ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR

PROGRESS REPORT NO. 2

INTERMITTENT DETONATION AS A THRUST-PRODUCING MECHANISM

January 1, 1954, to June 31, 1954

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July, 1954

FOREWORD

The work reported herein was conducted under University of Michigan Engineering Research Institute Project Number 2172, for the Wright Aeronautical Division of the Curtiss-Wright Corporation. All the work was done by personnel of the Aircraft Propulsion Laboratory.

ABSTRACT

Further tests were run to measure the impulse derived from hydrogen-air and acetylene-air detonations. While the impulse was appreciably lower than for the oxygen mixtures, the specific impulse was appreciably higher.

The effect of various end conditions of the detonation tube was investigated. Also, the problem of delay in the establishment of detonation was considered and some experiments run.

In an intermittent-detonation-cycle engine, the time required for purging the exhaust products and for introducing the fresh charge can seriously restrict the performance. Accordingly, an analysis was made and experiments conducted to study the feasibility of using a detonation wave only as a means of establishing a strong shock wave through the exhaust products. On the basis of these tests, which were confined to only one cycle, such a device appears quite profitable.

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INTRODUCTION

The first progress report[1] outlined the general procedure to be followed in attempting to attain a thrust-producing device operating on an intermittent-detonation cycle. An idealized theoretical analysis was made in order to indicate the possibilities of such a device and the effect of various parameters. A detonation tube was designed and fabricated and mounted as a ballistic pendulum so as to facilitate the measurement of impulse derived from a single detonation wave. The tube was also instrumented with an accelerometer which yielded information on the variation of thrust with time. With these techniques the impulse was measured for different hydrogen-oxygen and acetylene-oxygen mixtures. Also, tube acceleration-time traces were obtained for the acetylene-oxygen detonations.

Subsequent work has led to the measurement of impulse for detonations in air mixtures. The acceleration-time traces for hydrogen-oxygen detonations were also determined. Some effort was expended toward noting the effect of different end conditions on the detonation tube.

Close scrutiny of the problem of cyclic detonation suggests that two factors may have a pronounced influence on the performance characteristics of a device operating on a detonation cycle. First, there is the time delay involved in the initiation of detonation. Conceivably, this time could be quite appreciable as compared to the time required for the detonation wave to traverse the unburned mixture. Second, the relatively long time needed to exhaust the combustion products and introduce the fresh charge could serve to limit the cycling frequency and hence the performance. In view of these considerations, experiments and analysis have been conducted to evaluate these effects and, further, to attempt to minimize or circumvent them.

EXPERIMENTAL DETERMINATION OF THE IMPULSE DERIVED FROM A SINGLE DETONATION WAVE

As mentioned earlier, the initial tests were concerned solely with oxygen mixtures. In this period, the tests were extended to include a few air mixtures. The measurement of impulse was effected by noting the deflection of the pendulum.

The impulse derived from various hydrogen-air detonations is shown in Fig. 1. The specific impulse, or impulse per unit weight of hydrogen, is also plotted. Comparison with the results of hydorgen-oxygen detonations reveals that the impulse for air mixtures is much less. This is undoubtedly attributable to lower Mach numbers of detonation and longer time delays for the initiation of detonation. The detonation of hydrogen-air mixtures is also confined to a much narrower band of mixture ratios than in the case of oxygen mixtures. The specific impulse is somewhat higher than those with hydrogen-oxygen mixtures. This arises, of course, from not penalizing the propulsion system for the weight of the oxidant.

Figure 2 represents the same information for acetylene-air mixtures. Again, the impulse is much lower than in the case of oxygen mixtures, and the range of mixture ratios for detonation is more restricted. In regard to the limits of detonation, it should be mentioned that the tube used in these studies is about 2 inches in diameter. Use of smaller tubes may extend these limits.[2,3] The length of the tube is also of importance in that mixtures near the limit of detonation ordinarily require many diameters before detonating.

The specific impulse of the acetylene-air mixtures is noted to be much higher than that for the oxygen mixtures. The detonations in the oxygen mixtures, both for acetylene and hydrogen, appear to be much more reproducible than with air.

Acceleration-time oscillograph traces were obtained for various hydrogen-oxygen detonations. The technique utilized was the same as reported earlier[1], although a higher frequency-response accelerometer was used. Figure 3 is a plot of the information taken from these traces and is shown for three mixture ratios. The 50 percent mixture is seen to yield the highest pressures as well as the minimum delay time in establishing detonation. This is in accord with earlier measurements of impulse which indicate a maximum near this mixture ratio. The major contributions to the impulse for one cycle are ordinarily effected in about 25 milliseconds.

