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(1 June 1963 to 31 August 1963)

THE FEASIBILITY OF A ROTATING DETONATION WAVE ROCKET MOTOR

ORA Project 05179

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FOREWORD

This report is the Fifth Quarterly Progress Report, 1 June 1963 to 31 August 1963, on Contract No. AF 04(611)-8503, a contract between Edwards Air Force Base and The University of Michigan. The aim of this contract is to investigate the feasibility of a rotating detonation wave rocket motor.

Personnel associated with the various phases of the program as they are divided in the report are as follows:

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SUMMARY

This report presents the work accomplished on the rotating detonation wave engine feasibility program during the quarter 1 June 1963 to 31 August 1963.

Practically the entire effort during this period was directed to experiments with and in support of the 100 lb thrust chamber. The last progress report mentioned the difficulty experienced in achieving more than one cycle of the detonation wave. This difficulty still exists and must be overcome before any successful progress can be made. Suspected contributors to the quenching of the detonation after one pass include: (a) continuous burning around the starter tube, (b) improper injector configuration leading to poor fuel - oxidant distribution and/or recirculation zones, (c) insufficient mass flows, and (d) poor combustion chamber geometry. In order to shed light on and to eliminate some of these possibilities, experiments were performed with a linear motor which simulates the 100 lb motor (in part) and also on the 100 lb motor itself. These experiments are described herein.

I. ANALYTICAL MODEL OF THE ROTATING DETONATION WAVE ENGINE

In References 1, 2 and 3 a simplified analytical model of the rotating detonation wave rocket motor was developed. Numerical solutions for the case of an idealized rotating wave motor with gaseous propellants were presented in References 2 and 3. In Reference 3 the analytical model was extended to include the case of one propellant being in the liquid phase.

The theoretical work remaining was to obtain a numerical solution to the analytical model for this cryogenic case. This work has been temporarily discontinued due to the emphasis on the experimental phase of the program.

II. EXPERIMENTAL STUDY OF THE ROTATING DETONATION WAVE ENGINE

In the last progress report (Reference 3) mention was made of the difficulty experienced in obtaining successful operation of the 100 lb thrust motor. Initial tests utilizing either the detonation starter tube or a spark plug resulted in two detonation waves in the annular combustion chamber of the motor. These waves propagated in opposite directions in the annulus and hence collided at a position approximately 180° from the exit plane of the starter tube. The collision resulted in reflected shock waves which were rapidly attenuated and no subsequent detonations were observed. Attempts to eliminate this second "backward" propagating detonation by means of an expendable diaphragm in the combustion annulus near the starter were not successful. However, this "backward" propagating wave was eliminated by blocking several of the injectors in the vicinity of the starter. Whereas this resulted in the successful propagation of a single detonation in the desired direction, it was found that the detonation wave did not continue after one complete cycle of the motor. The reasons for this were considered to be: (a) that the detonation wave was attenuated by the buffer zone near the blocked injectors, (b) that recirculation of the burned gases resulted in continuous burning of the propellant emitted from the injectors after passage of the detonation wave, (c) that the starter tube projecting into the chamber acted as a flame holder and thus the fresh propellant charge was burning continuously rather than by detonation.

In view of these difficulties it was decided to build a linear model of the motor to investigate the starting problem. The construction of this linear motor is similar to the 100 lb thrust motor, and could be duplicated, except for the plexiglas windows, by cutting the 100 lb thrust motor along a radial line and forming it into a straight test section. Since the linear motor utilizes the same propellant feed system and test stand as the 100 lb thrust motor, the change from one test set-up to the other is facilitated so that indicated design changes may readily be tried in the 100 lb thrust motor. The linear motor allows optical studies as well as pressure, temperature, and ionization probe measurements of the development of the detonation wave pattern in the combustion chamber.

The linear motor was installed and 22 test runs were conducted during the report period.

A photograph of the linear motor on the test stand is shown in Figure 1. An exploded view of the linear motor is presented in Figure 2. The manifold, injector plate, and nozzle section are made of brass. The windows, which are made of plexiglas, are held in place with steel brackets. The ends of the test section are removable so that plexiglas can be inserted to facilitate optical study in the longitudinal direction also. The test section has a cross-section of 1/2 inch by 2 inches and is 24 inches long. The injector plate (see Figure 2) is provided with removable injector inserts so that the inlet area of the injectors can be varied. The 36 injector pairs are spaced 5/8 inch apart, and canted at 7.5° and 40° as in the 100 lb thrust motor.

A schematic diagram of the propellant feed system and of the instrumentation is shown in Figure 3. The sequencing of the valves and the timing of the spark must be controlled very accurately for the linear motor due to structural limitations of the test section. A typical oscillograph record of the sequence of operations, which are controlled by electronic time delay units, is shown in Figure 4. The desired operating pressures for the hydrogen and oxygen feed lines are set by means of Grove pressure regulators before the run. When the sequence button is pushed the hydrogen and oxygen valves are energized, the camera motor is energized, and the time delay units for the spark and valve shut off are initiated. The spark is timed to fire as soon as the H_2 and O_2 manifold pressures have reached a steady state pressure. The closing of the valves on the H_2 and O_2 feed lines is adjusted to allow about 10 milliseconds (approximately 50 rotations of a detonation wave) of steady state manifold pressure before shut off. Although the hydrogen and oxygen valves are energized by the same signal (and the valves are identical) the response of the oxygen valve is slower and causes excess fuel to be expended during a test run.

Two configurations of the linear motor, which are shown in Figure 5, were tested. Configuration (a) was used to study the propagation of the detonation wave from the starter to the motor under simulated starting conditions of the 100 lb thrust motor. The hydrogen and oxygen gas were fed from the manifold to two small mixing orifices at the upstream end of the starter tube and the mixture was then ignited with a spark plug. Optical studies of the wave propagation were conducted by means of schlieren spark photographs. Direct luminous photographs with the Beckman and Whitley camera at 26,000 frames per second were also taken but the spark photographs gave better resolution and more exact positioning of the wave. Also, utilizing an electronic flash light source (~9 m-sec duration) an unsatisfactory attempt was made to obtain shadowgraph pictures with the Beckman-Whitley camera. Configuration (b) was used to study the propagation of a second detonation wave down the linear motor at a distance of one test section length (24 in.) behind the first wave in order to simulate the second rotation of the detonation wave in the 100 lb thrust motor. The starting tube, which in this case was flush with the end of the test section as shown in Figure 5, had thin diaphragms on the end and was filled with a premixed hydrogen-oxygen mixture. A spark plug was used to initiate the detonation wave. In order to fill this starting system the propellant metering setup and premix tank from the earlier supporting experiments was utilized. Ionization probes and a Kistler 603 pressure probe were used to establish the wave patterns. (Note that a unidirectional wave is insured in this configuration). Optical study in this configuration was not attempted because the optical quality of the plexiglas was destroyed after each run and replacement is time consuming. Pyrex windows are being purchased to circumvent this difficulty.

