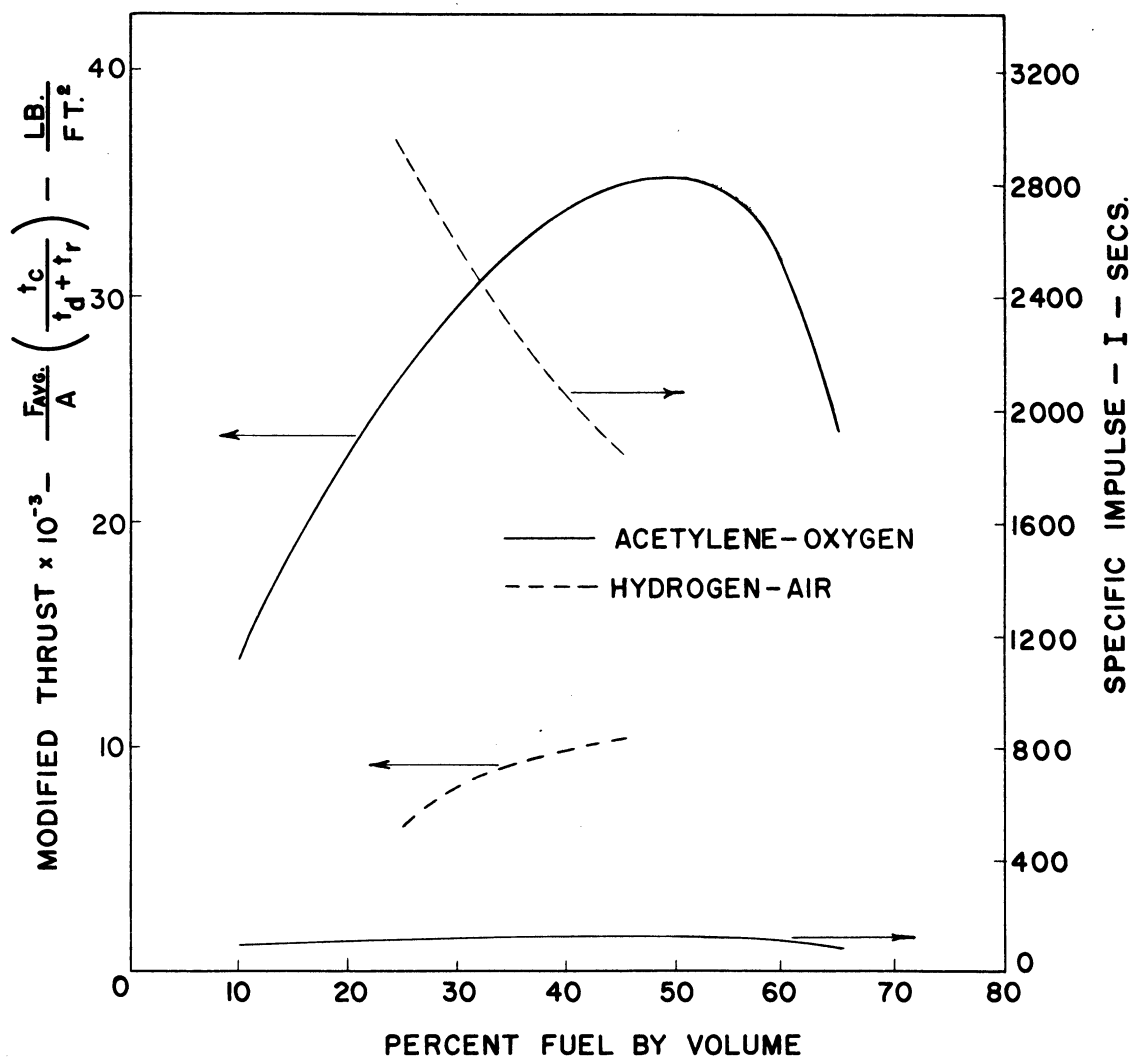


Fig. 6. Theoretical thrust and impulse characteristics of intermittent detonation.

The specific impulse may be evaluated from the relation

$$I = \frac{F_{avg}}{w_F + w_O} \quad (14)$$

In those cases where the oxidant is oxygen, the propulsion system is penalized for the rate of oxygen flow as well as the rate of fuel flow. In view of the relations

$$w_F = \frac{w_{fc}}{t_c} = \frac{\rho_f A L f}{t_c} \quad \text{and}$$

$$w_o = \frac{w_{oc}}{t_c} = \frac{\rho_o AL(1-f)}{t_c},$$

the specific impulse may be written

$$I = \frac{P_1 \left\{ \frac{1+\gamma_1 M_1^2}{1+\gamma_2} \left[ 1 - \frac{\gamma_2-1}{2} M_{2c} \right]^{\frac{2\gamma_2}{\gamma_2-1}} - 1 \right\} (t_D + t_r)}{L [\rho_f f + \rho_o (1-f)]}. \quad (15)$$

The length  $L$  may be eliminated by expressing  $t_D$  and  $t_r$  in terms of  $L$  and the respective velocities so that finally

$$I = \frac{P_1 \left\{ \frac{1+\gamma_1 M_1^2}{1+\gamma_2} \left[ 1 - \frac{\gamma_2-1}{2} M_{2c} \right]^{\frac{2\gamma_2}{\gamma_2-1}} - 1 \right\} \left\{ \frac{1}{V_1} + \frac{\gamma_1 M_1}{\gamma_2 a_1} \frac{(1+\gamma_2)}{(1+\gamma_1 M_1^2)} \right\}}{\rho_f f + \rho_o (1-f)}. \quad (16)$$

The results of these calculations for the same two gases are also included in Fig. 6.

In general it is seen that the thrust level is very high, for reasonable values of

$$\frac{t_c}{t_D + t_r},$$

but that the specific impulse is low. However, as mentioned earlier in the case of hydrogen-air mixtures the reverse situation is indicated.

#### EXPERIMENTAL DETERMINATION OF THE IMPULSE FROM A SINGLE DETONATION WAVE

The theoretical analysis just discussed involves a number of simplifying assumptions that could prove to be all important to the successful operation of an intermittent detonation engine. In order to isolate some of these parameters it was decided to perform preliminary experiments on a single detonation wave. It was felt that this approach would be more fruitful than a direct attempt at intermittent detonation where the detailed wave processes would be obscured. Accordingly a detonation tube was fabricated and suspended from the ceiling as a pendulum. The particular mixture to be studied was premixed in a stainless steel reservoir and admitted to the detonation tube by

means of a detachable line and petcock arrangement. After purging the tube with the mixture, the petcock was closed, the fuel line detached, and the downstream end of the tube sealed with a paper diaphragm. The mixture was ignited by a conventional spark plug or glow plug. The experimental arrangement is shown in Fig. 7.

The impulse derived from a single detonation wave was determined experimentally by noting the deflection of the pendulum. Representative runs are shown in Fig. 8 and 9 for hydrogen-oxygen and acetylene-oxygen mixtures, respectively. Comparison with theory was effected by dividing the impulse (calculated from the measured deflection) by the weight of mixture in the detonation tube. The results for hydrogen-oxygen (Fig. 8) reveal very good agreement between experiment and theory for mixtures richer than about 40%. This mixture ratio corresponds to the dividing line between relatively clean detonations and those where the combustion tends to lag the shock front. This lag increases as the mixture is leaned further. It appears reasonable that the leaner mixtures require greater time to detonate and consequently the impulse is lowered. It might be noted from the figure that the specific impulse continues to increase beyond the point of maximum impulse. This effect is attributable to the decreasing weight of the mixture with increasing hydrogen which is sufficient to overbalance the reduction in impulse.

The results for the acetylene-oxygen experiments (Fig. 9) reveal only fair agreement with theory. However, for those mixtures that would probably be used in an actual detonating engine the agreement is good. It is interesting that the point of perfect agreement, 50% acetylene, represents the mixture with the highest Mach number of detonation.

The above results, along with other similar results,<sup>9</sup> were encouraging and informative. However, this type of experiment was restricted to macroscopic results and hence yielded no information on the wave processes which would be so important in an actual engine. Accordingly, an accelerometer was mounted at the center of the detonation tube so that the acceleration of the tube and hence an indication of the thrust and pressure, could be obtained as a function of time. These results were displayed on an oscilloscope and photographed by means of a Polaroid Land Camera. The experimental setup and instrumentation for all the pendulum measurements are shown in Fig. 10.

Figure 11 shows the results of accelerometer measurements for two acetylene-oxygen mixtures. The simplified theoretical results are shown for comparison. Earlier it was noted that these mixtures gave good agreement between measured and predicted impulse. In view of Fig. 11, this merely implies that the area under the theoretical and experimental curves is the same but obviously the thrust-time history is markedly different. Time equals zero in Fig. 11 represents the time of spark plug energization so that the

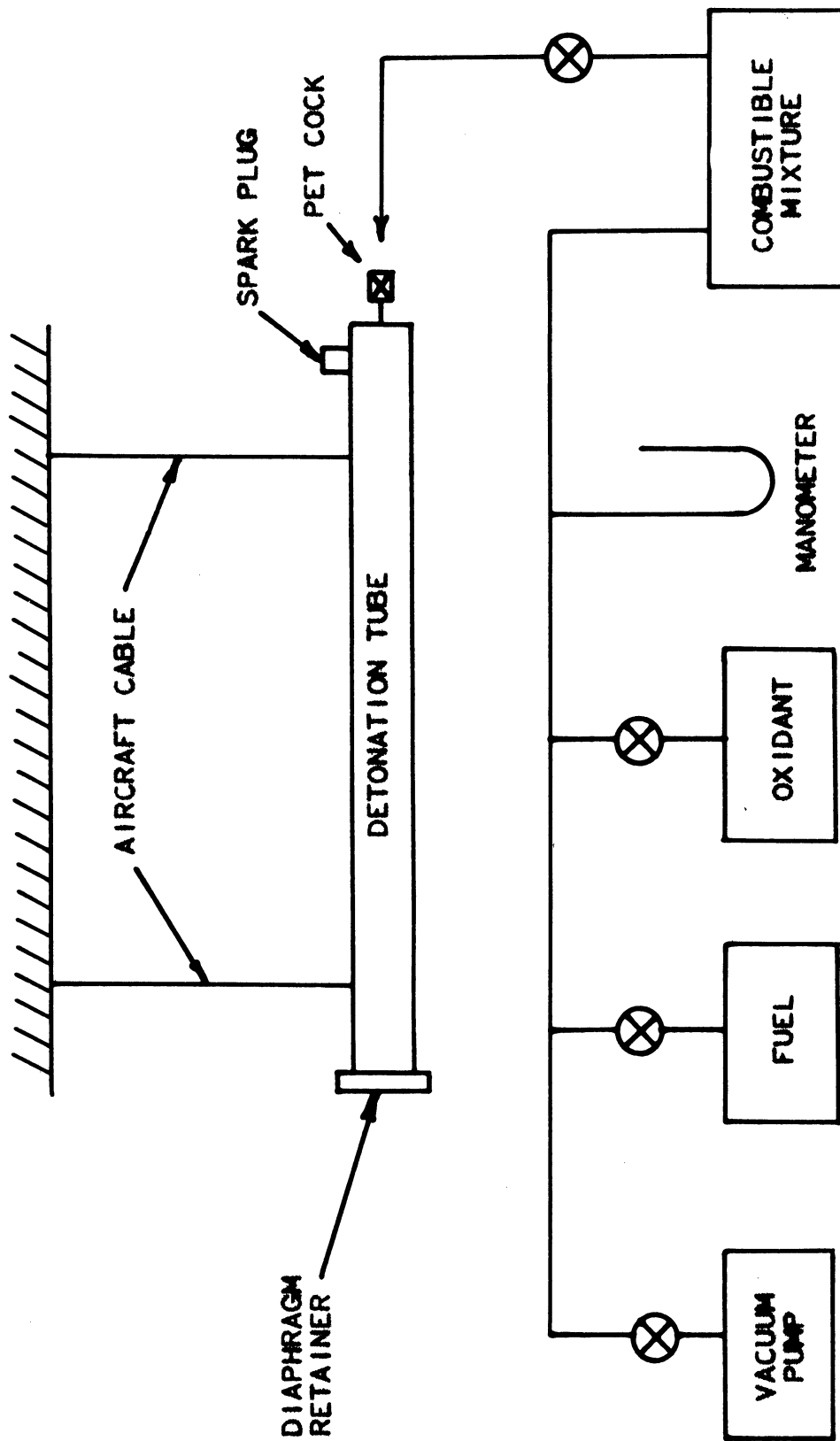


Fig. 7. Experimental arrangement.