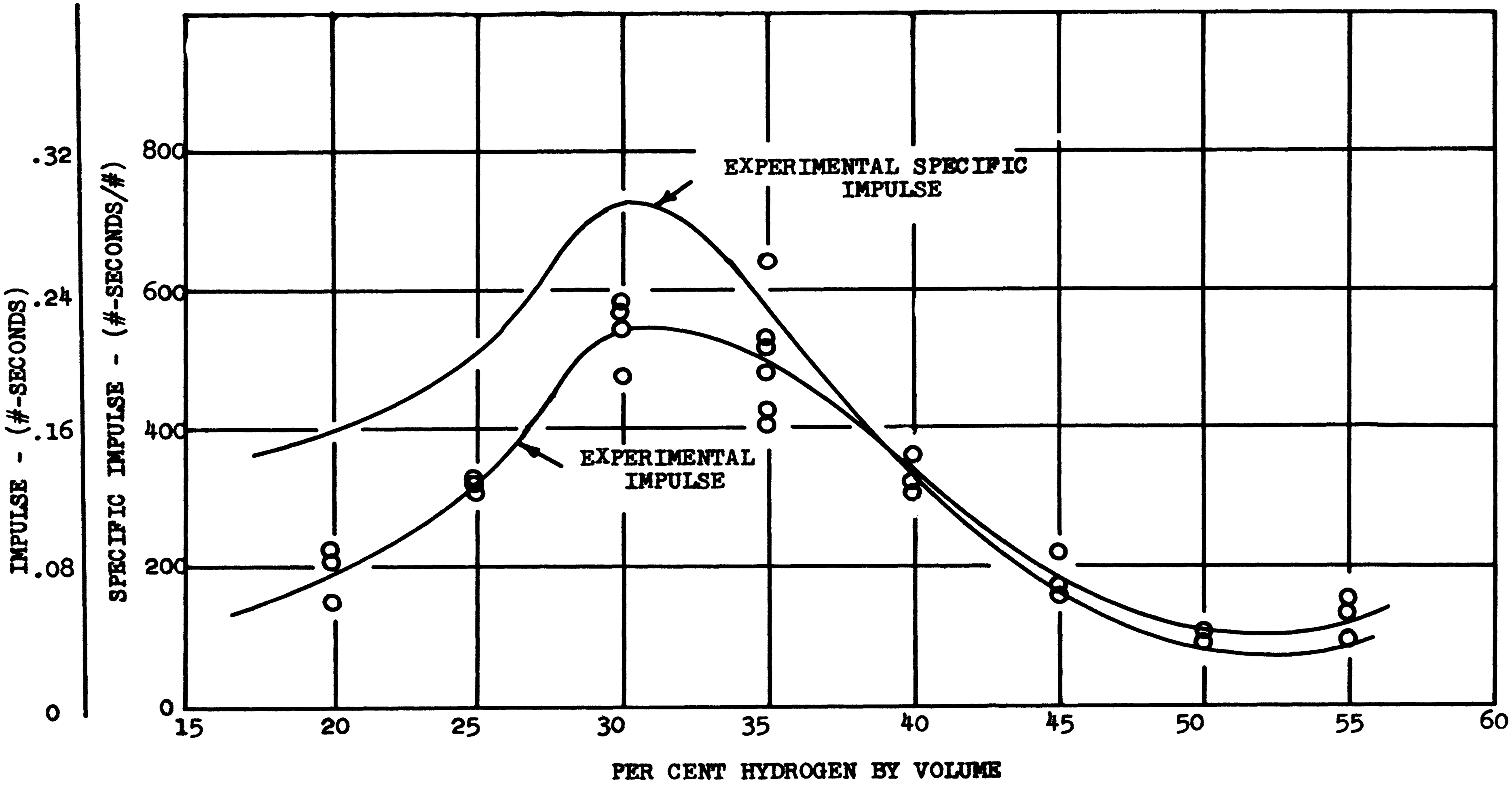


FIG. 1 - IMPULSE DERIVED FROM HYDROGEN-AIR DETONATIONS

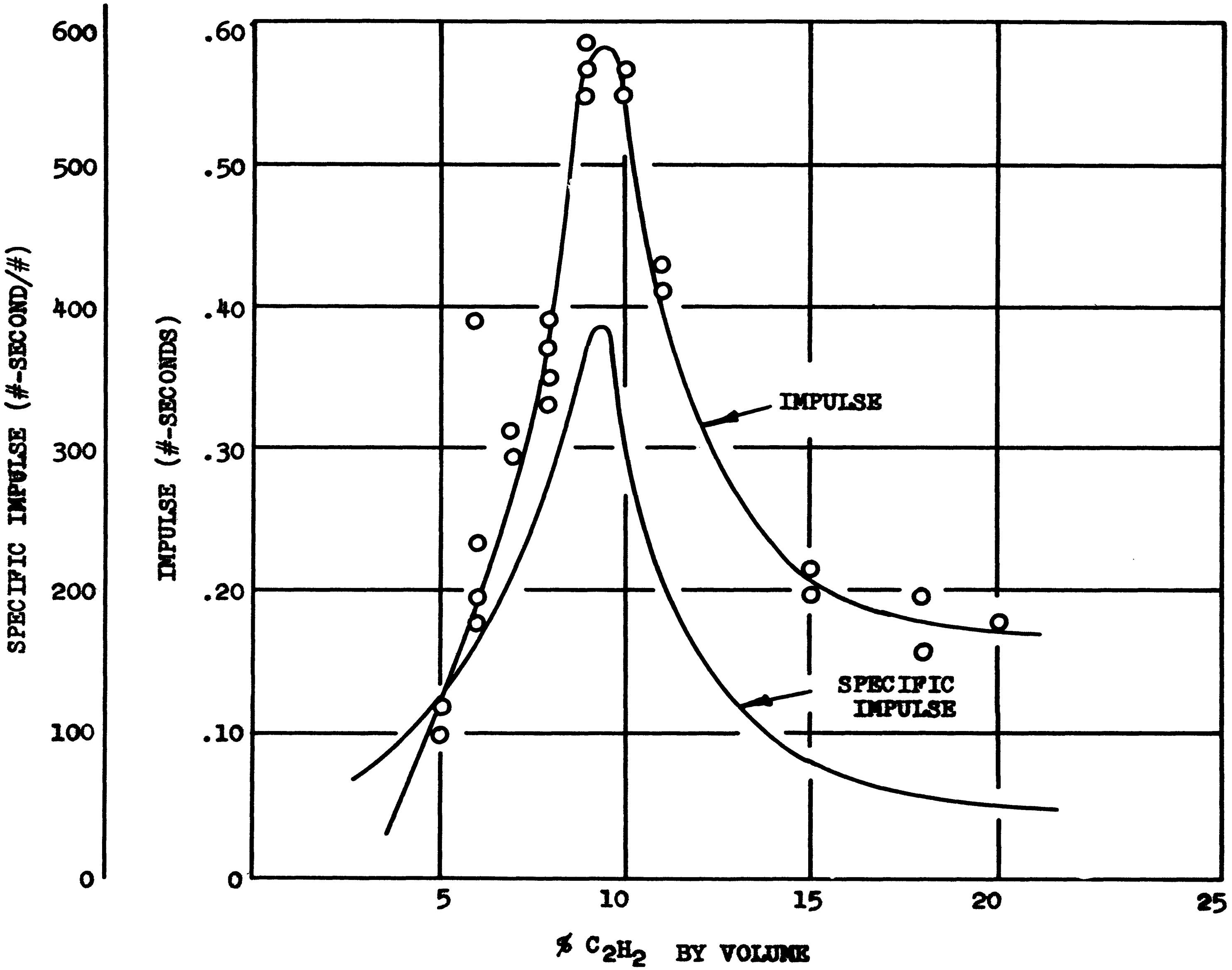


FIG. 2 IMPULSE DERIVED FROM ACETYLENE - AIR DETONATIONS

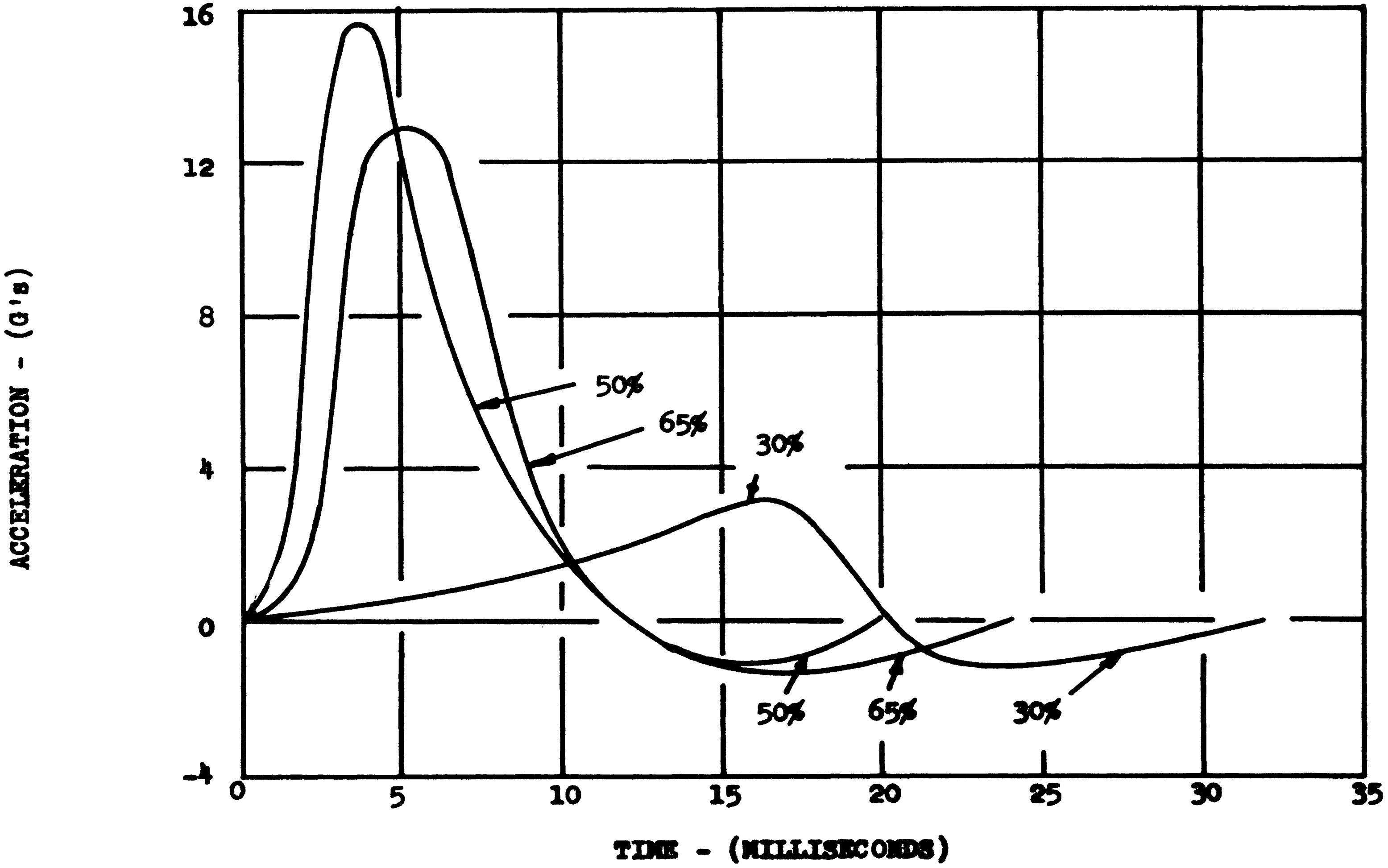


Fig. 3 ACCELERATION-TIME GRAPHS FOR HYDROGEN-OXYGEN DETONATIONS

INVESTIGATION OF END EFFECTS

In the original tests, the exhaust end of the detonation tube was sealed with a paper diaphragm in order to prevent interdiffusion of the combustible mixture with ambient air. A few tests were conducted toward determining the effect, if any, of this diaphragm. Accordingly, the tube deflection was noted with no diaphragm on the end as well as with diaphragms of other materials. These tests were run with the brass detonation tube and a 50 percent acetylene-oxygen mixture. The results are shown in Table I.