The following information was obtained from the linear motor configuration (a):

1. Before ignition the injected hydrogen and oxygen gas appears to mix significantly after a distance of about 1/2 inch from the injector face.
2. The detonation wave in the starter propagates in a somewhat spherical fashion so that for a stoichiometric mixture in both the starter and the motor a detonation wave is started readily in both directions as shown in Figure 6. Notice that the forward moving wave has traveled approximately twice as far as the backward moving wave at the time of this photograph.
3. The bright areas in the right side of Figure 6 indicate that the starter tube may act as a flame holder.
4. Thirty microseconds after the passage of the wave an interface between the burned and unburned gases was not evident.
5. The resultant stream from the impingement of the H_2 and O_2 injectors is not normal to the injector face but rather directed toward the hydrogen side which could cause an undesirable recirculation pattern of the burned gases in a plane normal to the windows. This was apparent from the fact that the injector pattern was etched heavily into the window on one side, but very lightly on the other side. A photograph of the heavily etched window is shown in Figure 7.

With respect to future tests on the 100 lb thrust motor the above facts dictate that the alignment of the injectors should be improved, and that the flame holding effect of the starter should be carefully examined.

Typical results from the linear motor configuration (b) tests are shown in Figures 8 and 9. Figure 8 is a modified Kistler 603 pressure recording of the starting pulses alone. In all of the tests a dc drift of the transducer ocurred. Figure 9 shows pressure recordings of runs 15 and 16 which were conducted under the same conditions but with the pressure transducer in two different positions. If the second wave did detonate in the combustion chamber a sharp rise should be evident at 200 μ-sec, which is not indicated in Figures 9a or 9b. In 9a a very weak pulse (from the starter tube) appears at about 200 μ-sec, while in 9b the reflected shock off the end of the combustion chamber appears at about 625 μ-sec. A criticism of these tests is that the second wave is emitted from a 1/4 inch I. D. tube, whereas in the 100 lb thrust motor the wave would start its second rotation filling the entire chamber. It would be possible to modify the linear motor to improve this situation, but the complexities involved do not appear to be warranted at this time. Also measurements of the detonation wave velocity in the combustion chamber were made with ionization probes (shown in Figure 5b). These measurements indicated that the first detonation wave travelled at nearly the same speed in the motor as in the starter tube. No significant time delay due to transition from starter to motor was observed.

Next the propellant feed lines were reversed in order to improve the alignment of the injectors thereby reducing the velocity gradients and recirculation in the combustion chamber. (The alternative to reversing the feed lines was machining a new injector face.) Again the second wave would not propagate down the motor. The pressure results were very similar to that shown in Figure 9.

Although many more tests would be possible, it was decided not to pursue the linear motor tests further but to apply what was learned to the 100 lb thrust motor realizing that the linear motor is not an exact simulation of the 100 lb thrust motor.

In order to interpret the results of the 100 lb thrust motor tests a shock tube calibration of the Kistler 603 pressure transducer is shown in Figure 10. The recorded pulse is from a 60% hydrogen-40% oxygen mixture by volume at 1 atmosphere and the second pulse is the reflection off the end of the tube. The oscilloscope was triggered by an ionization probe which was 12 3/4 inches upstream from the pressure transducer. Theory predicts a peak pressure of 275 psi behind this Chapman-Jouguet wave. The manufacturer's calibration for this transducer without the filter is 40 m volts/psi and thus from Figure 10 the maximum measured pressure is 75 psi. The rise time of the transducer accounts for only part of the difference between theory and experiment. Since at this point we are interested primarily in the order of magnitude of the pressure pulses in the motor, the results in the shock tube will be taken as the calibration, i. e., the sensitivity of the transducer will become 40 x 75/275 = 11 m volts/psi.

The first step in the next 100 lb thrust motor tests was to improve the alignment of the injectors by switching the hydrogen and oxygen feed lines. At equal manifold pressures this resulted in a mixture ratio of approximately 90% H_2 by volume. The ignitor feed lines were not switched so that a near stoichiometric mixture was used in the ignitor. (A 90% H_2 mixture in both the ignitor and motor would not detonate.) The results are shown in Figure 11. For this mixture ratio the C-J detonation velocity is 11, 500 ft/sec so that one revolution of the wave should occur in roughly 170 μ-sec. This is about the spacing of the three pulses in Figure 11 however, the amplitude of these pulses is only 200 mv or 17 psi which can hardly be considered a detonation wave. As the mixture ratio is decreased, Figures 12 and 13, the amplitude of the pulse increases. For the run shown in Figure 13 the C-J detonation velocity is about the same as in the run of Figure 11, but the time of the second pulse has decreased nearly 100 μ-sec so that the pulses are too rapid for a unidirectional detonation wave. From the relative position of the pressure transducer as shown in Figure 14 and from previous tests (see Ref. 2, Figure 5 for example) it is evident that Figures 12 and 13 are the result of two colliding waves. The same phenomena is probably occurring in Figure 11 but due to the weak nature of the wave the velocity of propagation has decreased. Thus it is not possible to judge the effect of the improved alignment of the injectors until a unidirectional wave can be established.

III. STUDY PLANS FOR THE NEXT QUARTER

During the next quarter, the last one of the contract, all personnel and funds necessary will be directed towards the attainment of successful motor operation. This is essential in order that experimental results can be interpreted in terms of earlier supporting studies and thus allow the question of feasibility to be answered. It is planned that satisfactory progress along these lines will allow for a few further exploratory experiments on hetergeneous detonation.

REFERENCES

1. Nicholls, J. A., and Cullen, R. E., et al., The Feasibility of a Rotating Detonation Wave Rocket Motor, Univ. of Mich. Eng. Res. Inst., Report 05179-2-P, Dec. 1962.
2. Nicholls, J. A., and Cullen, R. E., et al., The Feasibility of a Rotating Detonation Wave Rocket Motor, Univ. of Mich. Eng. Res. Inst., Report 05179-3-P, March 1963.
3. Nicholls, J. A., and Cullen, R. E., et al., The Feasibility of a Rotating Detonation Wave Rocket Motor, Univ. of Mich. Eng. Res. Inst., Report 05179-4-P, June 1963.