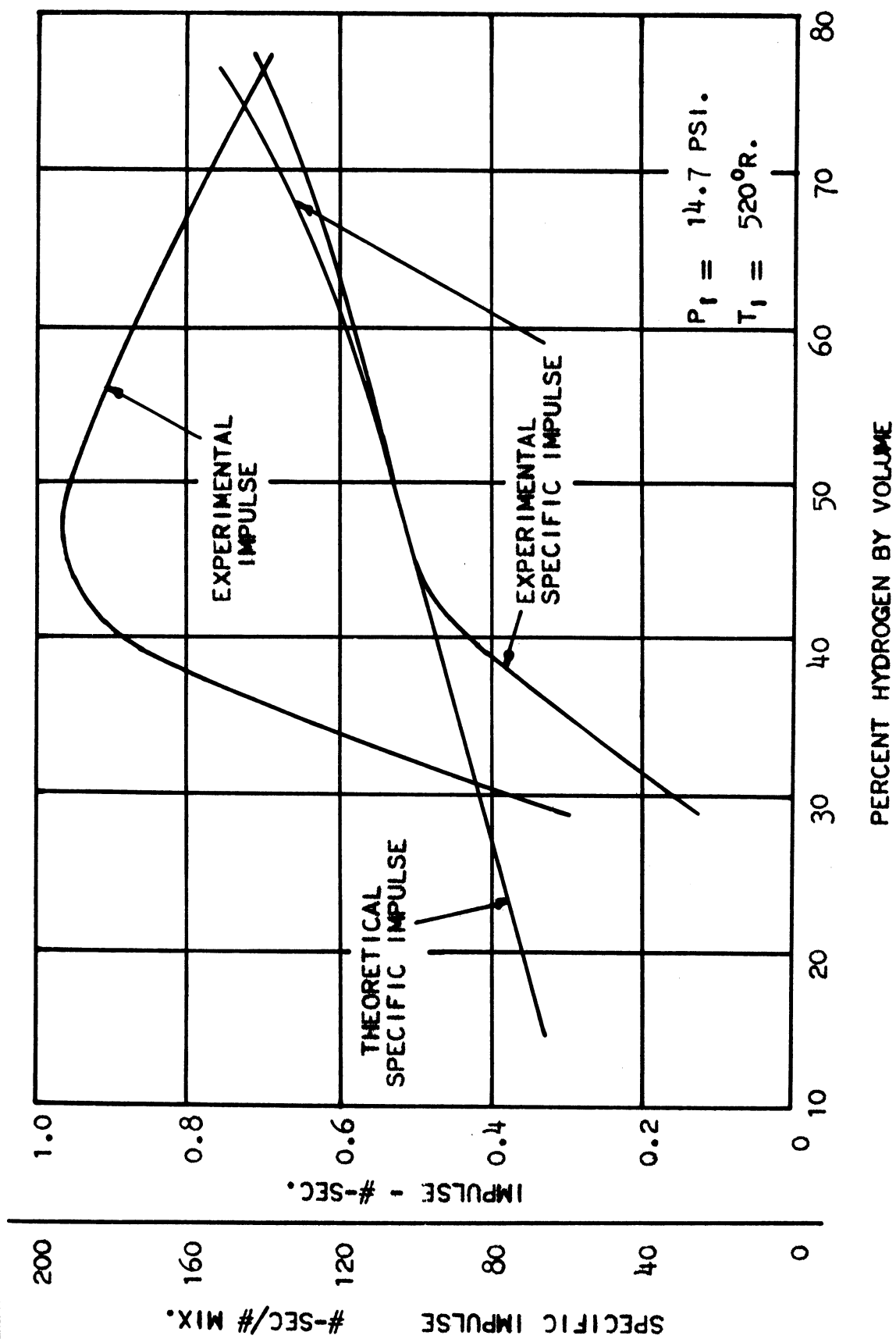


Fig. 8. Impulse derived from hydrogen-oxygen detonations.

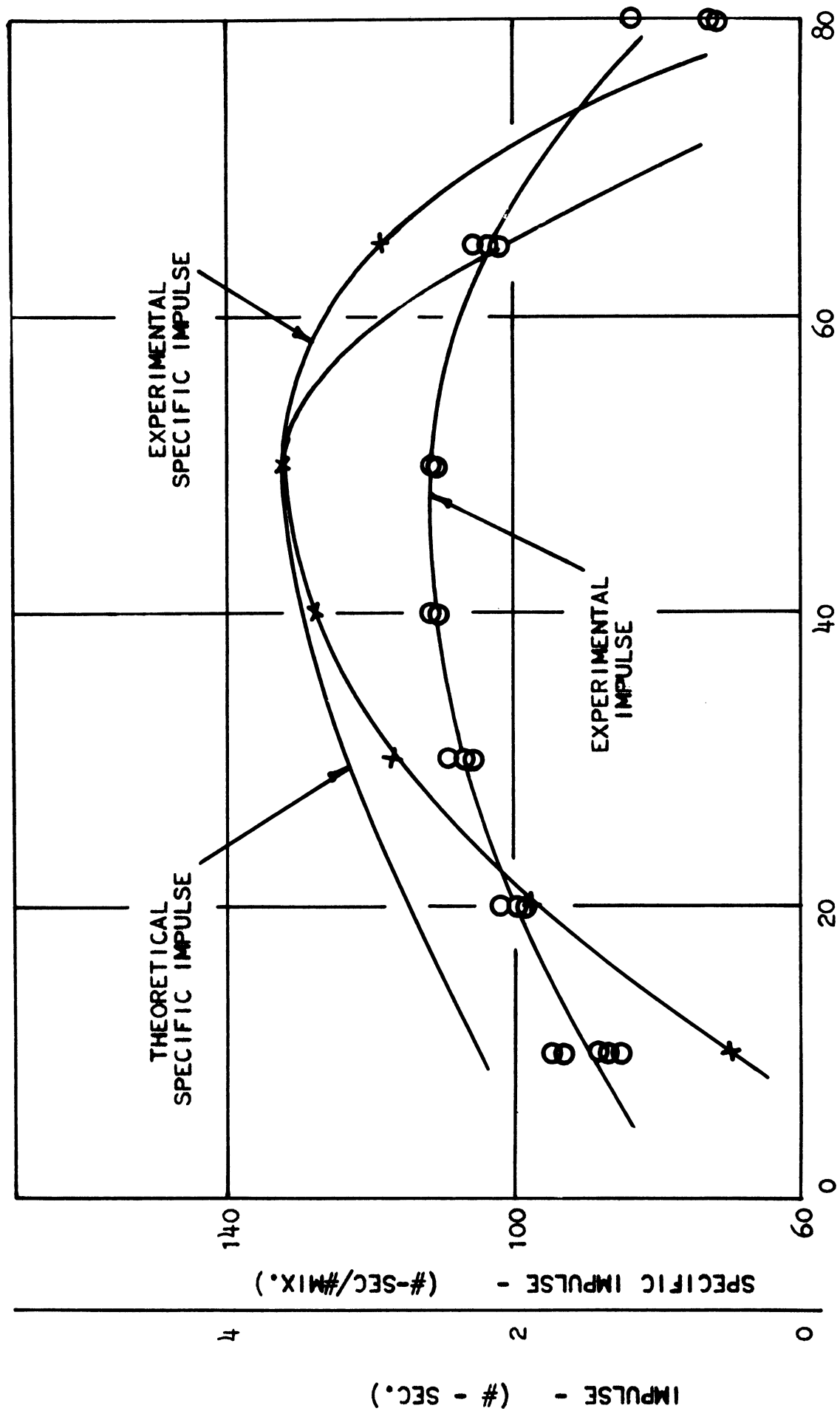


Fig. 9. Impulse derived from acetylene-oxygen detonations.



