NASA TECHNICAL MEMORANDUM

NASA TM X-3378

NASA TM X-3378

MEASURED OPENING CHARACTERISTICS OF AN ELECTROMAGNETICALLY OPENED DIAPHRAGM FOR THE LANGLEY EXPANSION TUNNEL

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1976

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM X-3378		

4. Title and Subtitle	5. Report Date
MEASURED OPENING CHARACTERISTICS OF AN ELECTROMAGNETICALLY OPENED DIAPHRAGM FOR THE LANGLEY EXPANSION TUNNEL	August 1976
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
John A. Moore	L-10796
	10. Work Unit No.
9. Performing Organization Name and Address	506-26-10-01
NASA Langley Research Center Hampton, Va. 23665	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Diaphragm Expansion tube Expansion tunnel	Unclassified – Unlimited Subject Category 09

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	30	$3.75

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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SUMMARY

Results from an experimental study of the opening characteristics of an electromagnetically opened, 15.24-cm-diameter diaphragm are presented. This diaphragm consists of a polyester film bonded to a preformed wire and is opened by passing a current pulse (capacitor discharge) through the wire. The purpose of this diaphragm is to separate the acceleration section of the Langley expansion tunnel from the nozzle so that the nozzle may be at a lower pressure than the acceleration section prior to a test. Opening times and cleanness of the opened area were examined for dependence on diaphragm thickness, on wire diameter, on technique of bonding the wire to the diaphragm, and on voltage and energy level of the energy source.

The opening time was examined by use of a high-speed framing camera during bench tests which were performed with atmospheric pressure on both sides of the diaphragm. Cleanness of the opened area was studied both during the bench tests and with the diaphragm installed in the expansion tube under a vacuum. The bench tests and the tests under vacuum revealed that the diaphragm generally opened into a triangular pattern at the periphery of the tube. The bench tests indicated that diaphragm thickness had no detectable effect on the opening time for the thickness range tested. However, the thinner diaphragms left less diaphragm material in the 15.24-cm tube opening than the thickest diaphragm. Best opening characteristics were obtained for values of energy per unit cross-sectional area of the wire from 0.3 to 0.4 kJ/mm^2. Higher energies caused breakage of the wires, which was deemed unacceptable. The bench tests showed that the minimum opening time of the diaphragm for the range of variables studied was approximately 800 to 1000 μs.

The reliability of diaphragm operation was increased considerably by use of a circuit, developed for this study, for triggering air gaps at low voltages.

Pitot-pressure time histories measured at the nozzle entrance location, 33 cm downstream of the diaphragm, showed that a flow-opened diaphragm was extremely detrimental to the flow quality at this location. Although the flow quality with the electromag-

netically opened diaphragm was greatly improved over that with the flow-opened diaphragm, the pitot-pressure surveys indicated some disturbance which was not present for the no-diaphragm tests. Additional tests indicated this disturbance was due to partial blockage of the tube at the diaphragm station. Recommendations are presented for employing the electromagnetically opened diaphragm in expansion-tunnel operation with a minimum disturbance to the nozzle entrance flow.

INTRODUCTION

A theoretical study by Trimpi and Callis (ref. 1) indicated that several advantages could be realized by adding a nozzle to an expansion tube (ref. 2). Hence, an experimental investigation was made of flow characteristics in a conical nozzle added to the Langley pilot model expansion tube (described in ref. 3). The results of these tests in the pilot model expansion tunnel (ref. 4) indicated that the nozzle starting process and the quasi-steady test-period duration improved when the nozzle was evacuated prior to a test. Nozzle evacuation was made possible by installation of a thin tertiary diaphragm to separate the acceleration section from the nozzle; however, when this diaphragm was opened by the flow, a reflected shock which proved to be detrimental to the nozzle flow quality was observed. An electromagnetic device was therefore developed for preopening the diaphragm (ref. 5), since it was believed that a self-opening tertiary diaphragm was required to avoid reflected shocks and to reduce flow contamination, and hence model damage, by diaphragm particles. The self-opening tertiary diaphragm described in reference 5 was used in the tests of reference 4. However, several operational problems, including unreliable energy-source triggering and loss of wires from partial openings, were encountered.

Provision was made for a third diaphragm to be located between the acceleration section and the nozzle entrance, when the Langley 6-inch expansion tube (ref. 6) was recently modified by the addition of a nozzle at the exit of the acceleration section. (The result of this modification is the Langley expansion tunnel.) A new diaphragm opener was designed to accommodate the larger diameter (15.24 cm compared with 9.53 cm for the pilot model expansion tunnel) and to incorporate improvements suggested by previous tests with the opener, reported in reference 4.

For successful expansion-tunnel operation, the opening time of a self-opening diaphragm must be accurately known. Accuracy is required because of the high flow velocities (typically 5 to 7 km/s) and because the opening process must be initiated such that the diaphragm is removed from the tube just prior to flow arrival. It is important that the diaphragm not be opened too soon in the flow sequence, since upon opening, an expansion wave propagates into the quiescent acceleration gas at the ambient speed of sound. Thus, the flow will experience a density gradient in the acceleration gas in the vicinity of the nozzle entrance. Shorter opening times reduce the time available for the spreading of this density gradient, provided the opening is initiated at the proper time in the flow sequence.