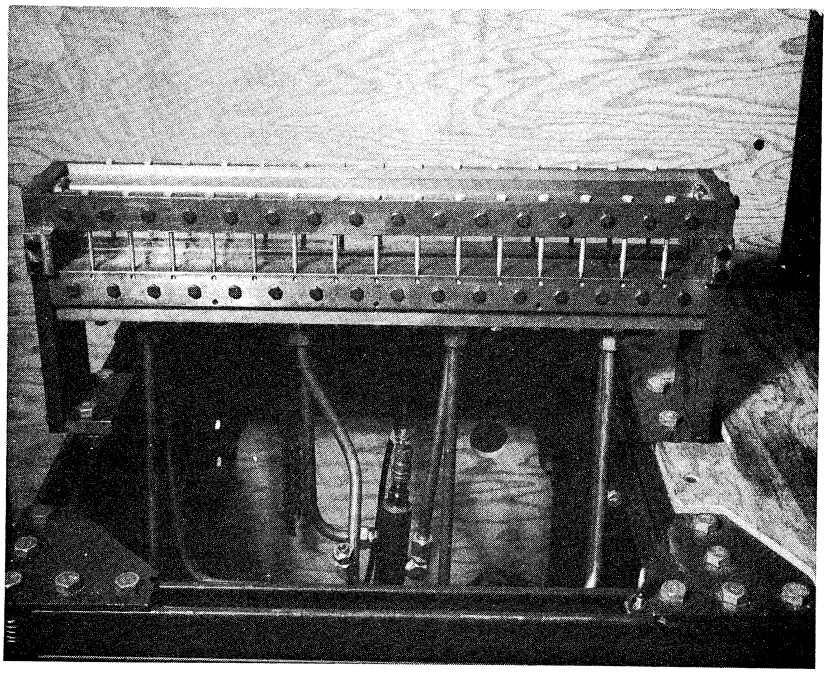


Figure 1. Photograph of the Linear Motor on the Test Stand.

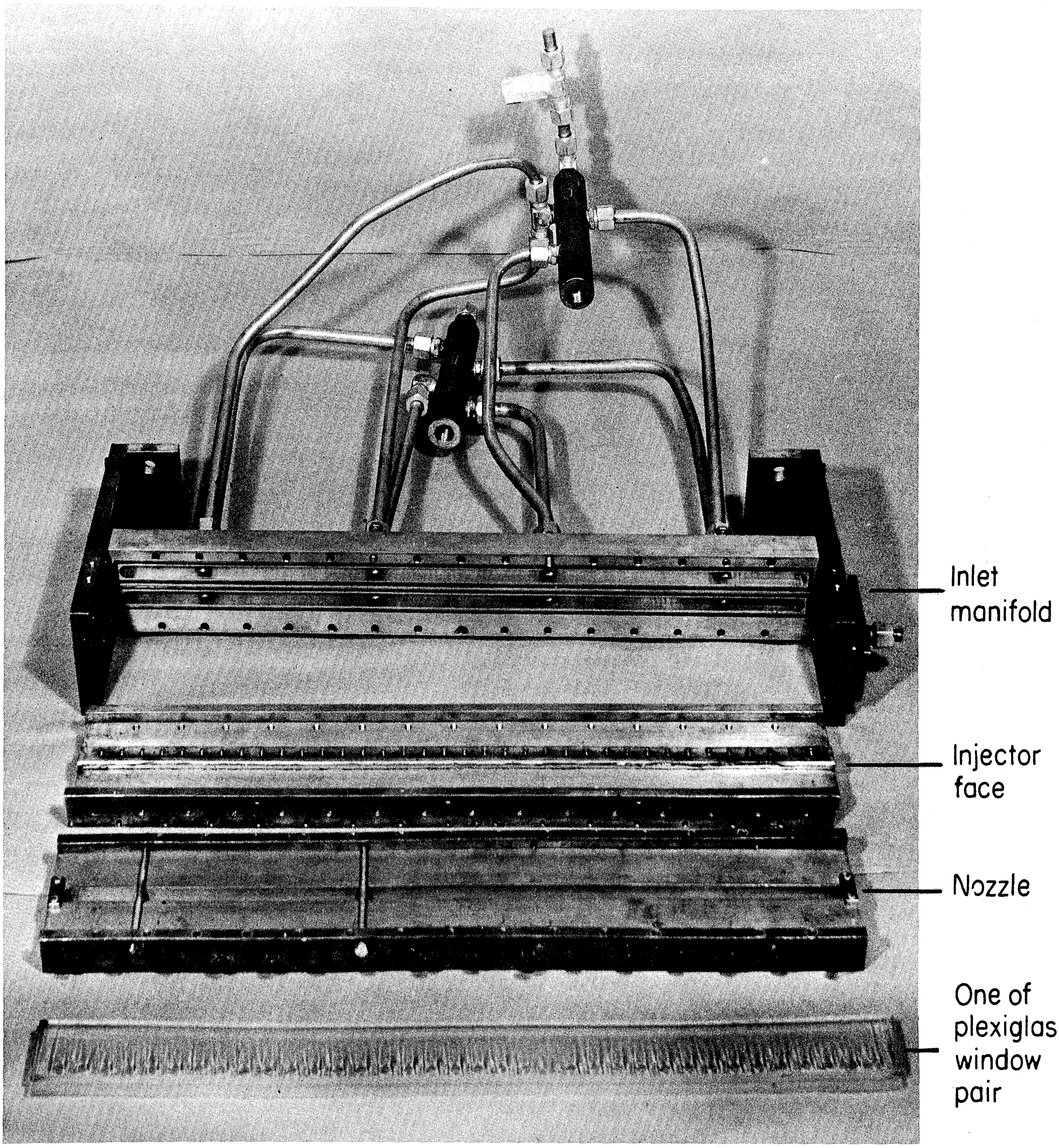


Figure 2. Photograph of the Components of the Linear Motor.