TABLE I

IMPULSE FOR DIFFERENT DIAPHRAGM MATERIALS

(All values in seconds)

Run	Open End	Paper Diaphragm	Photographic Film Diaphragm	Cardboard Diaphragm
1	2.82	2.61	2.91	2.84
2	2.40	2.42	2.71	2.84
3	2.61	2.29	2.61	2.45
4	2.40	2.29	2.45	2.48
Average	2.56	2.40	2.69	2.67

Apparently, there is very little effect attributable to the diaphragm. Any effect that might exist is obscured by the nonreproducibility of the detonative phenomena on successive runs.

For Chapman-Jouquet detonation the burned gases move at their local sonic velocity relative to the detonation front. However, this velocity is subsonic with respect to the tube walls. A supersonic nozzle was designed and fabricated which would expand these burned products to ambient pressure. This nozzle is shown in Fig. 4.

The measurements of impulse revealed an approximate 4 percent decrease in impulse when this nozzle was utilized. However, this represents only one configuration and a different geometry could yield more favorable results.

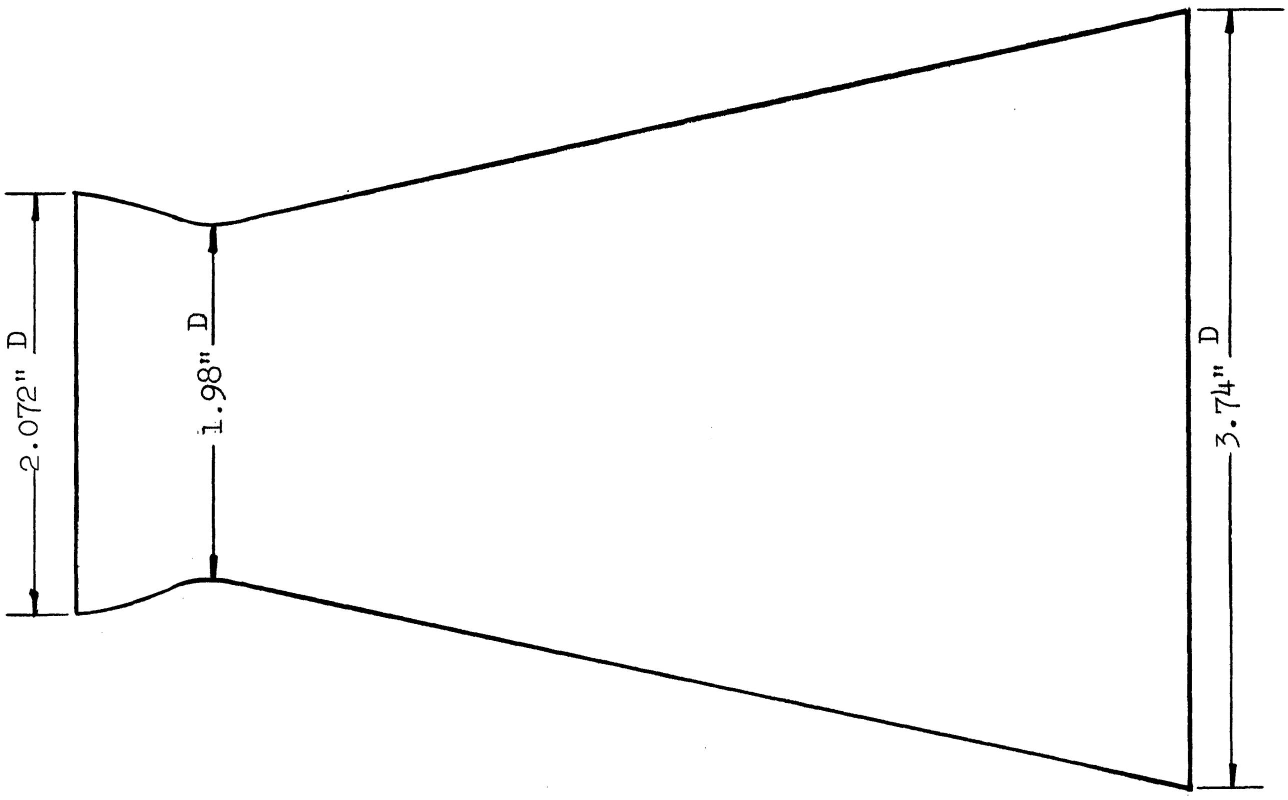


Fig. 4. Supersonic Discharge Nozzle

A series of runs was made with a flat-plate orifice on the end of the detonation tube. These orifices had circular cutouts of various diameters. The impulse derived from a particular mixture (50 percent hydrogen-oxygen) was measured for a number of these orifices. The results are shown in Fig. 5 where the abscissa is the ratio of orifice area to the open-tube area. For this condition there is a marked and continuous reduction in impulse with increasing blockage. Acceleration-time diagrams for a few of these runs are shown in Fig. 6. It is not surprising that the area under these curves (which is proportional to the impulse) continues to decrease with the smaller orifices, but the reason for the difference in initial slopes is not obvious. Apparently, by the time the retonation wave returns to the closed end of the tube the detonation wave has reached the orifice and generated a force opposing the thrust force. However, the various orifices do not affect the initial pressure level of the tube until the reflected waves are realized.