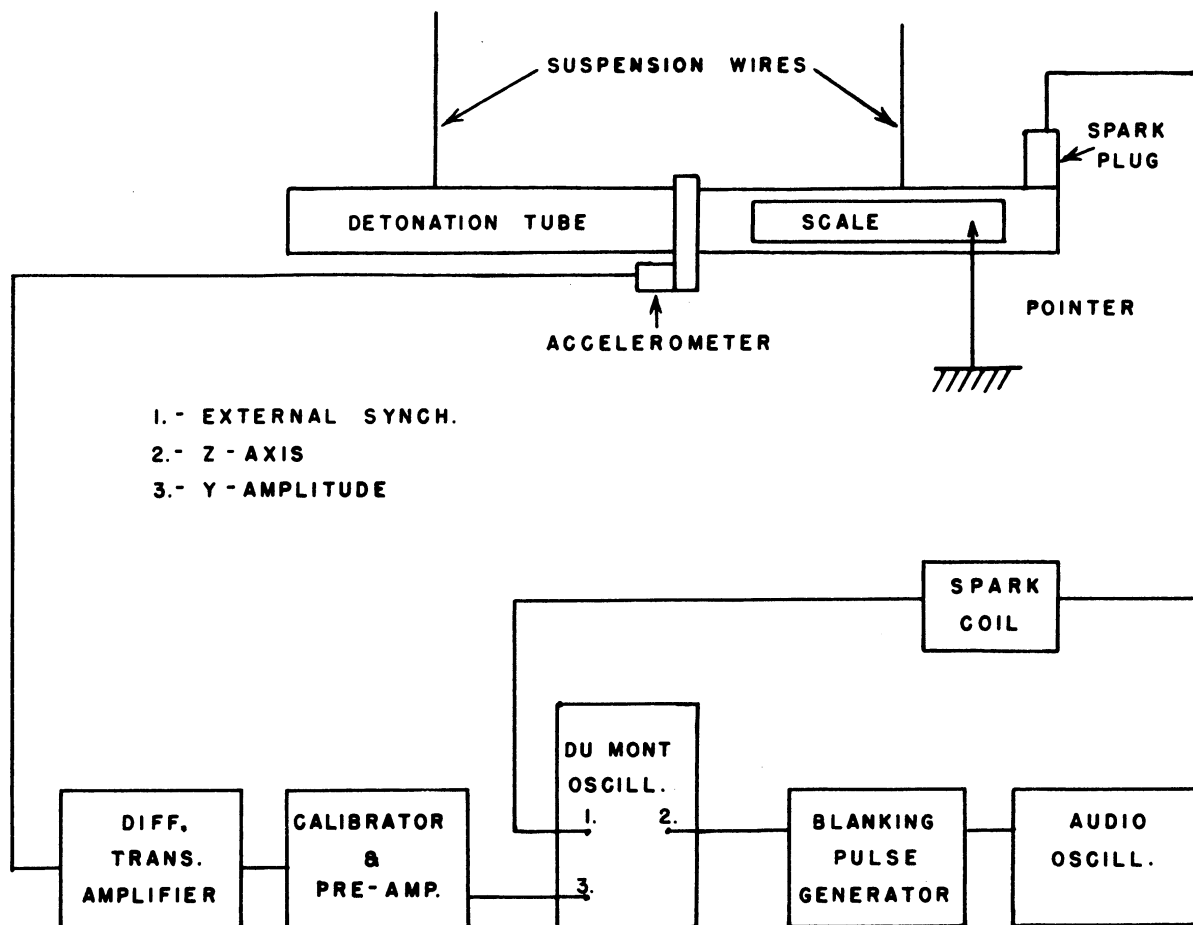
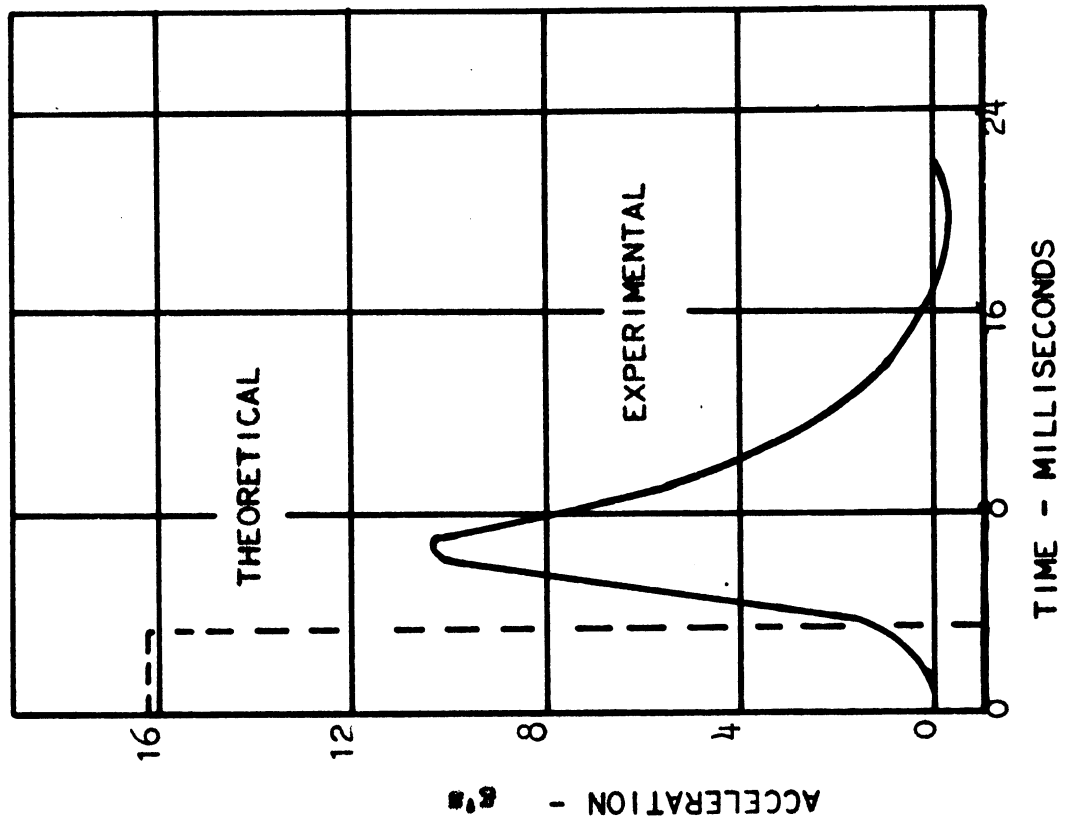


Fig. 10. Instrumentation for pendulum experiments.

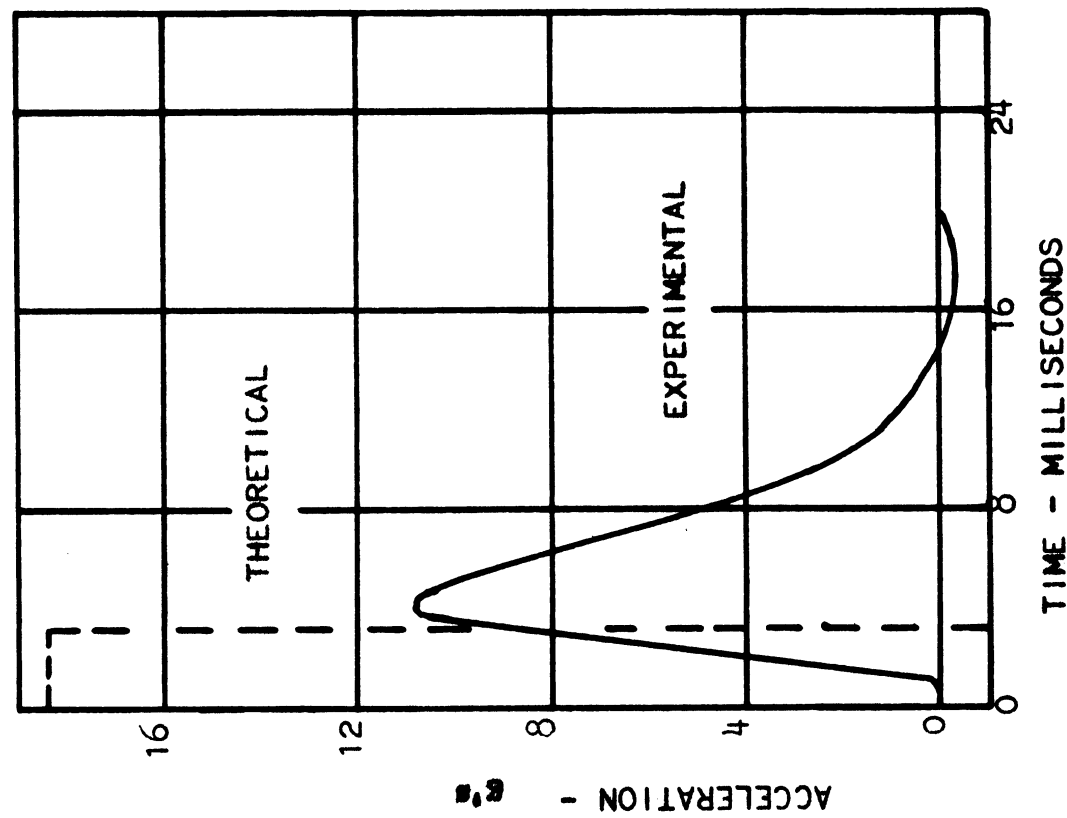
delay in establishing detonation is evident. Part of this delay, however, is the finite time for the force to be transmitted longitudinally through the tube walls and to the accelerometer. The rarefaction zone, assumed as a discontinuity for simplicity in the theoretical calculations, is seen to gradually reduce the pressure so that the time of the thrust-producing cycle is materially lengthened. The maximum acceleration (and hence pressure) as indicated by the accelerometer is undoubtedly somewhat lower than that actually experienced because of the finite frequency response of the accelerometer (about 800 cps).

For greater detail on any of the pendulum experiments the reader is referred to references 5 and 9.

Hoffman<sup>4</sup> had indicated that the spark plug position appreciably affected the thrust level of a cyclic detonation tube. Consequently, the influence of spark plug position on impulse was investigated in further experiments on the single detonation wave in the pendulum tube.<sup>10</sup> The results indicated very little effect of spark plug position with this particular arrange-



60% ACETYLENE



50% ACETYLENE

Fig. 11. Acceleration-time graphs of acetylene-oxygen detonations.

ment. In the case of pulsating detonation and with a diffuser it is entirely possible that there would be a pronounced effect.

### CYCLIC DETONATION TUBE

The experiments on a single detonation wave were of considerable value in gaining insight into such problems as the delay in establishing detonation and the approximate pressure-time variation. It was also valuable to find that the crude theoretical calculations of impulse were of good engineering accuracy as long as a mixture near the limits of detonation was not selected. As indicated theoretically, and intuitively, the time to introduce the fresh charge is of extreme importance. This consideration, along with the consideration of other parameters that could not be investigated profitably in a single detonation, indicated the judiciousness of designing a cyclic detonation tube at this time. It was felt that initial tests should be confined to as simple a system as possible in order that a good understanding of the unsteady gas dynamics and the effect of major variables be realized.

The initial attempt<sup>10</sup> at achieving intermittent detonative combustion was made on a tube of about 1 inch inside diameter and 6 feet in length. Hydrogen and oxygen were injected separately through check valves and impinged on the automotive-type spark plug at the closed end of the tube. Operation of this tube did not prove successful as the first detonation resulted in continuous burning of the ensuing fresh charge. The charging system was altered so that the fresh gases were directed coaxially downstream at a velocity of around 150 fps. The spark plug was located at about 10 tube diameters downstream of the initial mixing plane of the two gases. The charging arrangement is shown in Fig. 12.

Hydrogen-oxygen mixtures were tried on the revised tube and again the same difficulty was experienced. Further tests were made with the spark plug in different locations. The results were the same but it was noted that the tube walls always got hot immediately downstream of the active spark plug. Evidently the initial detonation was sufficient to establish the spark plug or the walls as a flameholder.

Successful cyclic detonative operation of the same tube was achieved in January, 1955, by utilizing hydrogen-air mixtures. With the mixture ratio adjusted correctly the tube fired in very sharp, clear, even explosions and estimated frequencies of 35 cps were attained.

This tube was mounted and instrumented so that measurements of thrust, air flow, hydrogen flow, and temperature could be made. The tube

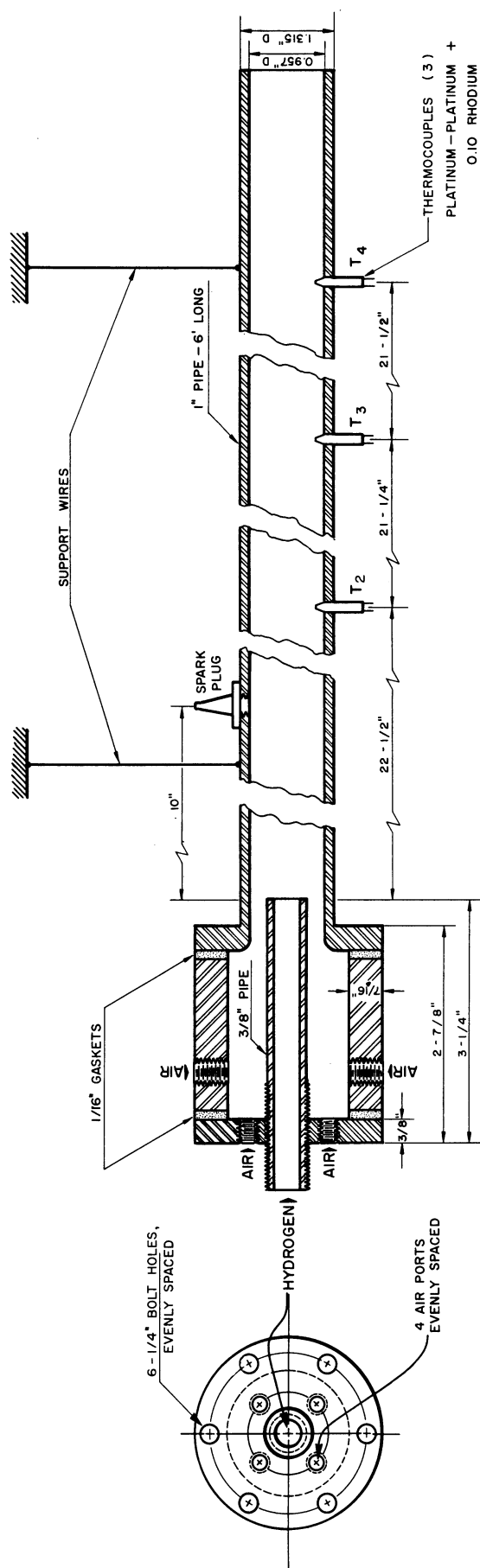


Fig. 12. Cyclic detonation tube.

details are shown in Fig. 12. A photograph of the tube is shown in Fig. 13.