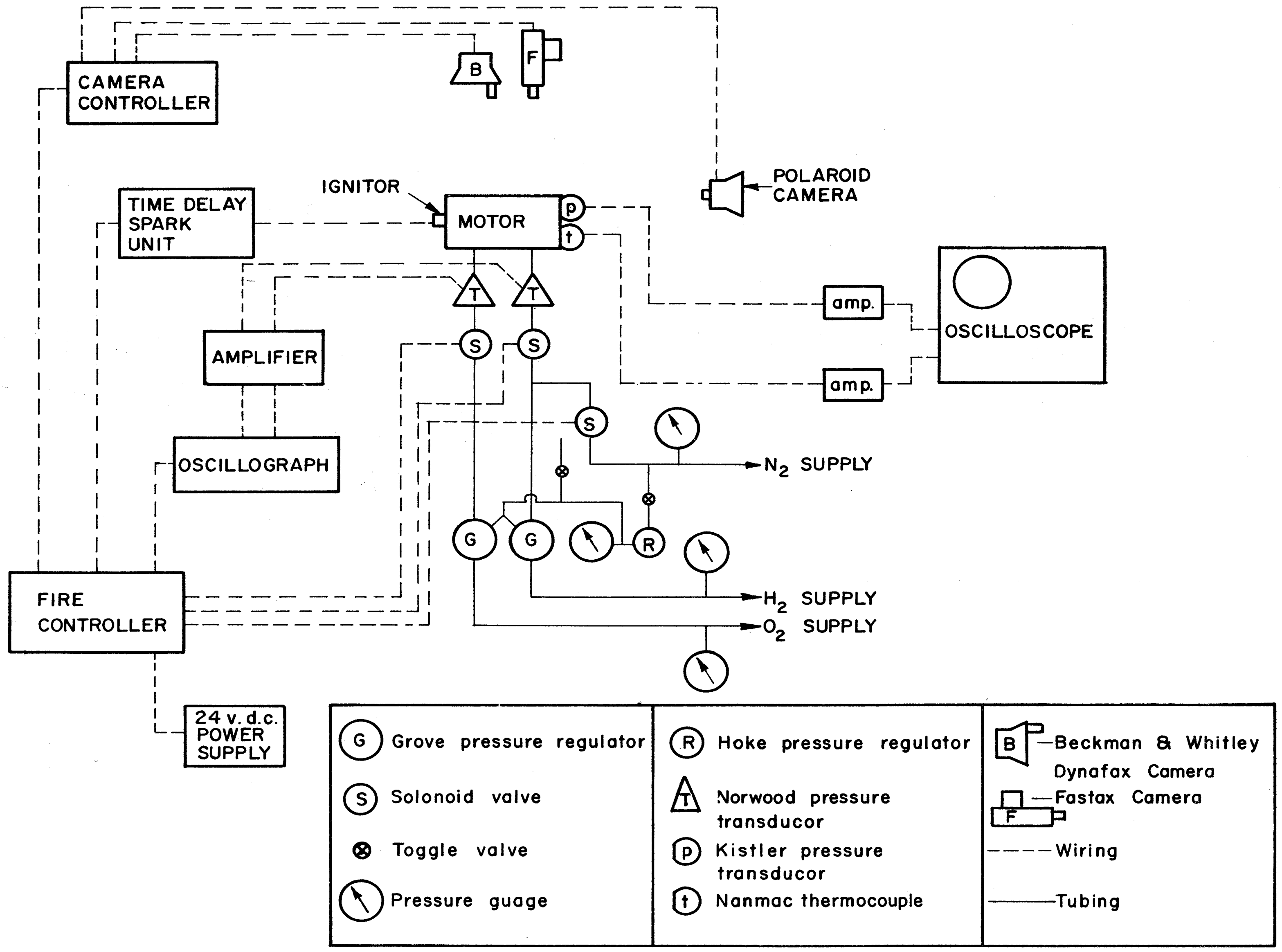


Figure 3. Schematic Diagram of Propellant Feed System and Instrumentation for the Linear Motor.

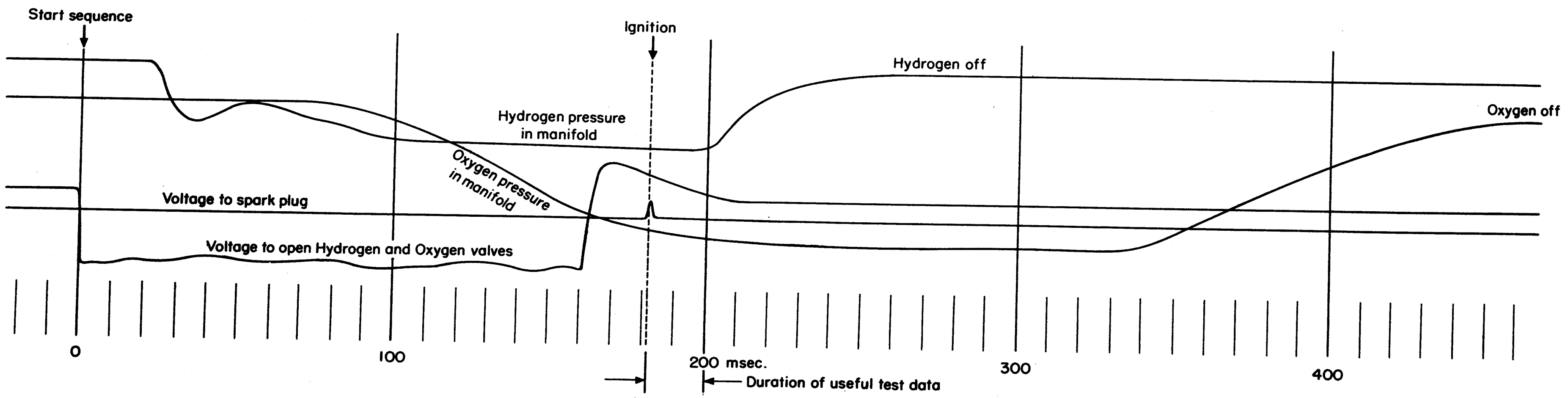


Figure 4. Typical Oscillograph Record of Propellant Sequencing for the Linear Motor.