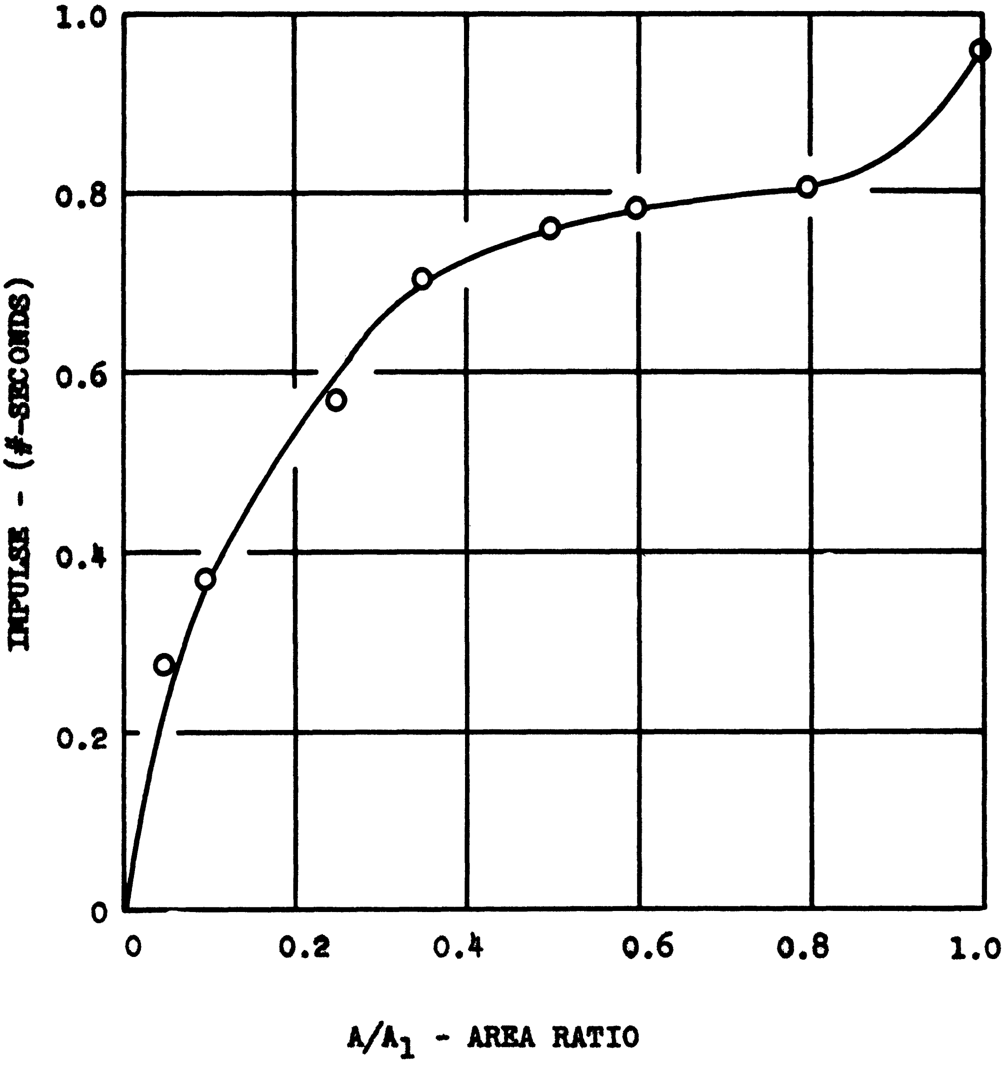


FIG. 5 - IMPULSE FOR VARIOUS DISCHARGE AREAS

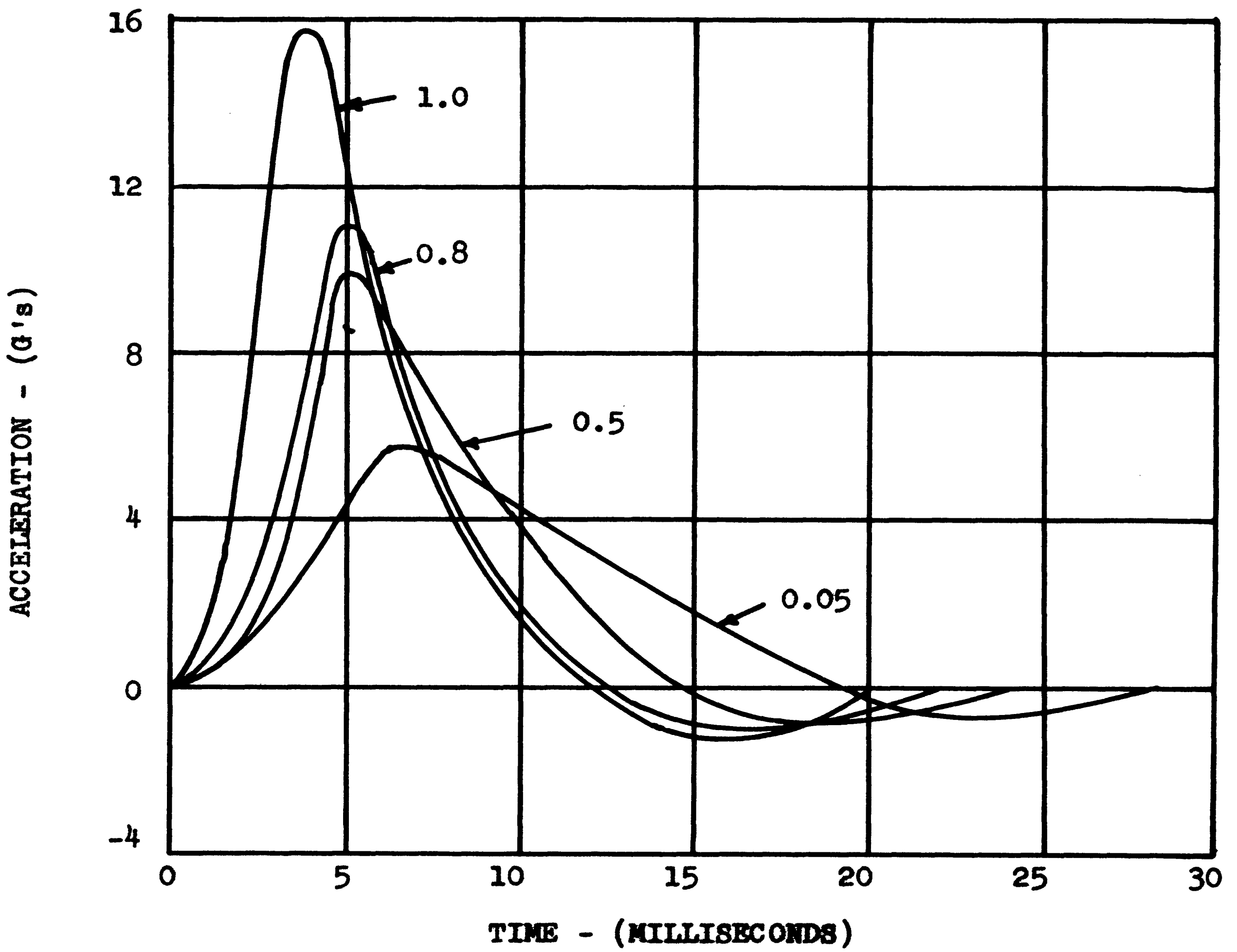
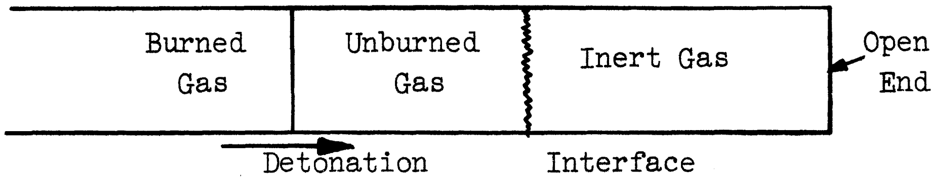


FIG. 6 ACCELERATION - TIME DIAGRAMS FOR DIFFERENT DISCHARGE AREA RATIOS

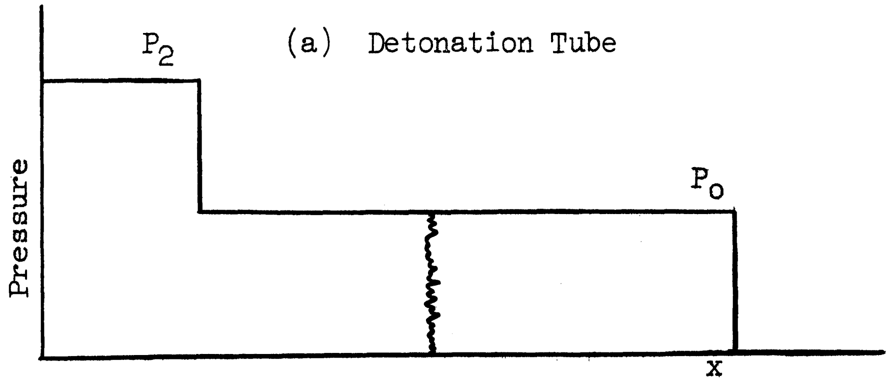
COLLISION OF A DETONATION WAVE WITH A GASEOUS INTERFACE

One serious deterent to high performance foreseeable in an intermittent-detonation-cycle engine is the appreciable time required for exhausting the burned products and introducing the fresh charge. The possibility exists that only a small amount of a combustible mixture (one highly susceptible to detonation) could be added to the tube. This would then serve as a "primer" to initiate a shock wave in the exhaust products. Such a scheme, if possible, could be of twofold benefit. First, only a small portion of the burned gases would have to be purged, and second, the amount of fuel utilized would be less.

The question arises as to exactly how the pressure level of the tube would be affected by this device. For example, if a strong rarefaction is reflected toward the closed end of the tube, the loss in thrust may render the scheme unfeasible. On the other hand, if only a weak rarefaction, or more optimistically a shock wave, is reflected, then there may be a definite advantage. To answer such questions as these the following analysis is made of the collision phenomenon in the direct neighborhood of the collision. The procedures utilized are identical to those followed in other contractual work at the Aircraft Propulsion Laboratory.[4] Consider a constant-area detonation tube which is partially filled with a detonable gas and an inert gas. These gases are assumed to be separated by a diaphragm of infinitesimal thickness. It will be further assumed that Chapman-Jouquet detonation is established in the combustible gas. Prior to the collision of the detonation wave with the interface, the conditions that exist are as shown in Fig. 7.