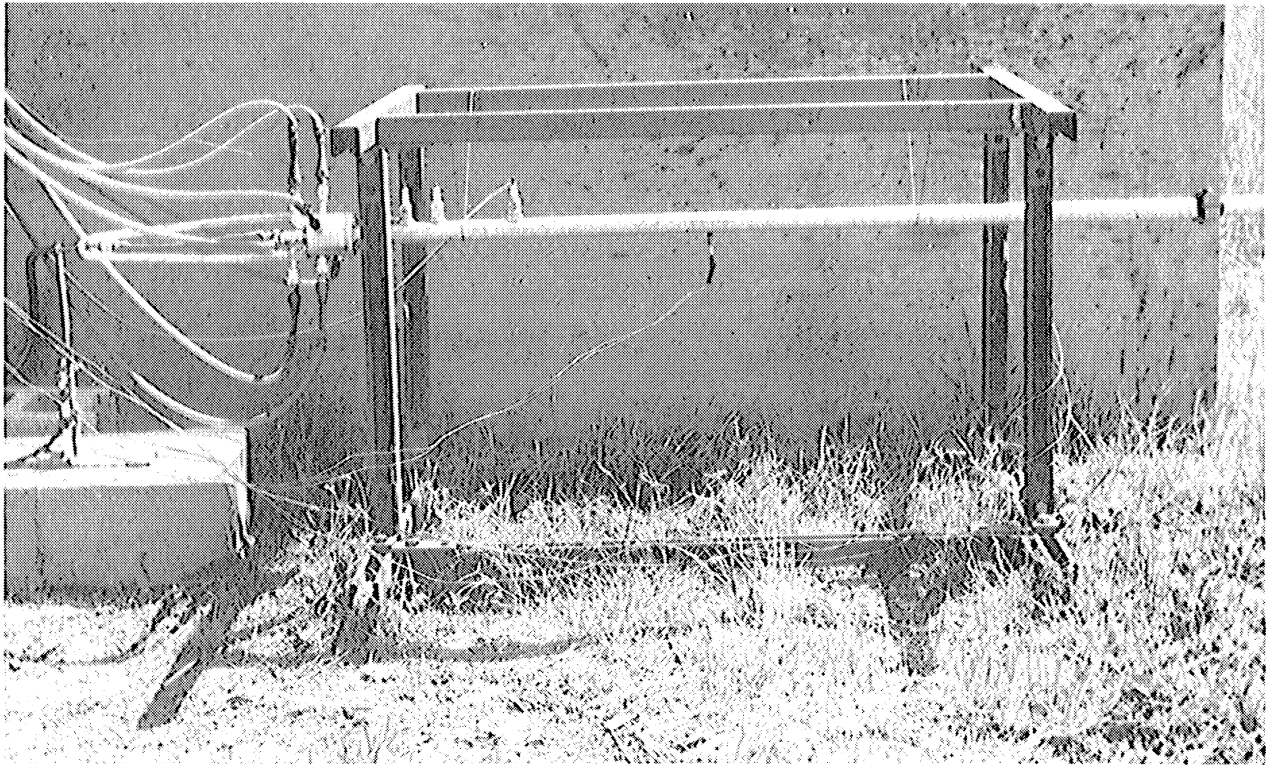


Fig. 13. Photograph of the cyclic detonation tube.

As shown, hydrogen was introduced in the downstream direction by means of a length of standard  $3/8$ -inch pipe. An air manifold surrounding the hydrogen injector was fed by eight inlet lines and served to admit the air coaxially with the hydrogen. A 0.090-inch-diameter orifice was located in the hydrogen line at the inlet to the tube so as to prevent partially gas dynamic coupling between the charging line and the detonation tube. Similarly, a 0.125-inch-diameter orifice was placed in each of the air lines. The three thermocouple locations and spark plug location are indicated on the figure. Initial tests were made where the spark plug was located 2 inches and 5 inches downstream of the initial mixing plane. These positions produced spasmodic firing so the position 10 inches downstream was used in all tests reported. An attempt to detonate the tube with the plug 6 inches from the open end was unsuccessful.

A schematic of the experimental setup and instrumentation is shown in Fig. 14. The compressed air was obtained from two 80-cubic-feet, high-pressure, air-storage vessels. These vessels were ordinarily charged to about 1000 psi by means of two Ingersoll-Rand compressors although the system has a potential of 3000 psi. The air flow was regulated by means of two Grove dome control valves connected in parallel. Bottled nitrogen with a regulator was used to control the dome pressure. The air flow was measured by a 0.284-

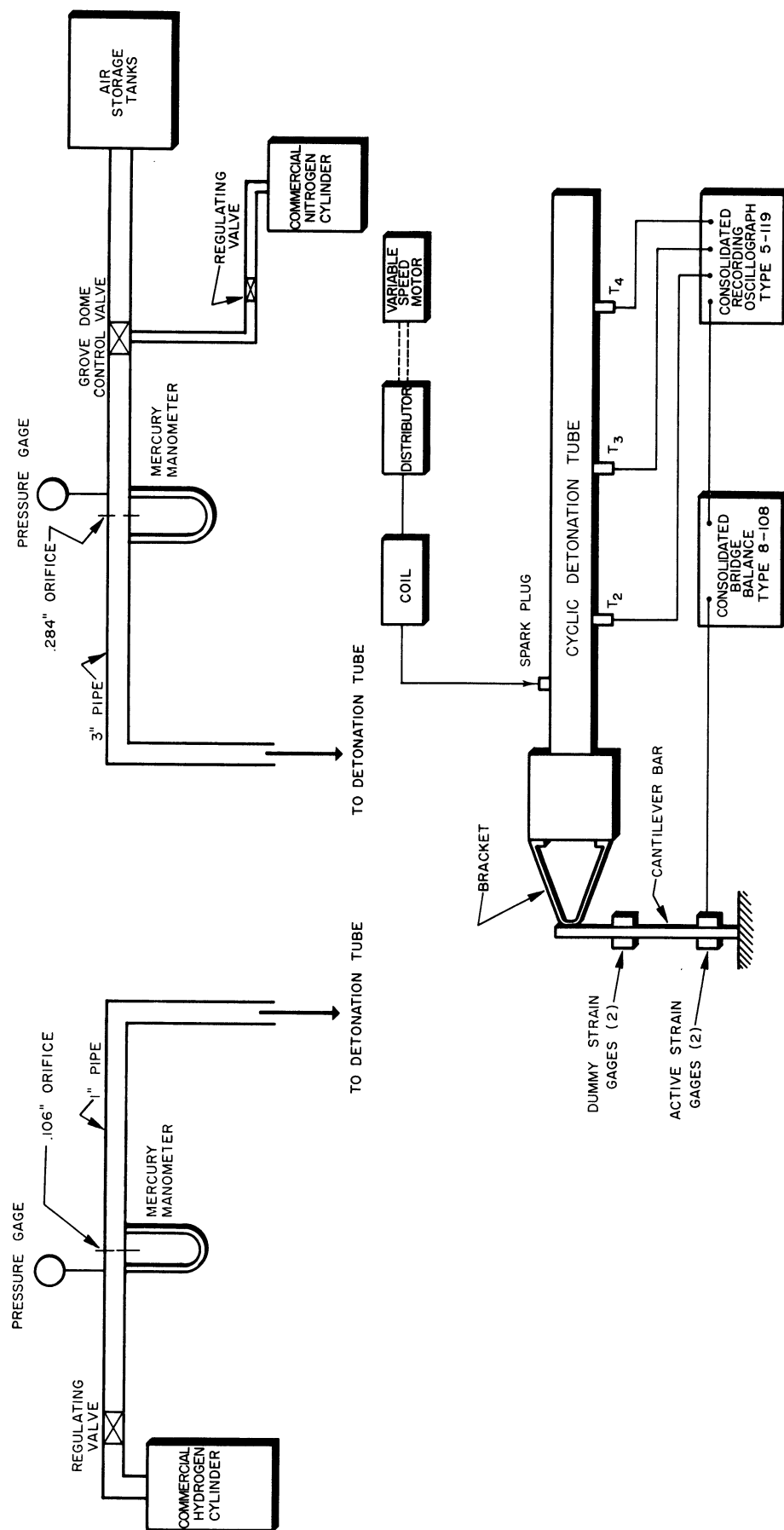


Fig. 14. Experimental arrangement for intermittent detonation tests.

inch-diameter orifice in a 3-inch pipe. The hydrogen flow was controlled by means of a regulator on a commercial gas cylinder. The flow was metered by a 0.106-inch-diameter orifice in a 1-inch pipe. During operation of the cyclic detonation tube no unsteadiness was experienced in the air orifice readings so that the average flow rate was obtained. The pressure drop across the hydrogen orifice did oscillate, but not severely. Upstream orifice pressures were read on a Bourdon-type pressure gage and the orifice pressure drops were read on mercury manometers.

An automotive-type spark plug was used with the conventional distributor and spark coil arrangement. The distributor was driven by a variable-speed brush-controlled motor so that cycling frequency could be varied as desired.

Three platinum-platinum +0.10 rhodium thermocouples were mounted along the tube as shown in Fig. 14. The junctions were arranged so that a gas temperature near the tube wall would be obtained. The response time of the thermocouples restricts the measurements to average values although qualitative cyclic changes were discernible. The outputs of the thermocouples were fed to galvanometer movements of a 50-channel Consolidated Recording Oscillograph, Type 5-119. The data were recorded photographically and then developed on the Consolidated Oscillogram Processor, Type 23-109.

The measurement of thrust was achieved by mounting the thrust end of the tube to the free end of a cantilever beam. Two active SR-4 strain gages, one in tension and one in compression, were mounted near the supported end of the beam so that the thrust could be calibrated in terms of the bending stresses. Two dummy strain gages of the same type completed the bridge circuit. A Consolidated ridge balance, Type 8-108, was used as the control link between the strain gages and oscillograph. The thrust readings were restricted to average values. Although good frequency response was desired, it had to be sacrificed in order to get sufficient strain-gage output.

The experimental procedure in making test runs was to adjust the air for the desired flow rate, adjust the motor speed to the desired frequency, regulate the hydrogen flow, close the spark circuit and then record the data. Because of the rapid use of hydrogen it was often necessary to record data while the cyclic detonation tube and strain-gage mount were oscillating at relatively high amplitudes. In those cases it was necessary to take the average reading of the sinusoidal thrust curve.

## RESULTS OF INTERMITTENT DETONATION EXPERIMENTS

The thrust data to be presented for the tests on intermittent detonative combustion are actually gross thrust and have not been corrected for the thrust increment due to the momentum of the fresh gases. For the most part this introduces little error. A typical run as recorded on the oscillograph paper is shown in Fig. 15. The parameters measured are indicated in the figure.