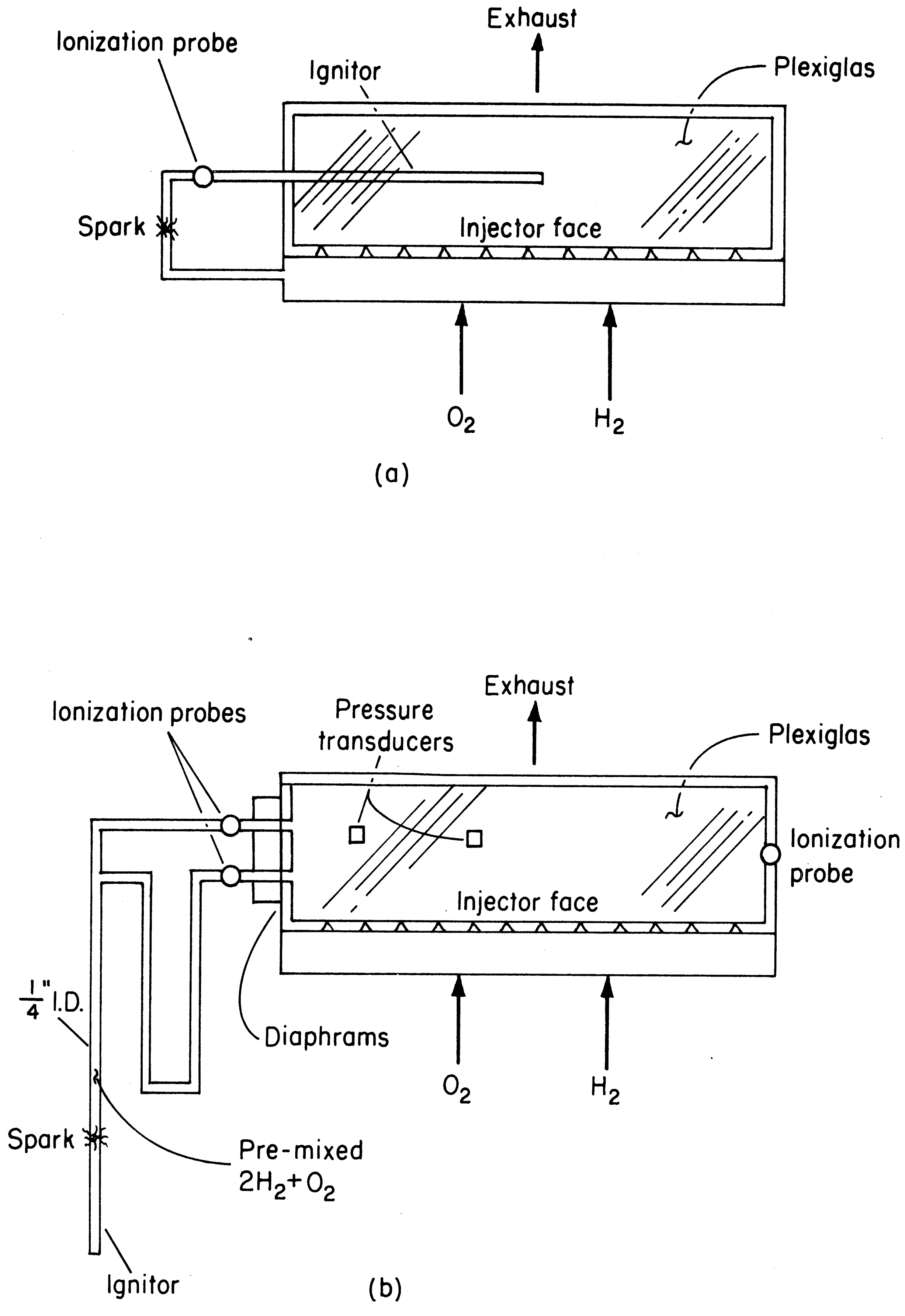
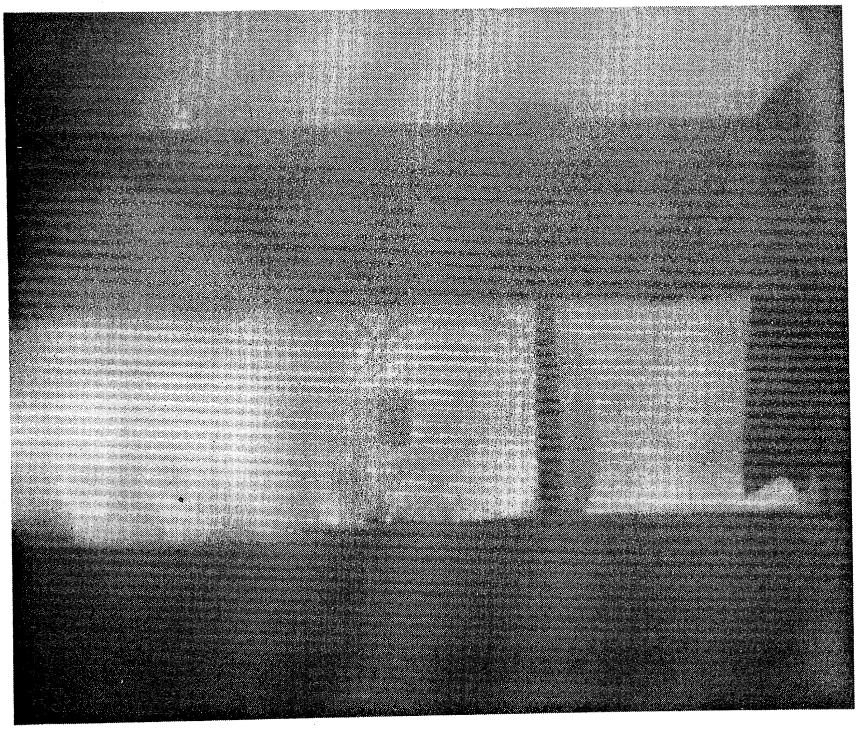


Figure 5. Schematic Diagram of the Linear Motor Test Configurations.



Input Data:

H_2 Manifold Pressure: 1,000 psi

O_2 " " "

Mixture Ratio: 0.67 % Mole Fraction Hydrogen

Nominal Mass Flow: 0.36 Lbs. Propellant Per Second

Figure 6. Spark Schlieren Photograph of Test in Linear Motor Configuration (a).