Preliminary bench tests were performed to examine the opening characteristics of an electromagnetically opened diaphragm designed specifically for the Langley expansion tunnel. Since these bench tests were not made in an evacuated chamber, they did not completely simulate actual conditions in the expansion tunnel. At the completion of bench tests, the unit was installed in the expansion tunnel, and a number of no-flow tests were made at evacuated conditions to examine the cleanness of the opened area. Additional tests in which a pitot-pressure survey rake was installed at the nozzle entrance were then conducted with the electromagnetically opened diaphragm.

This report presents a description of the electromagnetically opened diaphragm for the Langley expansion tunnel and the results of varying primary parameters affecting the opening characteristics. High-speed photographs recorded the opening phenomena to obtain time histories of the displacement of the wire and diaphragm. The effects of diaphragm thickness, wire diameter, technique of bonding wire to diaphragm, and voltage and energy level of the energy source on opening time and cleanness were investigated. The combination of parameters giving the best opening characteristics is discussed. Sample results are also presented from preliminary tests of the effect of the electromagnetically opened diaphragm on the test gas pitot pressure at the entrance of the expansion tunnel nozzle.

SYMBOLS

C	capacitance, F
E	energy, J
f	frequency, Hz
I	current, A
L	inductance, H
p_t	pitot pressure, Pa
R	resistance, Ω

t time, s

t_o opening time, s

ϵ energy per unit of wire cross-sectional area, J/mm^2

ω circular frequency ($\omega = 2\pi f$), rad/s

DESCRIPTION OF FACILITY

A detailed description of the Langley 6-inch expansion tube is given in reference 6 and a sketch showing the facility in the expansion-tunnel mode is given in figure 1.

The flow sequence for the expansion tunnel is shown in figure 2. The sequence begins with the rupture of the primary, or high-pressure, diaphragm separating the driver and driven sections. An incident shock propagates into the static test gas, and an expansion wave propagates into the driver gas. The shock ruptures the secondary diaphragm, and a second incident shock propagates into the static acceleration gas. An upstream-facing expansion wave moves into the test gas. The second incident shock propagates down the acceleration section and approaches the tertiary diaphragm separating the acceleration section from the evacuated nozzle section. To avoid a reflected shock, this tertiary diaphragm is opened just prior to the arrival of the second incident shock. Following the nozzle starting process, the test gas undergoes a steady expansion in the nozzle. A detailed discussion of the theoretical flow process for this facility is given in references 1 and 2.

DESCRIPTION OF DIAPHRAGM OPENER AND ASSOCIATED EQUIPMENT

Photographs of the various diaphragm-opener parts designed for the Langley expansion tunnel are shown in figure 3. The physical dimensions of the opener, as installed in the tube, are given in figure 4. The basic diaphragm opener consists of (1) a wire formed into three legs of parallel wires in proximity (see fig. 3(c)), (2) a diaphragm bonded to the wire, and (3) the energy system to power it.

The material for the diaphragm was poly(ethylene terephthalate) plastic (ref. 7). Diaphragm thicknesses of 6, 12, and 24 μm were chosen to cover the practical range of pressure differentials between the acceleration section and the nozzle. Diaphragms less than 6 μm thick could not be handled consistently without physical damage. The 6-μm- and 24-μm-thick diaphragms (without wire) can withstand pressure differentials of about 17 and 90 kPa, respectively, in the 15.24-cm-diameter tube. The 24-μm-thick diaphragm provides for greater pressure differentials than are presently expected but may be required for future application. This particular diaphragm material was chosen because of its availability, resistance to damage from normal handling, transparency to the microwave signal (used to measure shock velocities in the intermediate and acceleration sections), and high strength-weight ratio.

Enamel-coated copper magnet wire was formed to the desired configuration, bonded to the diaphragm with DuPont number 46950 cement, and cured in an oven at 400 K for 1/2 hour. The ends of the copper wire were connected to a coaxial electrical feedthrough when the diaphragm was installed in the retainer. The other two legs were supported by pins in the retainer (fig. 4). For the bench tests, cement was applied to both the wire and the diaphragm. When the cement was dry, the wire was placed on the diaphragm, and cement was flowed over the wire.

Laminated fiberglass with epoxy resin was used for the diaphragm retainer and as insulators for the coaxial electrical feedthrough. This material has high tensile strength, has good insulation characteristics, and is easily machinable. A cavity with a larger diameter than the tube was cut into the retainer in the plane of the wire (fig. 4). A duct-sealing putty was placed in the cavity to lessen the impact of the wires on the retainer as the wires were accelerated toward the circumference of the tube. The diaphragm was placed on the acceleration-section side of the wire opener so that the slightly higher pressure in the acceleration section would push the diaphragm against the wire during the operation of the tunnel. This allows the wires to pull the diaphragm into the cavity of the retainer.