Figure 16 represents the variation of thrust with fuel-air ratio for a number of operating frequencies and at one air flow rate. The same information at two other air flow rates is shown in Figs. 17 and 18. During the runs, too lean or too rich a mixture caused a continuous burning rather than intermittent detonation. Reference to the figures reveals no strong influence of fuel-air ratio and the range of fuel-air ratios corresponds quite well to known detonation limits of hydrogen-air mixtures. Some of the scatter in the experimental points may be attributed to a slight change in cycling frequency during the course of the run. Fig. 19 shows the variation of thrust with cycling frequency for a fuel-air ratio of 0.040 and for the different flow rates. This information is taken from the data in Figs. 16, 17, and 18. As would be expected, the influence of frequency is all-important. It is seen that the curves for the lowest and highest air flows reach a maximum and then fall off. This is not surprising in that high cycling frequencies imply that the fresh charge does not fill the entire length of the tube. Consequently, there will be a collision of the detonation wave with the burned products of the previous cycle, which will probably result in a mild rarefaction reflected upstream and a shock transmitted downstream. This will lead to some loss in thrust but, over a certain range, should result in greater fuel economy. This aspect has been treated mathematically in reference 5.

The intermediate air-flow run in Fig. 19 indicates no maximum in the range shown. Additional data had been obtained on cyclic frequencies to 51.7 cps at this air flow rate but the thrust readings were doubtful and hence were discarded.

The results shown in Fig. 19 may also be plotted to show the variation of specific impulse with cycling frequency for this same fuel-air ratio of 0.040. This plot is shown in Fig. 20 and it is seen that quite high specific impulse is realized for the higher frequency runs. Comparison of Figs. 19 and 20 reveals that the thrust increases with higher flow rates while the specific impulse decreases.



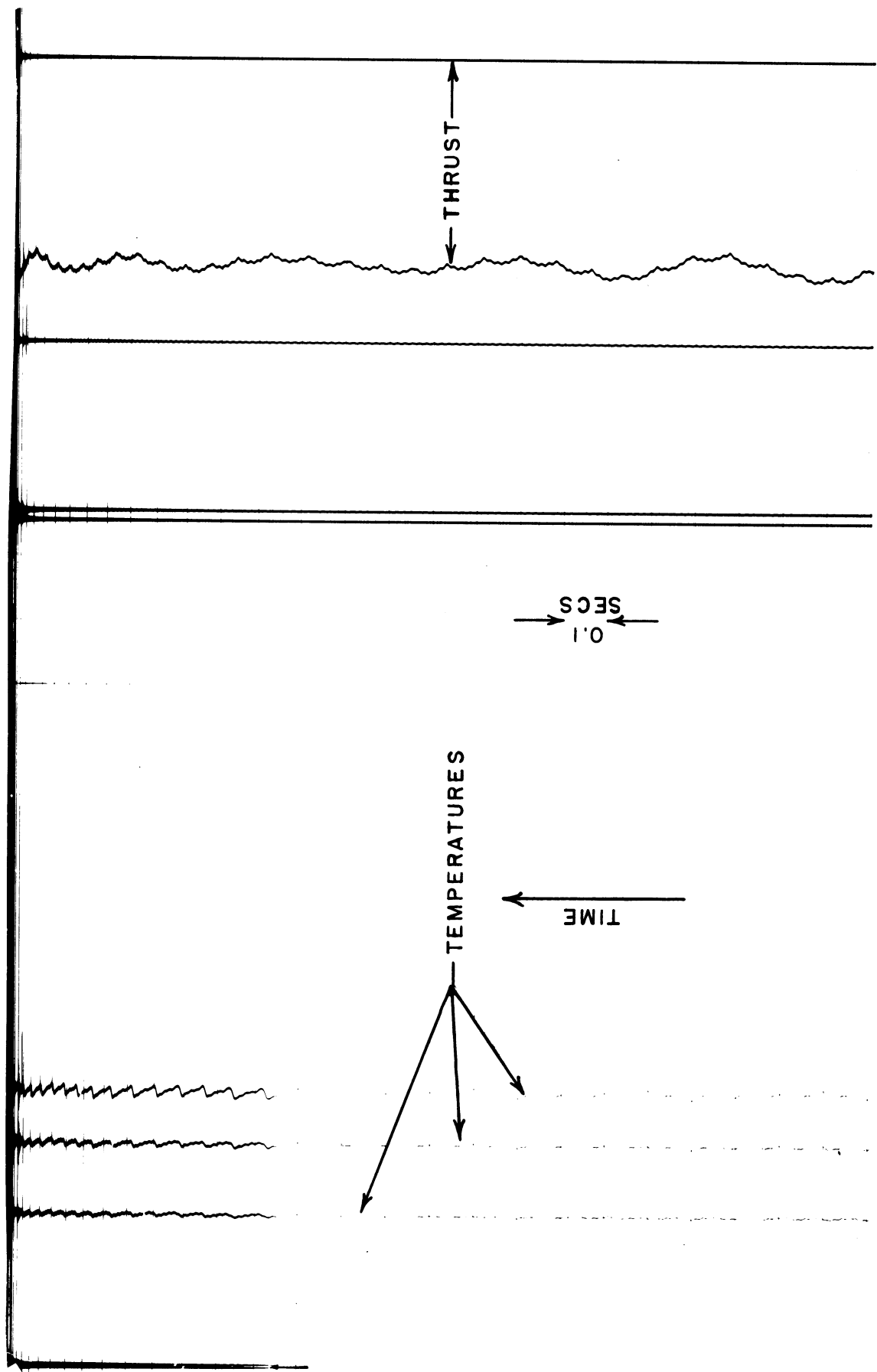


Fig. 15. Oscilloscope trace.

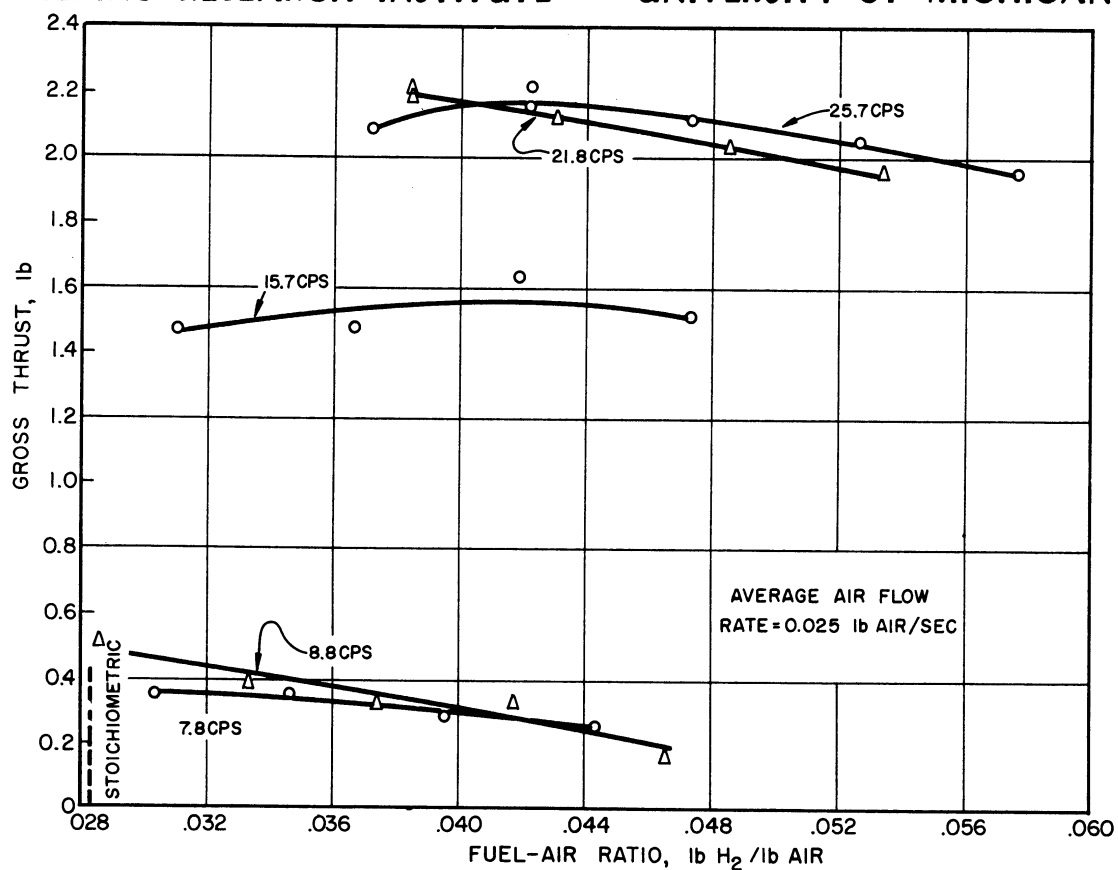


Fig. 16. Thrust vs fuel-air ratio for various frequencies.

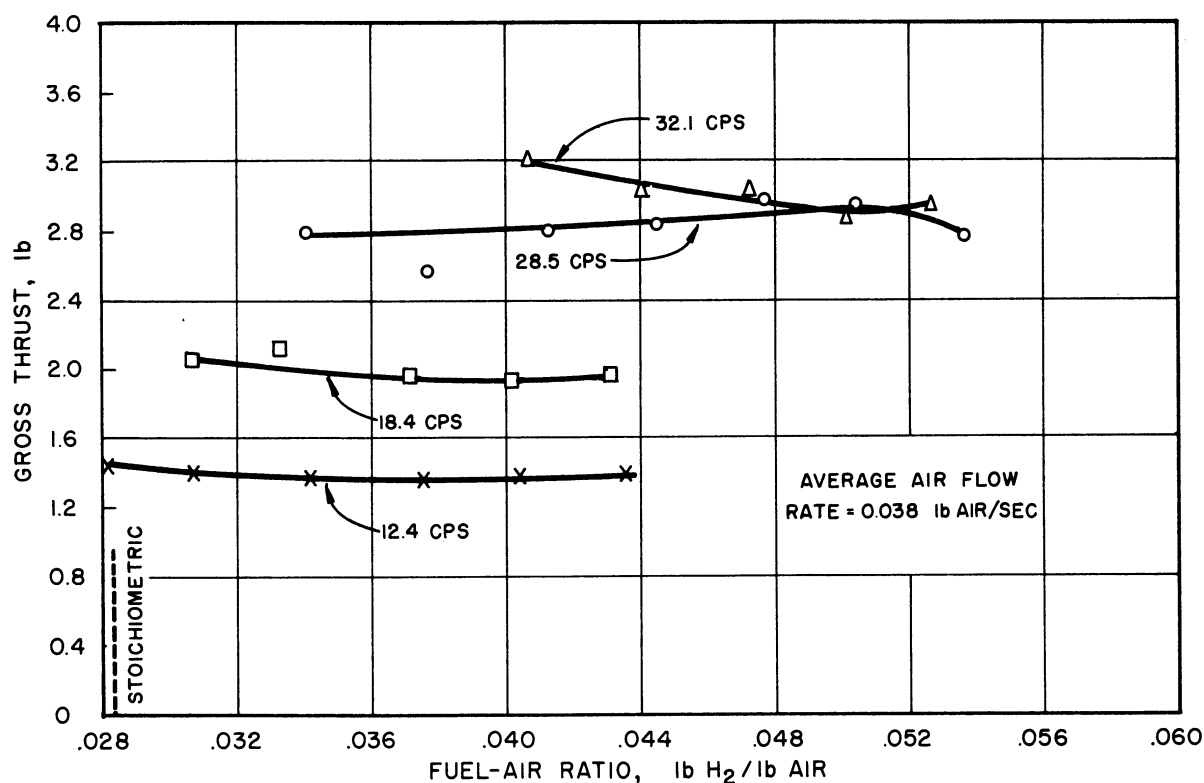


Fig. 17. Thrust vs fuel-air ratio for various frequencies.