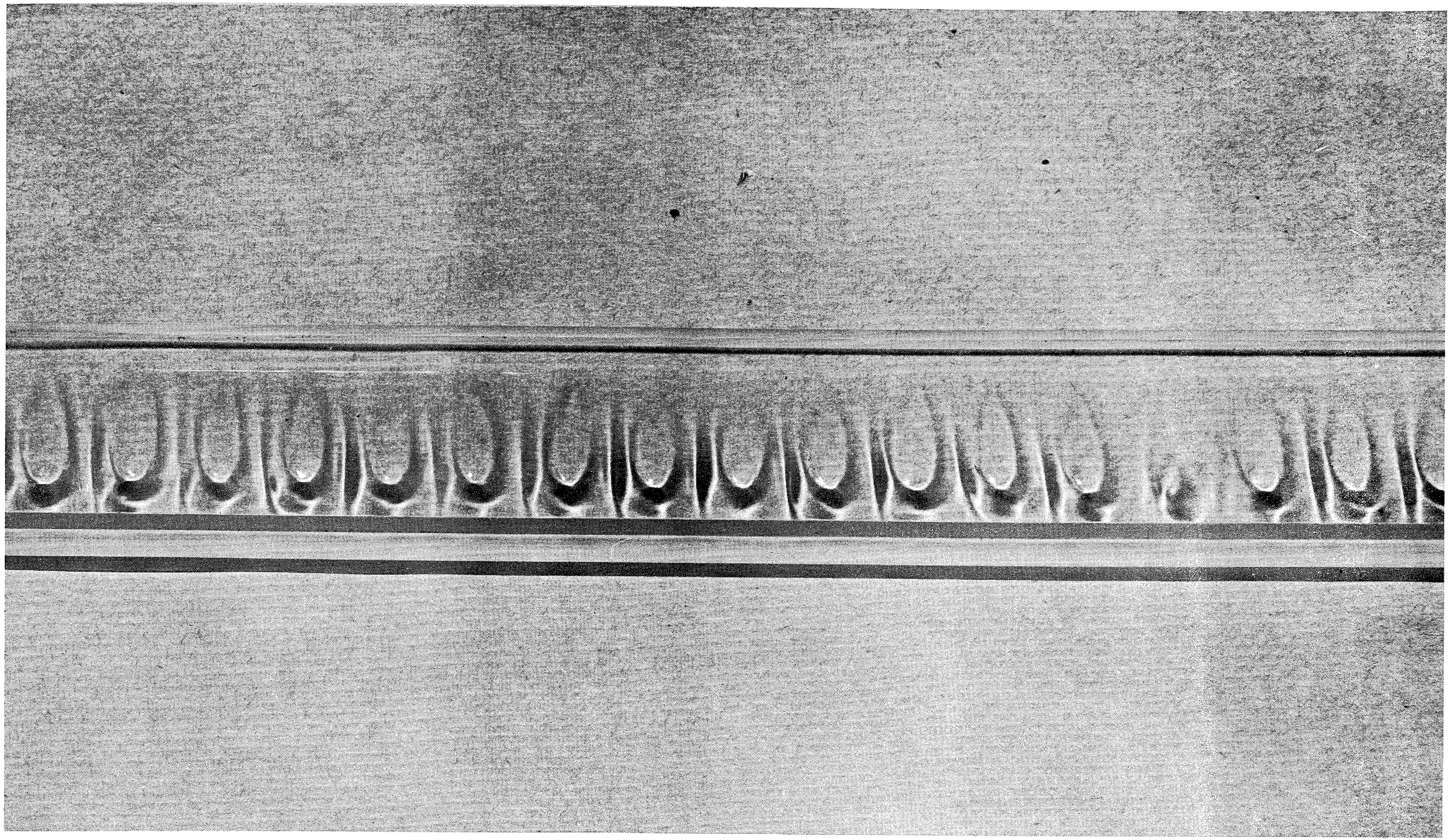
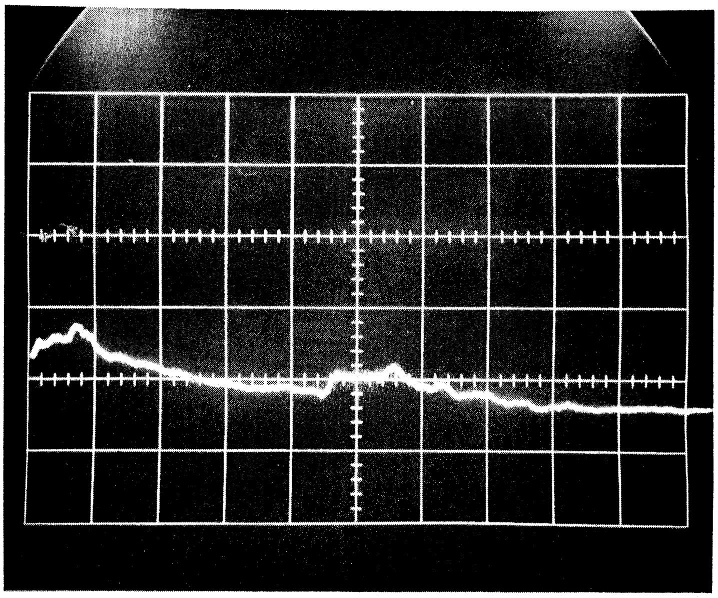


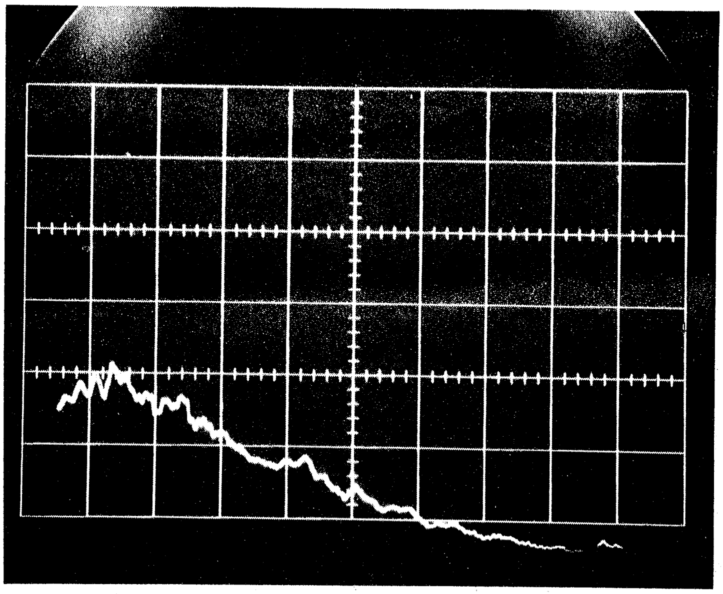
Figure 7. Photograph of Plexiglas Window from Linear Motor after Test