(a) Detonation Tube



(b) Pressure-Distance Variation

Fig. 7. Conditions Before Collision

The collision of the detonation wave with the interface will cause a shock wave to be transmitted through the inert gas. Also, depending on the particular conditions, either a rarefaction or a shock wave will be reflected, although one set of conditions exists wherein only a Mach wave will be reflected. For any given case it becomes necessary to assume the type of reflection and then attempt to obtain a solution. For the case of immediate interest a reflected rarefaction wave will be assumed. Immediately after collision the conditions established are as shown in Fig. 8.

Across the shock wave the mass and momentum equations may be combined and written in the form

$$P_4 - P_0 = \rho_0 U_s U_i \, , \tag{1}$$

or

$$U_i = \frac{\left(\frac{P_4}{P_2} \cdot \frac{P_2}{P_0} - 1 \right) P_0}{\rho_0 U_s} \, , \tag{2}$$

where

P = static pressure,
ρ = density,
U_s = velocity of transmitted shock,
U_i = velocity of interface,

and the subscripts are as shown in Fig. 8.

From shock relations we have

$$\frac{P_4}{P_0} = \frac{2\gamma_0 \, Ms^2}{\gamma_0 + 1} - \frac{\gamma_0 - 1}{\gamma_0 + 1} = \frac{P_4}{P_2} \cdot \frac{P_2}{P_0} \tag{3}$$

where

$Ms = \frac{U_s}{a_0}$,
γ = ratio of specific heats,
a = speed of sound.

Substitution in Equation 2 yields

$$U_i = \frac{\left(\frac{P_4}{P_2} \cdot \frac{P_2}{P_0} - 1 \right) P_0 \sqrt{2\gamma_0}}{\rho_0 a_0 \left[(\gamma_0 + 1) \left(\frac{P_4}{P_2} \cdot \frac{P_2}{P_0} \right) + \gamma_0 - 1 \right]^{1/2}} \, . \tag{4}$$

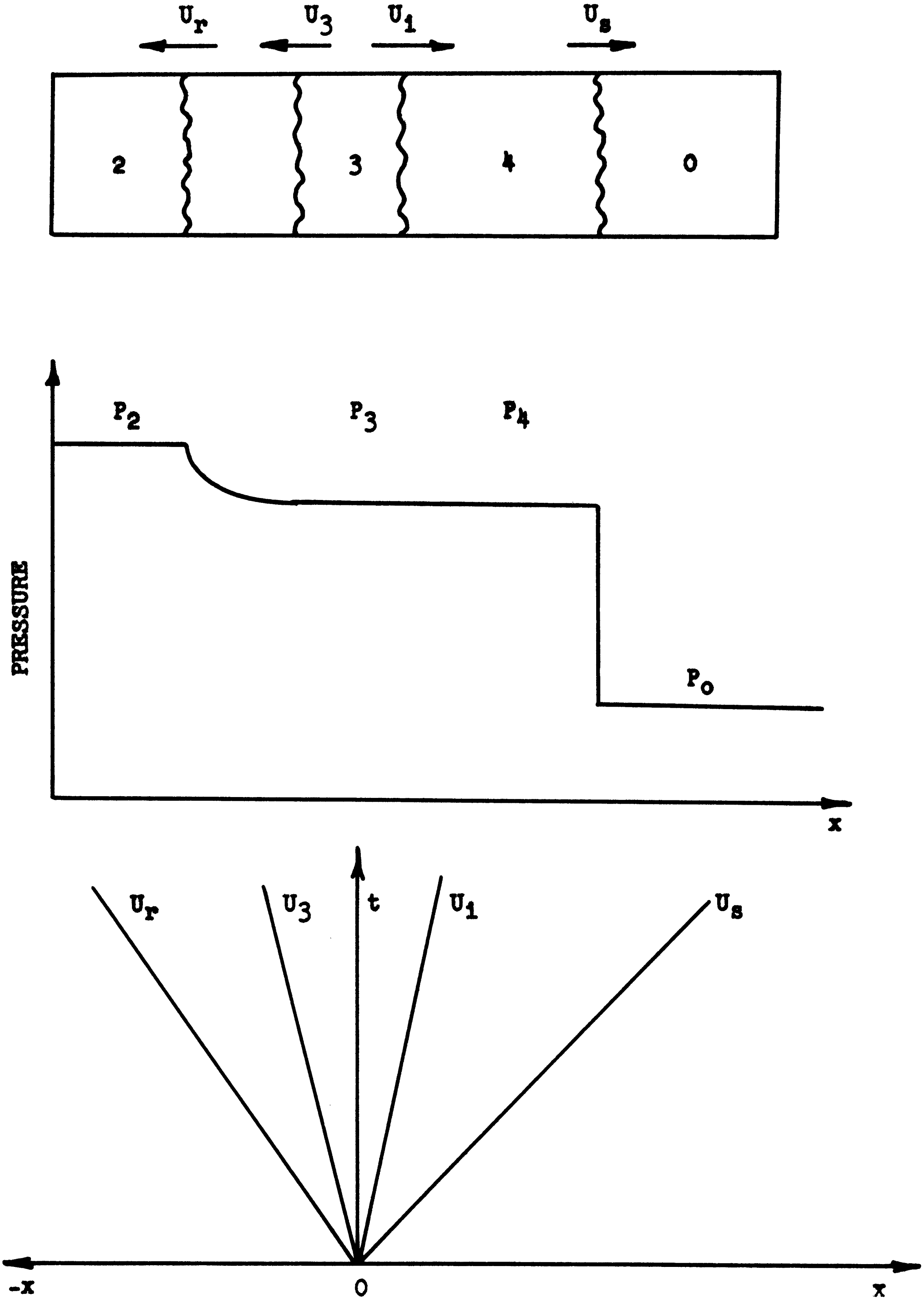


FIG. 8 - CONDITIONS AFTER COLLISION

The conditions across the reflected rarefaction wave are connected by the relation[5]

$$U_i = U_2 + \frac{2a_2}{\gamma_2 - 1}\left[1 - \left(\frac{P_3}{P_2}\right)^{\frac{\gamma_2 - 1}{2\gamma_2}}\right] . \qquad (5)$$

The boundary conditions to be satisfied specify that the interface velocities are identical and that a pressure plateau exists across the interface. The expression to be solved is then,

$$\frac{\left(\frac{P_4}{P_2}\cdot\frac{P_2}{P_o} - 1\right) p_o \sqrt{2\gamma_o}}{\rho_o a_o \left[(\gamma_o + 1)\left(\frac{P_4}{P_2}\cdot\frac{P_2}{P_o}\right) + \gamma_o - 1\right]^{1/2}} = U_2 + \frac{2a_2}{\gamma_2 - 1}\left[1 - \left(\frac{P_4}{P_2}\right)^{\frac{\gamma_2 - 1}{2\gamma_2}}\right] ,$$

the solution of which involves a trial-and-error procedure.

This problem has been solved for the case of a Chapman-Jouquet detonation in a 50 percent hydrogen-oxygen mixture colliding with a column of air at standard pressure and temperature. For this case it was found that a rarefaction wave was reflected into the reservoir which depleted the pressure level by about 10 percent. The results are shown in Fig. 9 where U_6 is the wave velocity of the lower pressure level of the rarefaction wave.

From this preliminary analysis it appears that the specific impulse and cycle rates could be improved. Of course, a number of factors have been ignored, such as unsteady flow considerations and other wave reflections. Also, the inert gas should be the burned products rather than air. However, the use of air can be readily investigated experimentally and should at least be indicative of general trends.

The thoughts underlying the above analysis were further amplified in a series of tests. It was desired that the variation of impulse with interface location be determined for a few combustible mixtures. Accordingly, a diaphragm retainer was fabricated which would facilitate the separation of the two gases at any point desired in the stainless-steel detonation tube. This retainer is shown in Fig. 10.