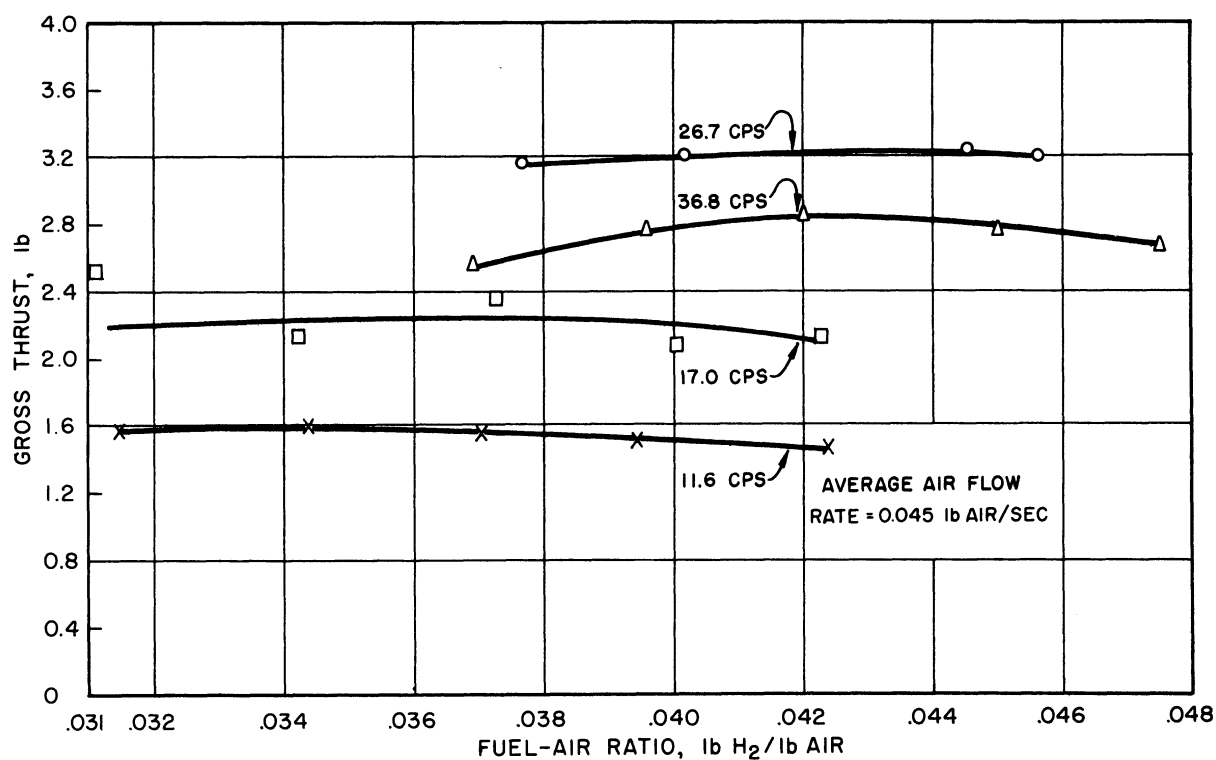


Fig. 18. Thrust vs fuel-air ratio for various frequencies.

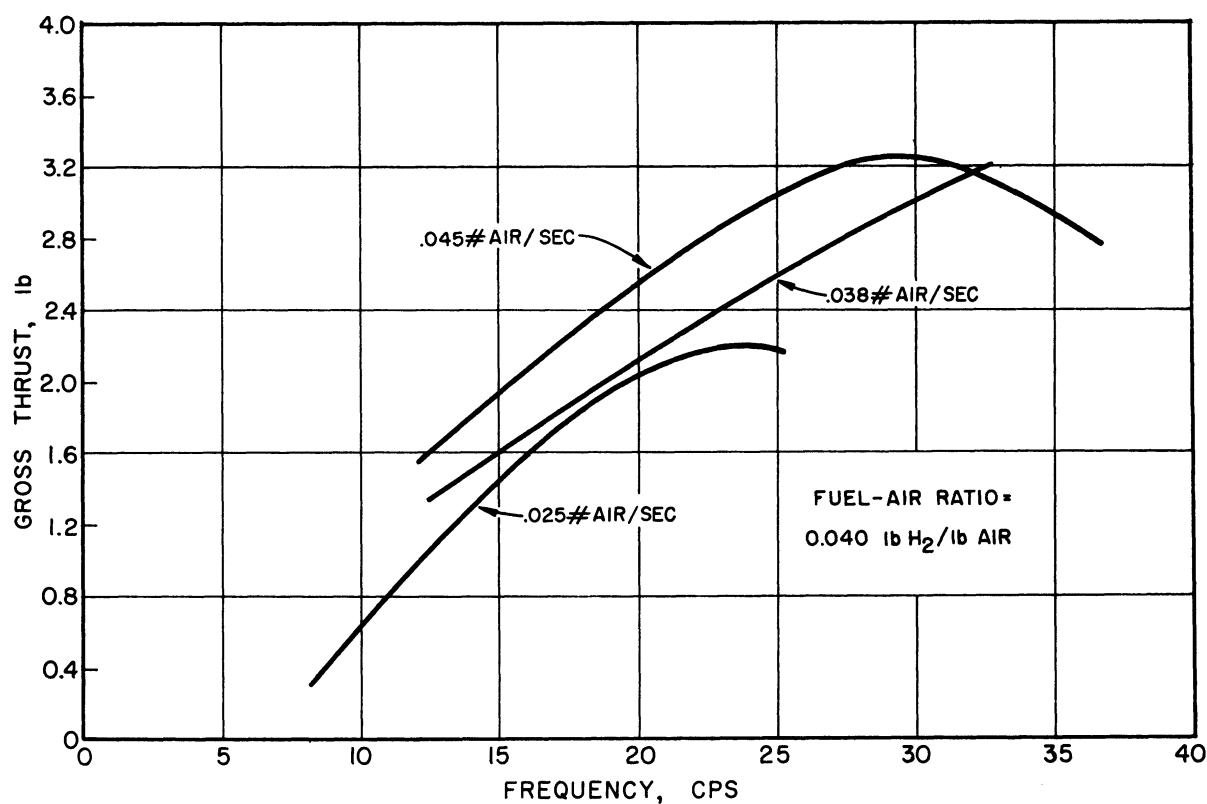


Fig. 19. Thrust vs frequency for various air flow rates.

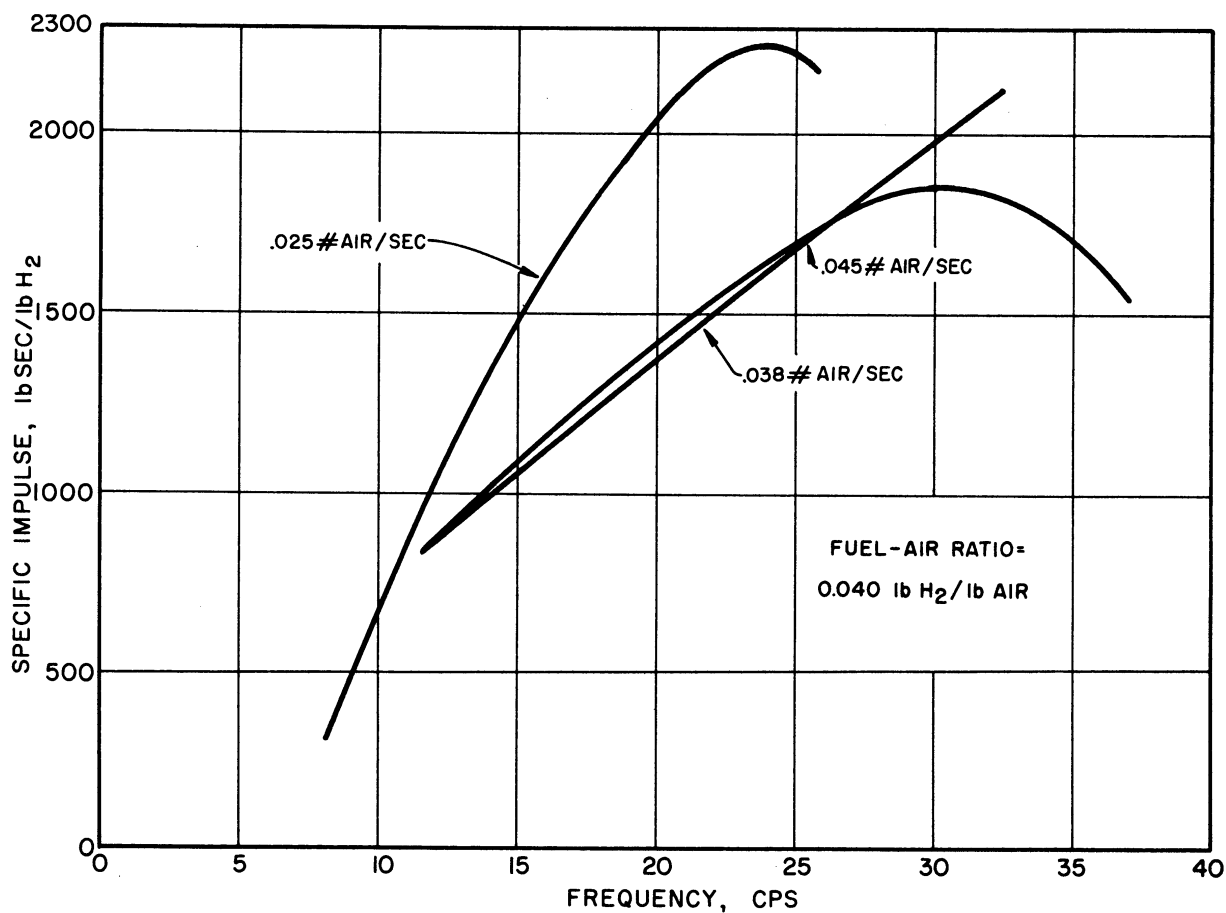


Fig. 20. Specific impulse vs frequency for various air flow rates.

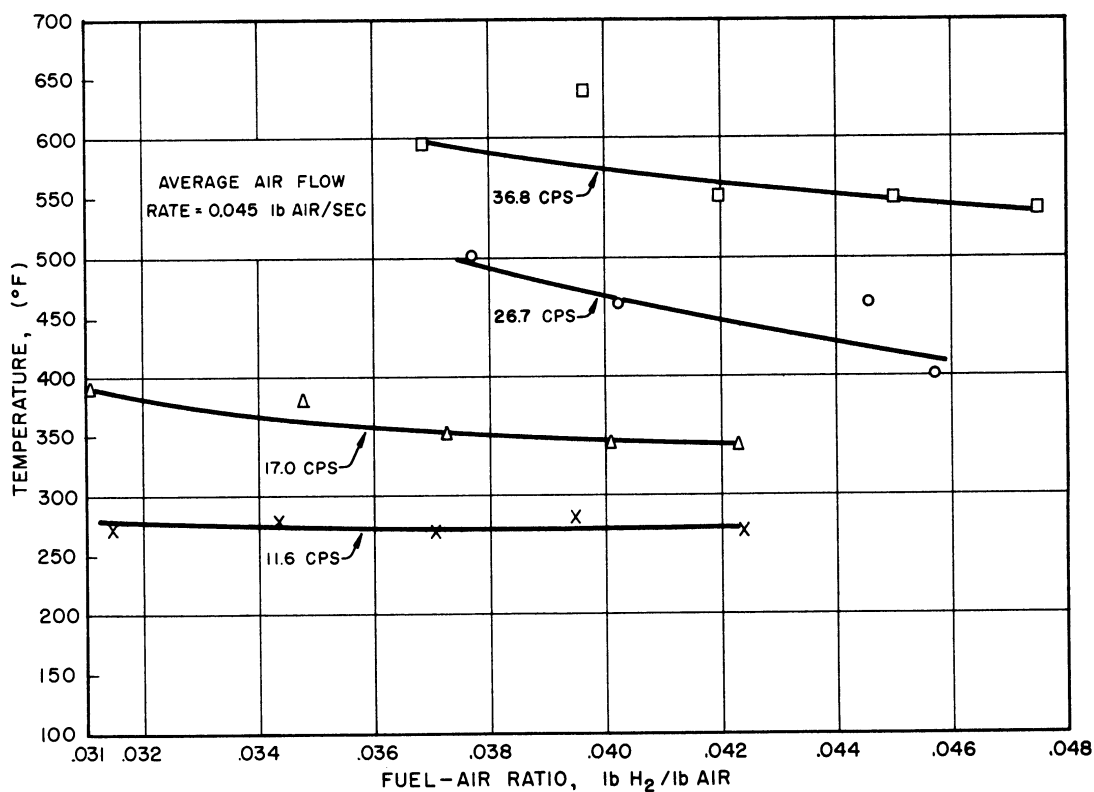


Fig. 21. Temperature ( $T_2$ ) vs fuel-air ratio for various frequencies.