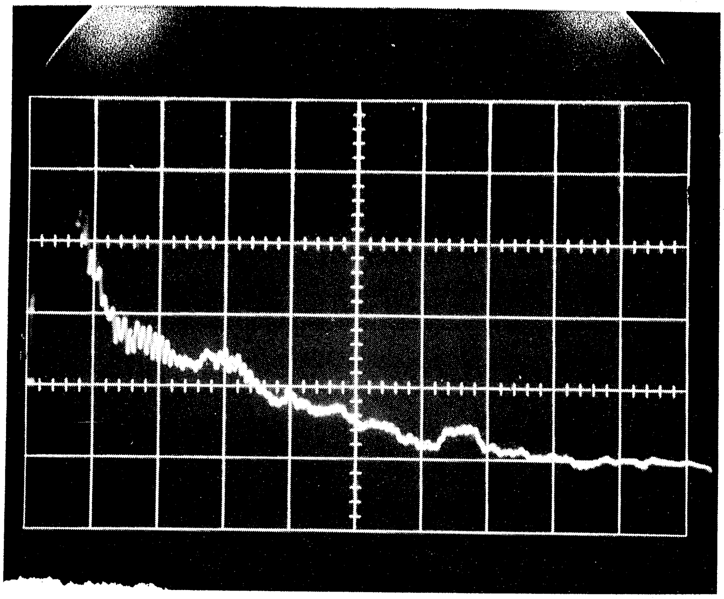
Horizontal Scale: 50 μsec./cm.
Vertical Scale: 0.5 Volts/cm.

Transducer located 1 3/4 inches from starter face and 7/8 inch from injector.

Figure 8. Pressure Recording of Starter Tube Fired into Stagnant Air-Linear Motor.



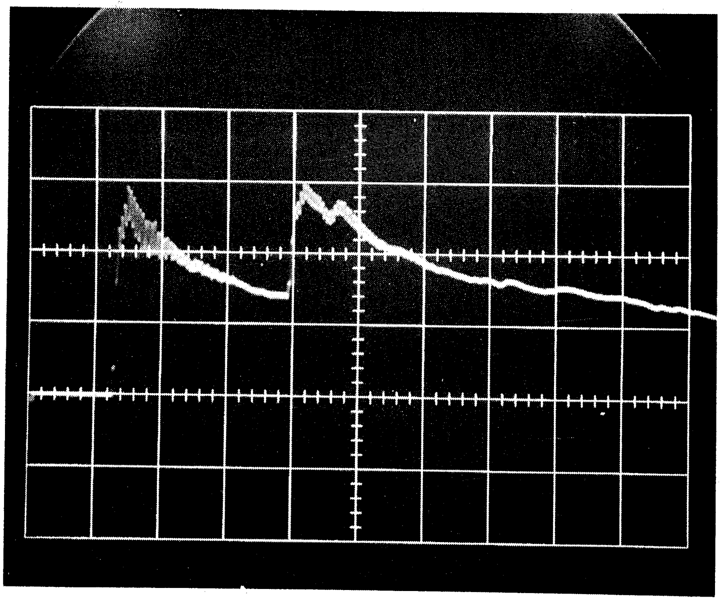
(a) Transducer 1 3/4 inches from starter



(b) Transducer 7 1/4 inches from starter

Horizontal Scale:	50 μsec./cm.
Vertical Scale:	0.5 Volts/cm.
Hydrogen Manifold Pressure:	1,000 psi
Oxygen " "	1,000 psi
Nominal Mass Flow:	0.46 Lbs./sec.
Mixture Ratio:	0.67 % H_2 by Volume

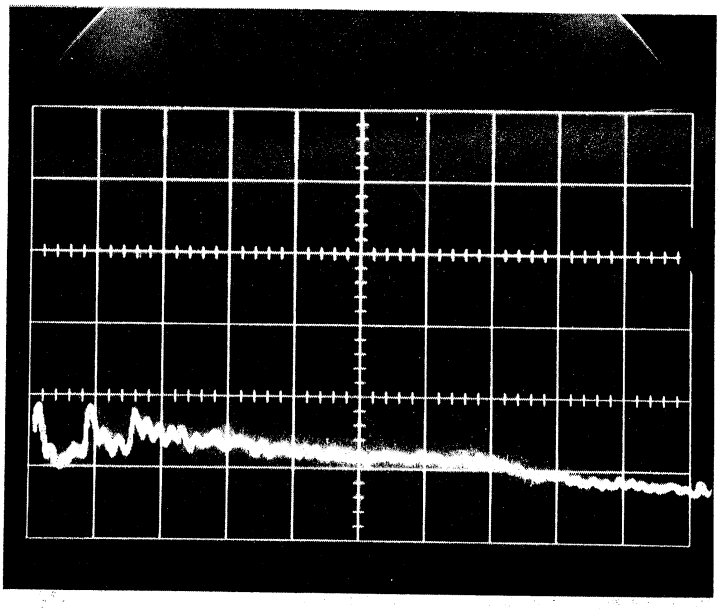
Figure 9. Pressure Recording of Linear Motor Configuration (b)
Tests 15 and 16



Horizontal Scale: 100 μsec./cm.
Vertical Scale: 1 Volt/cm.

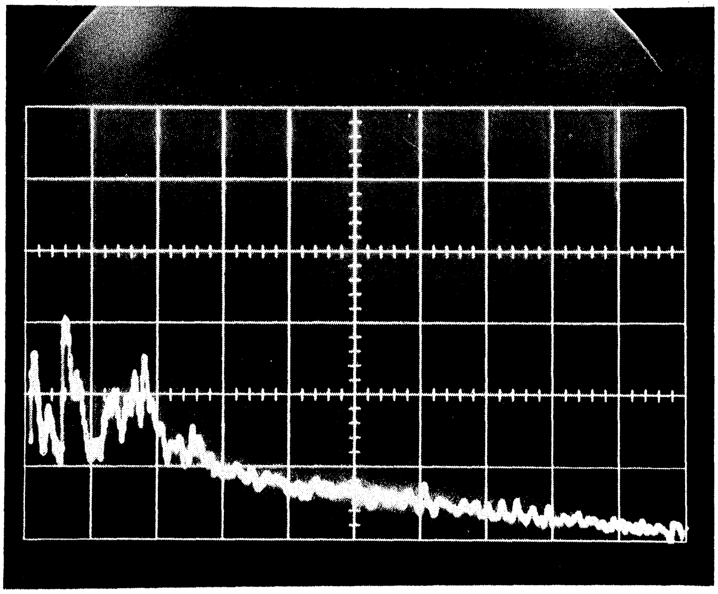
Hydrogen-Oxygen detonation wave 60% H_2 by volume; 1 atmosphere; 20° centigrade. Transducer 6 inches from closed end.

Figure 10. Shock Tube Calibration of Modified Kistler 603 Pressure Transducer Used in Tests.