The procedure followed in making these tests was as follows. The detonation tube was first filled with combustible gas. The inlet fuel line was then disconnected but the inlet valve left open. The diaphragm was

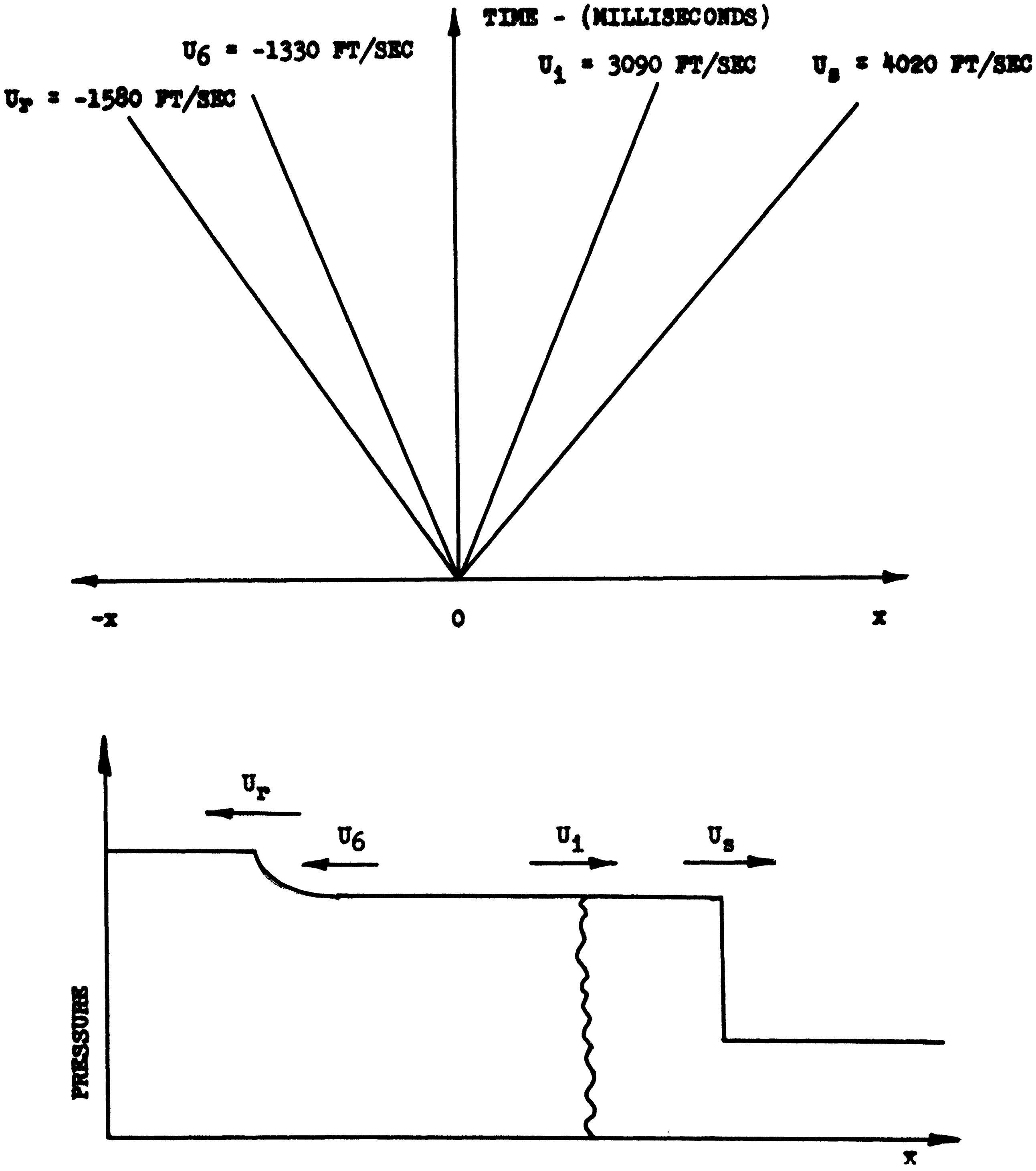


Fig. 9 RESULTS OF THE COLLISION PROBLEM

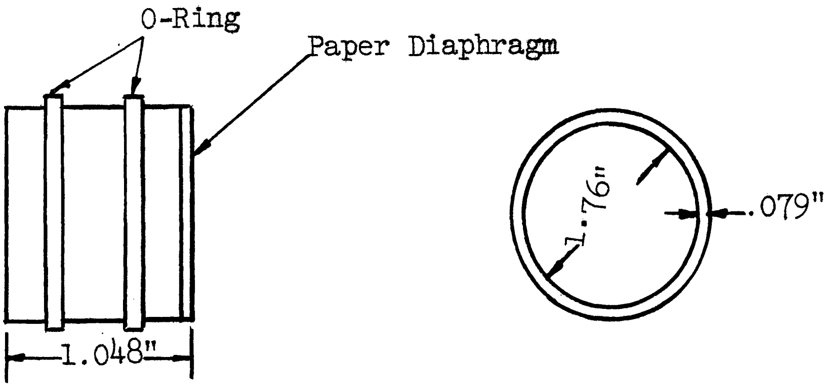


Fig. 10. Diaphragm Retainer

inserted from the open end and pushed to the desired location by means of a rod. As the diaphragm was being inserted, some of the combustible mixture was exhausted out through the inlet valve while air filled the downstream portion of the tube. In this way the entire tube was maintained at atmospheric pressure. The diaphragm was on the upstream end of the retainer.

The results for a few hydrogen-oxygen detonations colliding with air are shown in Fig. 11 where the diaphragm position was varied. Although the deflection of the detonation tube is plotted, it should be mentioned that the impulse is approximately proportional to the deflection. While the impulse continually decreases with the smaller amounts of fuel used, there is a wide range where the specific impulse would be materially improved. For example, when the diaphragm is placed 5 feet from the closed end and a 50 percent mixture is used, the specific impulse may be improved by about 35 percent.

The sharp drop-off in each of the curves of Fig. 11 corresponds to the position at which there is insufficient distance for detonation to be established. This transition range could not be detected by the noise level of the blast. Also, there was appreciable scatter in the data around this transition phase.

DELAY IN THE INITIATION OF DETONATION

In a pulsating detonative device, the time required for the accelerating flame front to initiate detonation is appreciable. Hence, a knowledge of this delay becomes quite pertinent to the design and performance of a cyclic engine operating on this principle. The initiation of