Figures 21, 22, and 23 are plots of the three experimental temperatures (see Fig. 12) as a function of fuel-air ratio and for various frequencies. Only one air flow is shown as the lower flow rates produced only slightly lower temperatures. In most cases the oscillograph traces indicated that the temperature had stabilized and it is somewhat surprising that the level is so low. Different fuels could, of course, appreciably increase this level. The fuel-air ratios are richer than stoichiometric which explains the decreasing temperature with fuel-air ratio.

The above temperatures are plotted against frequency for one fuel-air ratio, 0.040 lb  $H_2$ /lb air, in Fig. 24. The linear relationship (approximately) is to be expected when measuring average temperature.

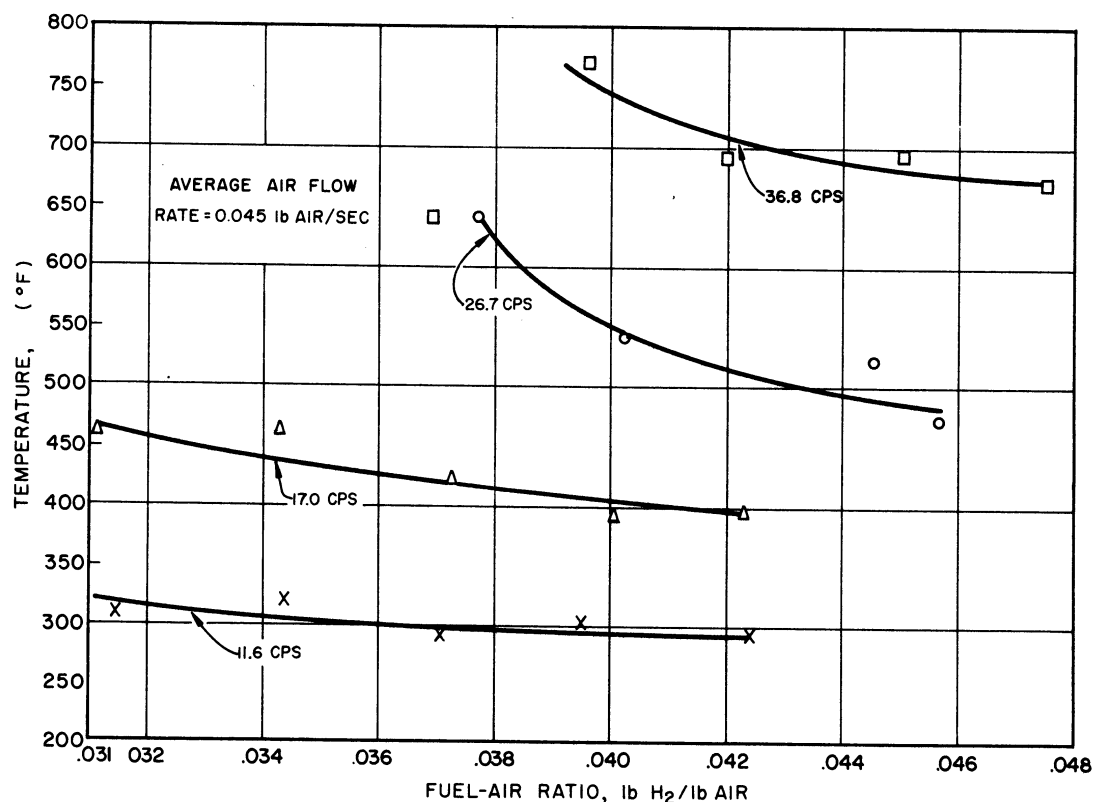
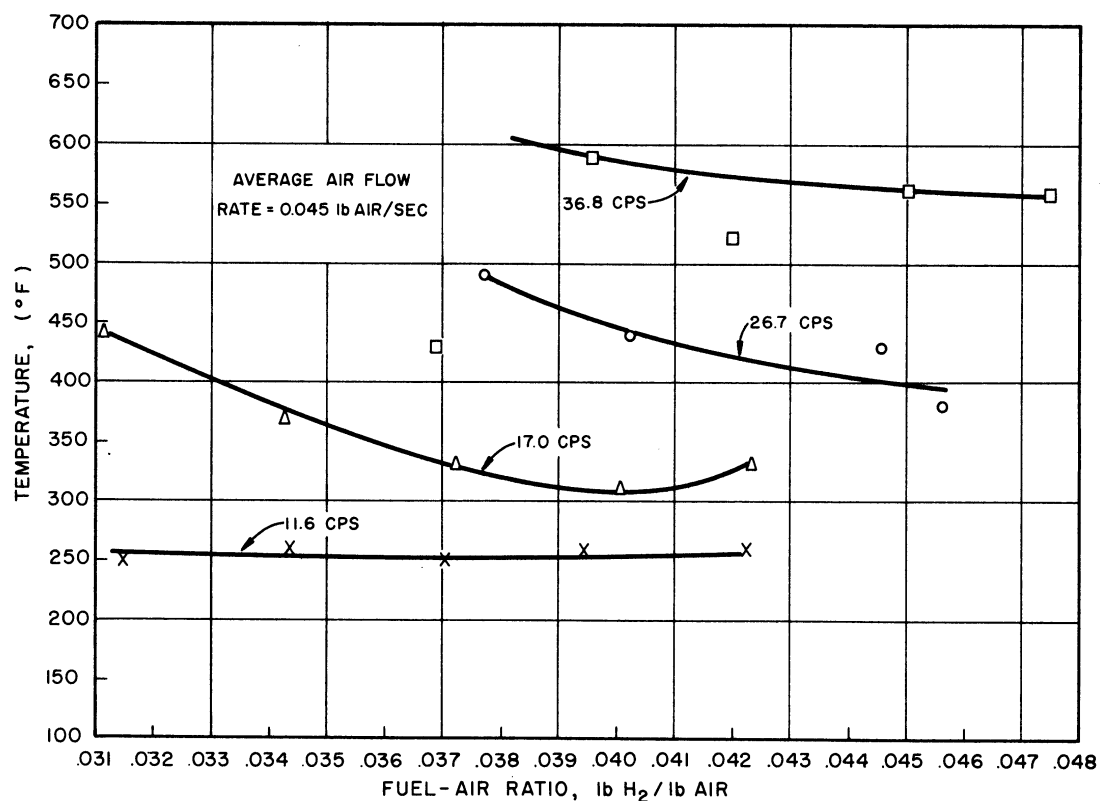
Prior to the time that the detonation tube was instrumented, a test was run wherein the spark plug was replaced by a glow plug so that ignition was obtained from a hot wire. After the initial energization of the wire, the tube detonated intermittently and evenly at some moderate frequency without further energization of the wire. The fuel supply had to be cut off in order to cease firing. This aspect may be of great utility in an actual engine.

In order to prove that the detonation tube was actually detonating, a Control Engineering Corporation, Model 2DC, Engine Pressure Indicator was procured locally on a loan basis and mounted 16 inches from the open end of the tube. The response of this pickup is quoted by the manufacturer as linear to 20,000 cps. The output of the pickup with its associated bridge balance was connected to the vertical input of a Tektronix oscilloscope, Type 513-D. With the detonation tube in operation at moderate frequencies and the horizontal sweep of the scope set at 1 millisecond per centimeter, the initial pressure indication for each cycle appeared as a perfect discontinuity. This evidence, along with the mixture ratios over which the tube operated intermittently, the type of noise generated, and the close agreement with theory leaves little doubt that the tube was actually detonating.

Unfortunately, the above pressure pickup yielded insufficient output for quantitative work.

## DISCUSSION

One of the primary motives of this initial work on intermittent detonation has been to establish an order of magnitude on the discrepancy between experiment and theory. With such information it is possible to extrapolate to some future potential on the basis of a merit factor that would evolve in

Fig. 22. Temperature ( $T_3$ ) vs fuel-air ratio for various frequencies.Fig. 23. Temperature ( $T_4$ ) vs fuel-air ratio for various frequencies.

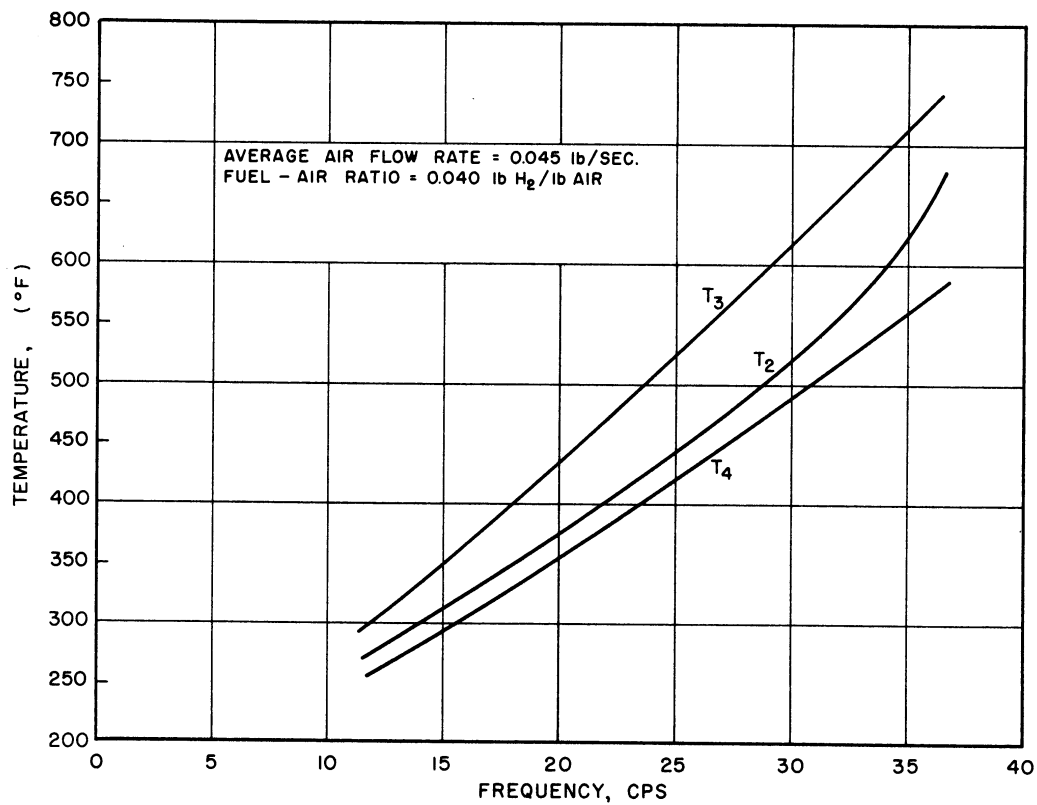


Fig. 24. Temperature vs frequency for constant fuel-air ratio.