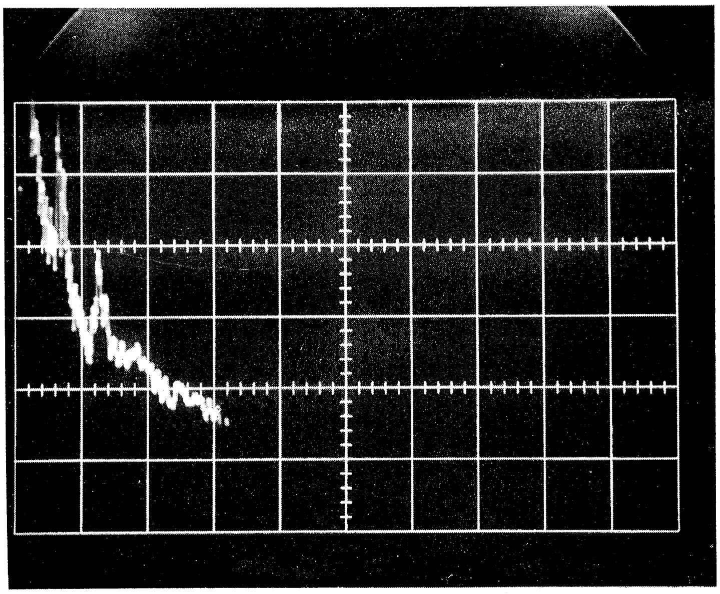
Horizontal Scale: 200 μsec./cm.
Vertical Scale: 0.2 Volts/cm.
Hydrogen Manifold Pressure: 1,400 psi
Oxygen " " 1,350 Psi
Nominal Mass Flow: 0.40 Lbs./sec.
Mixture Ratio: 89.9 % H_2 by Volume

Figure 11. Pressure Recording of 100-lb Thrust Motor Run 53.



Horizontal Scale:	200 μsec./cm.
Vertical Scale:	0.2 Volts/cm.
Hydrogen Manifold Pressure	1,400 psi
Oxygen " "	1,590 psi
Nominal Mass Flow:	0.45 Lbs./sec.
Mixture Ratio:	87.5 % H_2 by Volume

Figure 12. Pressure Recording of 100-lb Thrust Motor Run 51.



Horizontal Scale:	200 μsec./cm.
Vertical Scale:	0.2 Volts/cm.
Hydrogen Manifold Pressure:	500 psi
Oxygen " "	700 psi
Nominal Mass Flow:	0.62 Lbs./sec.
Mixture Ratio:	83.6 % H_2 by Volume

Figure 13. Pressure Recording of 100-lb Thrust Motor Run 59.

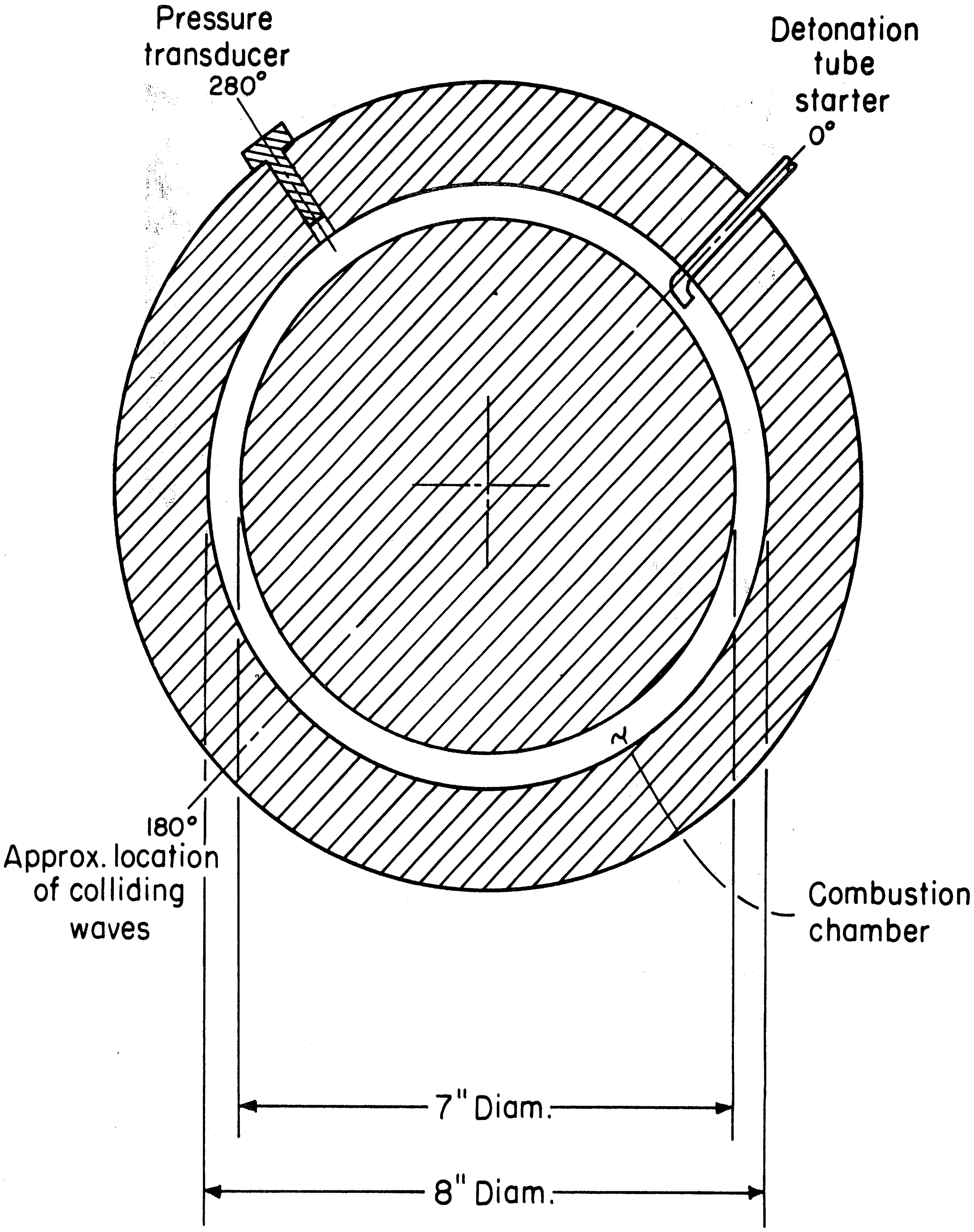


Figure 14. Schematic Diagram of Pressure Transducer Location in 100-lb Thrust Motor.

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