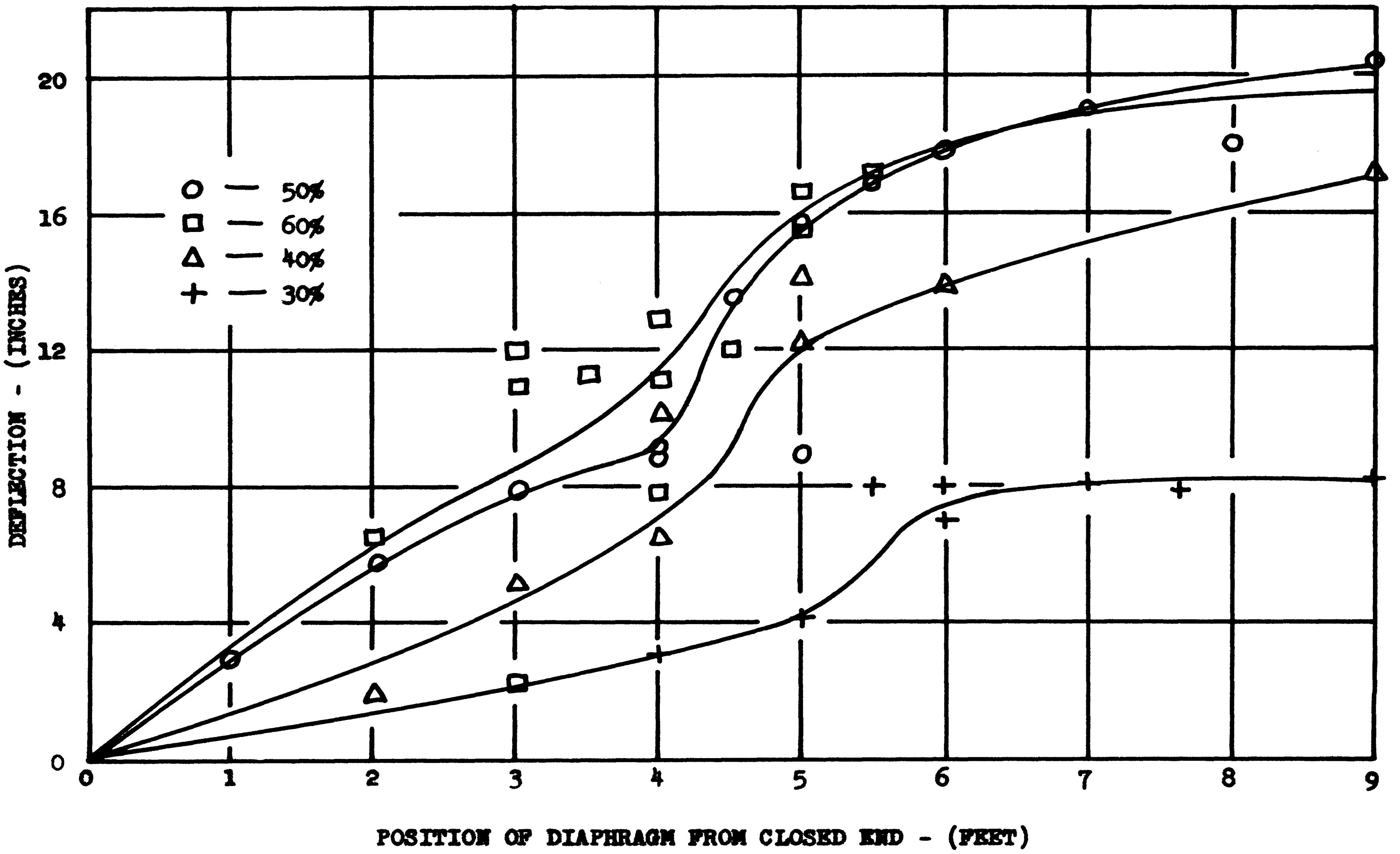


FIG. 11 VARIATION OF IMPULSE WITH DIAPHRAGM POSITION

detonation is dependent on many parameters such as temperature, pressure, properties of the mixture, tube size, and spark energy. Some representative data taken from Lewis and von Elbe[2], although information is meager on this particular aspect, are reproduced in Fig. 12. It can be seen that tube size is of prime importance.

As mentioned earlier, the irregularities in the curves of Fig. 11 correspond to the length required for the initiation of detonation. These positions are replotted in Fig. 13 as a function of mixture ratio. These detonation-lag distances are probably not too accurate as there was appreciable scatter in the original data. However, it is felt that the variation is of the right order.

Consideration of detonation delay may dictate that smaller diameter tubes be used in an actual engine. This would probably incur some loss in performance due to a lower thrust-per-weight ratio. In order to minimize this delay, it may be feasible to reflect a portion of the detonation wave back to the closed end so as to initiate detonation in another tube. Appropriate tests are planned to investigate these possibilities.

DISCUSSION OF PERTINENT REFERENCES

There are very few references to cyclic detonation in the literature. Unfortunately, some of the more pertinent of these are classified. The two references that can be discussed are summarized in the following paragraphs.

One of the earliest investigations into the problem of pulse-detonation jet-engine systems was made by H. Hoffman in Germany during the year 1941.[6] In this report the author describes the development of a simple reaction apparatus without valves and control mechanisms. This apparatus consists of a tube closed at one end and with a mixing nozzle at the other end. Acetylene and oxygen are mixed in the nozzle and this highly explosive mixture is ignited in the tube by a spark which leads to a detonation propagating toward the closed end of the tube. This detonation gives rise to the thrust. When the detonation front arrives at the closed pipe end, a reflection of the pressure wave takes place. This reflected pressure wave overtakes and accelerates the outpouring gases. Part of the pressure wave is also transmitted to the gas feed lines. This imposes a short period of restriction of the incoming gases. After the removal of the exhaust gases the tube is ready for filling again.

Experiments are conducted with various kinds of fuel-oxygen mixtures and curves of thrust against fuel-air mixtures are shown. These experiments have led to the following important conclusions:

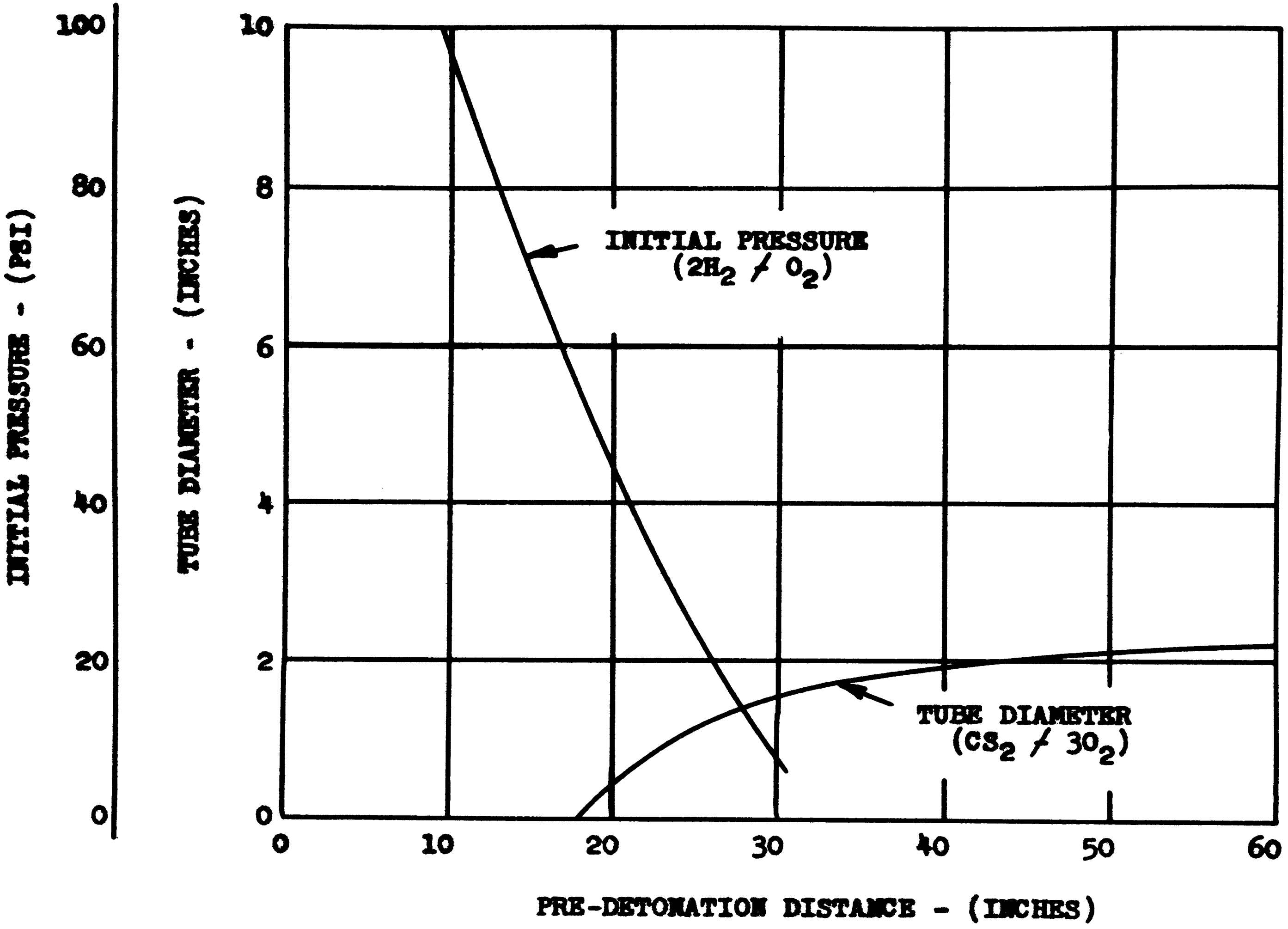


FIG. 12 DELAY IN INITIATION OF DETONATION (ref.2)