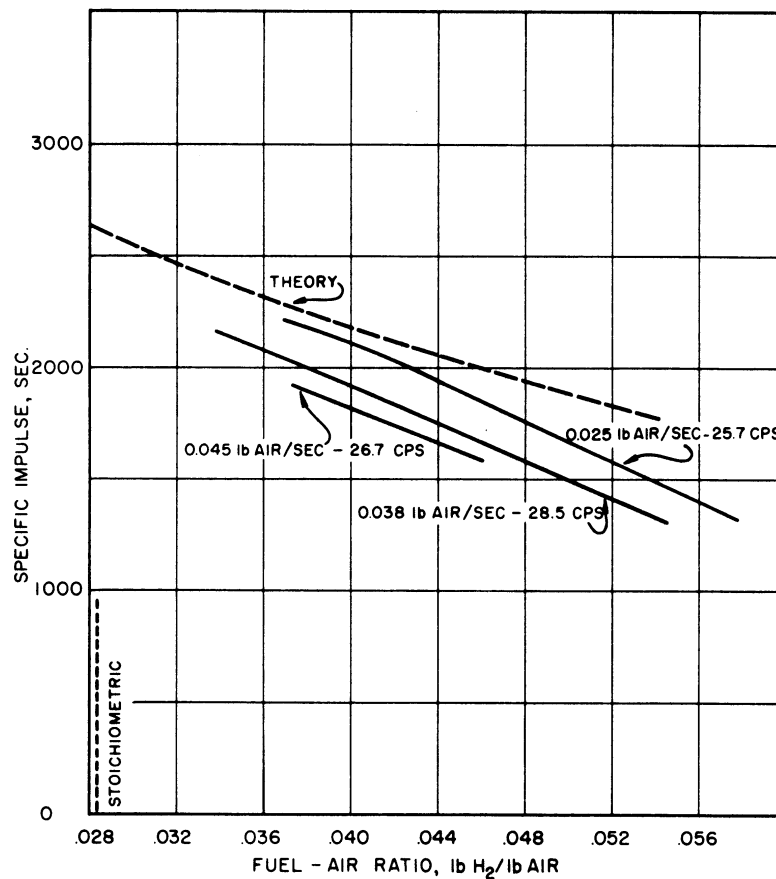


Fig. 25. Specific impulse vs fuel-air ratio.

development work. The experimental work reported here has been concerned with only hydrogen-air mixtures. It appears reasonable that other gaseous mixtures could be utilized with about the same deviations from theory. To be sure, certain mixtures may involve difficulty, such as a tendency to detonate or burn prematurely, and it may be a practical but solvable problem to overcome it.

The results of the experiments with hydrogen-air are compared with theory in Fig. 25. Only one frequency is shown for each of the three air flow rates. The close agreement for the lower mass flow rates is encouraging, but rather surprising in view of the simplifying assumptions made in the analysis. The same information is plotted in terms of specific thrust (pounds thrust per square foot of tube area) in Fig. 26. As predicted, hydrogen-air mixtures yield low values of specific thrust. It may be noted that the thrust increases with higher mass flow whereas the specific impulse dropped off. The theoretical predictions of thrust are expressed in the form of a modified thrust term which is the average thrust per unit area multiplied by a time parameter,

$$\frac{t_c}{t_D + t_r} \cdot$$

Comparing the experimental value of specific thrust obtained for a fuel-air ratio of 0.043 (38.2% by volume) and an air flow rate of 0.045 lb/sec (Fig. 26) with the theoretical value from Fig. 6, the time parameter indicated is 15. This agrees quite closely to the calculated value based on the experimental 26.7 cps although admittedly the experimental arrangement was slightly different from that used for the theoretical calculations.

A cross plot of Figs. 25 and 26 is shown in Fig. 27 and serves to show the penalty incurred in specific impulse for the sake of higher thrusts, or vice versa. The influence of fuel-air ratio and mass flow rates is also shown.

The successful operating range for intermittent detonation with hydrogen-air mixtures was practically all in the rich mixture range. This agrees with known detonation limits<sup>2</sup> although some of this effect may be attributed to incomplete mixing at the spark plug where the mixture would be somewhat lean. Consequently, a different spark plug location could conceivably move the operating range toward leaner mixtures.

Hoffman<sup>4</sup> has indicated the importance of spark plug location in reference to tube length and diffuser length. This aspect has not been investigated in the present program but is a logical extension. It is believed that material gains over present performance could be achieved by such investigations. Also, there are undoubtedly many improvements in the charging system that could be effected as well as changes in the tube geometry.



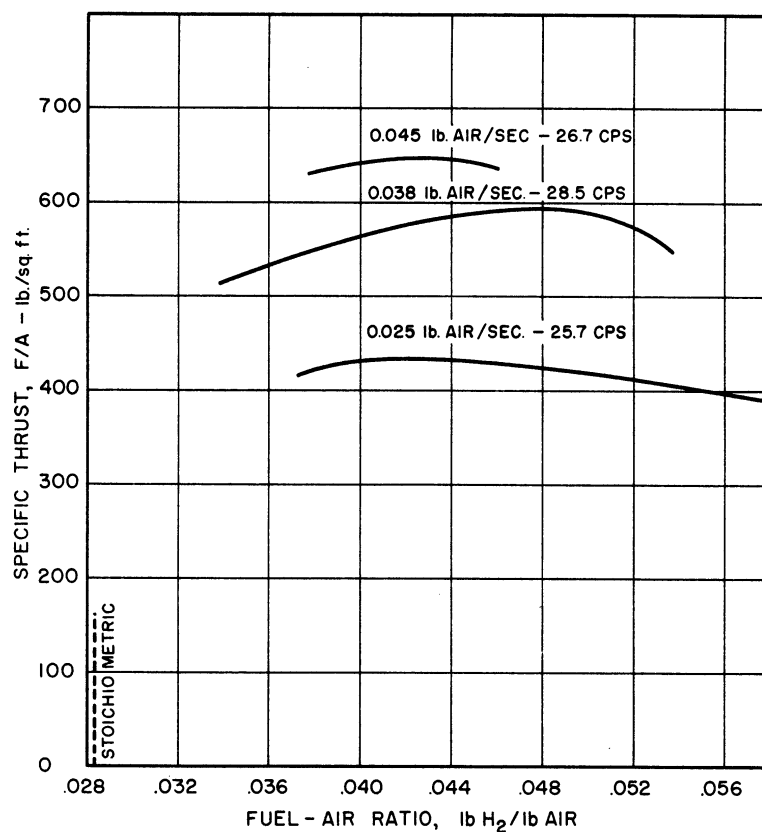


Fig. 26. Specific thrust vs fuel-air ratio.

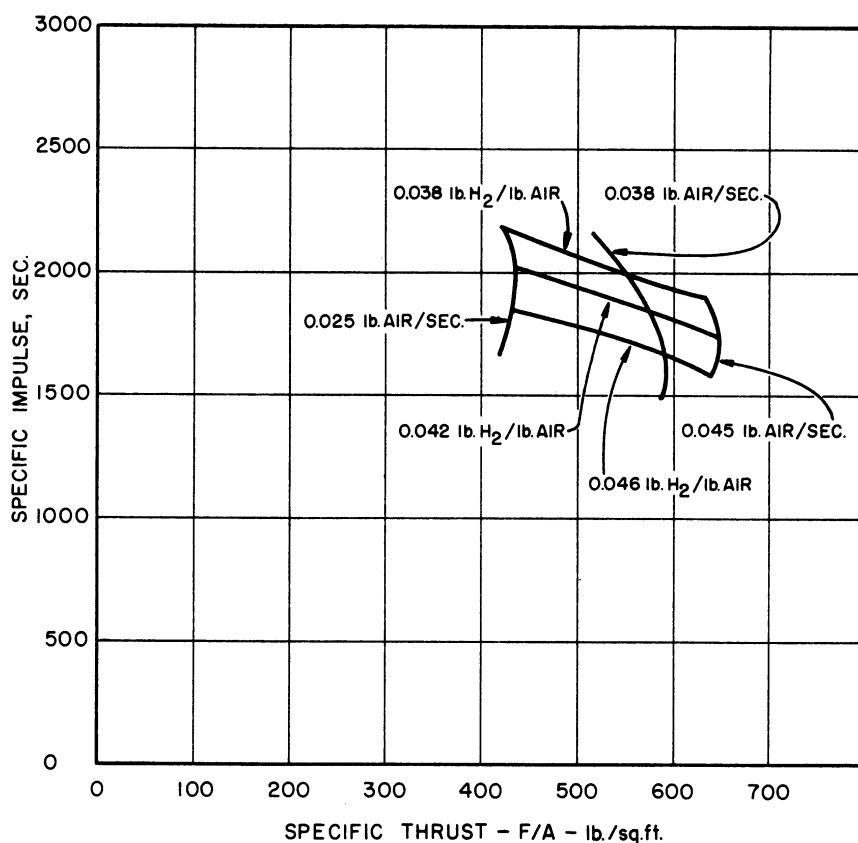


Fig. 27. Specific impulse vs specific thrust.

Hoffman operated successfully with acetylene-oxygen mixtures by using water-vapor additions to prohibit premature burning. He failed to give tube dimensions so that the values of specific thrust attained are not known. However, if we assume the value of the time parameter as 15 (as indicated by the hydrogen-air tests), the theoretical calculations would predict a specific thrust of  $2400 \text{ lb/ft}^2$ , which is quite high. But this is based on very preliminary studies and it is believed that considerable improvement could be realized with further research and development.

### CONCLUSIONS

A simplified theoretical analysis of a reaction device operating on intermittent detonation waves predicts high thrust levels and low specific impulse for most gaseous mixtures. However, in the case of hydrogen-air mixtures the reverse characteristics are indicated. Preliminary experimental results on a cyclic detonation tube operating on hydrogen-air mixtures show good agreement with theory and a specific impulse of over 2100 sec has been obtained. Conceivably, other mixtures could be utilized wherein the performance would be toward high thrust levels but at the expense of fuel economy.

The anticipated critical problem of excessive temperatures did not materialize in that maximum temperature levels were of the order of  $700^\circ\text{F}$ . Higher frequencies of operation would increase this level.

The experiments reported were confined to a single tube with a single source of ignition. It is doubtful that an intermittent detonation engine could operate efficiently with a single tube and single source of ignition, as the diameter required for the thrust demands would involve prohibitive lengths for the development of detonation. However, a bank of small tubes could be mounted very compactly so that the frontal area would be quite small compared to other reaction devices of the same thrust level. A rotating valve may be ideally suited to such an arrangement.

It appears that an intermittent detonation engine would offer many advantages. Among these advantages are:

1. extreme mechanical simplicity,
2. static thrust capabilities as well as efficient operation at supersonic velocities, and
3. high thrust levels or high fuel economy, depending on the fuel utilized.

The results to date would seem to warrant further exploration into the intermittent detonation cycle engine. Those areas of research deemed to be the most fruitful are those involving valving, charging arrangement, tube length, spark plug position, and diffuser. Consideration should also be given to "tuned" frequencies where ignition is effected through reflected shocks or detonations or by hot wire.

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