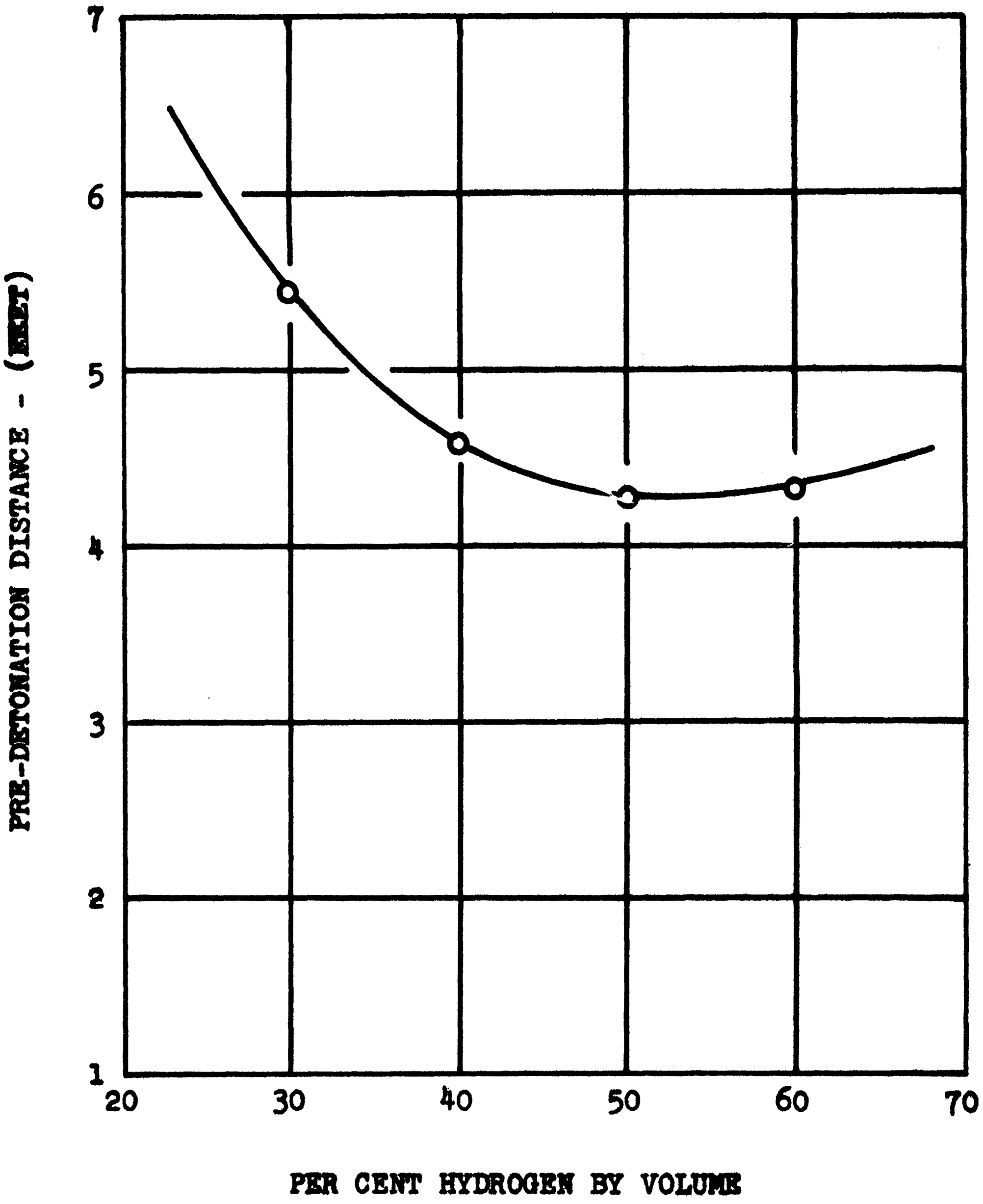


FIG. 13 DELAY IN INITIATION OF DETONATION

a. Intermittent combustion without valves and control mechanisms is possible, if the high pressure of the combustion effects a sufficient compression and the velocity of the exhaust gases is higher than the stream velocity of the fresh gases entering the combustion chamber continuously.

b. The maximum thrust is attained under very specific conditions, one of these conditions being the tube length.

c. Guiding of the exhaust gases and the pressure waves after leaving the combustion chamber is absolutely necessary.

d. A considerable increase of the thrust is given by the arrangement of suitable diffusions.

e. A suitable admixture of air leads to a combination of the rocket propulsion unit with a jet propulsion apparatus and to an increase in the efficiency with respect to fuel consumption.

f. The highest thrusts were found with mixtures rich in fuel, but detonative combustions are also possible with lean mixtures over a wide range. The lean mixtures, when used for jet propulsion, may yield lower fuel consumption, assuming that sufficient air is available.

g. The efficiency of the simple detonation pipe in the optimum range is better than that of a usual reaction apparatus of the same dimensions.

The author also gives suggestions for a large-scale construction of the apparatus. He believes that the low initial costs and maintenance costs and the expected great reliability in service justify the high costs during operation. The reaction apparatus at all temperatures is immediately ready for service and requires no warm-up period.

A preliminary performance analysis of the Pulse-Detonation Jet-Engine system was given in 1952 by D. Bitondo and W. Bollay. In their first progress report[7], the relations for the specific fuel consumption, thrust per unit area, and pounds of thrust per pound of air per second have been calculated for a range of flight Mach numbers and a range of pressure and temperature ratios. These performance computations have been carried out in two stages:

1. for an ideal cycle with simplifying assumptions and no losses, and
2. for an actual cycle including frictional losses and the effect of finite opening and closing time of valves.

The performance analysis in the authors' first report has been confined to subsonic flight speeds but indications are made of incorporating supersonic flight speeds in the near future.

Their assumed model consists of a tube with exhaust valves at one end and fitted with intake valves and a conical shaped dome at the other end. The cycle is divided into the following phases:

a. Pulse Compression Phase. The exhaust valve closes at a rate such that it becomes completely closed just as the burned gases are completely scavenged. This closing process sends forth a series of weak compression waves which combine at a distance into a normal shock wave. The normal shock is directed into a conical shaped dome at the front end of the tube while the intake valves have just been closed. In this dome the shock is focussed and strengthened to the point where detonation is initiated.

b. Burning Phase. The detonation wave sweeps through the tube, thereby increasing the pressure and temperature.

c. Exhaust Phase. The exhaust valve is designed to open as soon as the high pressure hits it. It will move at a predetermined rate so that a constant average thrust is obtained instead of a pulsating force during the exhaust part of the cycle.

d. Scavenging Phase. When the pressure of the exhaust nozzle has dropped to atmospheric, the valve is opened completely and scavenging is initiated. It is possible to reduce the pressure in the duct to subatmospheric and use this pressure difference to initiate the scavenging part of the cycle. The duration of scavenging is given by the time required for the interface between the new mixture and the burnt gases at the inlet valve to travel down the tube.

A brief discussion of the problem of detonation of commercially available, easily handled fuels is also included in the report and experimental investigations are being planned.

The results for an actual cycle are calculated for several flight speeds and the performance curves are included in the report. A preliminary discussion of valve design and duct arrangements are also given.

Further investigations of the problem of detonations, valve design, and ignition technique will be carried out with the ultimate goal of forming a prototype model of a single-duct engine which can be tested for performance. Paralleling the experimental research on detonation, the theoretical investigations will be started to give the burning efficiencies of this phase of the cycle. The results of the experimental research will be used in conjunction with the theory. The theory for detonation-wave velocities, pressure ratios and temperature ratios have been developed in the literature and it is hoped to apply it to the common propulsion fuels. This will include the effects of dissociation. From this theoretical work, a better estimate of the duration required for burning will be obtained, and better estimates of the pressures and temperatures actually obtainable can be made.

Finally, the authors hoped to present a detailed comparison of the performance of a pulse-jet engine with present jet-propulsion units including calculations of efficiencies (overall, compression, thermal, etc.).

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