The components of the expansion tunnel that accept the diaphragm opener were mounted on a bench for tests in which the opening process was photographed. Complete simulation was not achieved, since no provision was made to operate the opener either in an evacuated condition or with a pressure differential across the diaphragm.

A schematic of the electrical circuit for the operation of the diaphragm opener is shown in figure 5. Four RG8A/U coaxial cables in parallel connect the energy storage system to the wire opener. A triggerable air gap isolates the coaxial cables from the energy storage capacitors. These energy storage capacitors are each rated at 5000 V and 100 μF of capacitance; and one, two, or three capacitors are used to obtain the energy level selected.

At the voltages required for operating the diaphragm opener, techniques normally used at higher voltages for triggering an air gap proved to be unreliable. This led to the development by Wilfred J. Friesen, of the Langley Research Center, of a very reliable circuit for triggering the air gap at voltages as low as 500 V. The gap was set at approximately 0.3 cm, which normally will break down at about 10 000 V in air at atmospheric pressure. The system dumps about 10 J of energy into the trigger from a triggerable circuit that is isolated from the main energy storage system by means of an RG58C/U coaxial cable used as a transformer.

INSTRUMENTATION

The physical opening of the diaphragm during bench tests was recorded with the 35-mm high-speed framing camera described in reference 8. The diaphragm opener was backlighted by use of a 1.5-ms-duration xenon flash tube as a light source. The camera was focused directly on the opener and was run at a speed of approximately 67 000 frames per second. A photomultiplier was used to detect the initial illumination from the light source, and the signal from this photomultiplier was used to trigger the energy storage system. Typical photographs obtained by this technique are shown in figure 6. The time from one frame to the next is 14.6 ± 0.4 μs. The time to open the diaphragm was assumed to be the time from the first frame to the frame indicating that the wire opener velocity was zero. The accuracy of determining the opening times was approximately two to three frames, or about 30 to 50 μs. The extent to which the wire opener was clear of the tube diameter was determined primarily from the photographs and additionally from visual examination of the diaphragm after each test.

The voltage on the capacitors of the energy storage system and the current in one of the four coaxial cables to the wire opener were monitored and recorded with oscilloscope-camera combinations. A Rogowski coil was used to monitor the rate of change of the current. The output of this coil was integrated to obtain the time history of the current. The oscilloscopes were triggered by the signal from the photomultiplier monitoring the light source. Typical records of the time histories of the voltage, the output voltage of the Rogowski coil, and the current are shown in figure 7.

To determine the effect of a tertiary diaphragm on the flow conditions at the nozzle entrance, a seven-probe pitot-pressure survey rake was installed at the nozzle entrance location. The probes were alined in a vertical plane and were 33 cm downstream of the tertiary diaphragm location. The probe spacing was 1.91 cm, and the center probe was 0.64 cm above the center line of the nozzle. Pitot pressure was measured by means of a miniature piezoelectric (quartz) transducer in conjunction with a charge amplifier. The output was recorded with an oscilloscope and camera.

OPERATIONAL THEORY OF DIAPHRAGM OPENER

The operation of the diaphragm opener is based on the principle of magnetic interaction between currents in adjacent conductors. This was experimentally studied by Ampere, who found that the force exerted on the conductors depended directly on the product of the currents and inversely on the distance between the wires carrying the current. Since the wires begin to move apart as soon as current flows, the practical application of Ampere's results to the present problem requires a buildup of current in the shortest possible time. Releasing the energy stored in capacitors into an inductive-resistive load gives an increase in current with time that is limited mainly by the inductance of the circuit. Particular efforts were made to minimize the inductance of the total circuit.

The simplest configuration for the wire opener would be two parallel wires on the diameter of the tube. Since each wire would ideally lie on one-half the circumference when opened, each wire would have to increase in length from an initial length of 1 diameter to a final length of $\pi \;\; 2$ diameters. Preliminary tests indicated that the wires could not withstand this increase in length without breaking and thereby adding contamination to the flow. To minimize this increase in length and thereby reduce the probability of breaking the wire, a three-loop configuration was examined in reference 5 and was utilized in the present tests. This wire configuration increases the initial length to about 3 diameters, and thus only about 5-percent increase in length occurs during opening.

TEST CONDITIONS

Parameters varied during the bench tests were the thickness of the diaphragm, the diameter of the wire used as the opener, and the total energy and voltage of the energy storage system.

As mentioned previously, the thickness of the diaphragm was chosen to cover the range of pressure differentials expected to be encountered in the operation of the expansion tunnel. Three sizes of enamel-coated copper magnet wire were used for the wire opener: 1.448-mm diameter (15 AWG); 1.143-mm diameter (17 AWG); and 0.813-mm diameter (20 AWG), where AWG is American Wire Gage.

The capacitance of the energy storage system was varied by using one, two, or three capacitors. At each capacitance value, the voltage was varied to change the energy level of the energy storage system. The range of operating conditions is given in the following table:

Wire diameter		Diaphragm thickness, μm	Number of capacitors	Voltage, V	Energy, J
mm	AWG				
1.448	15	6	3	1400 to 2200	295 to 720
↓	↓	6	2	1800 to 2800	325 to 785
↓	↓	6	1	2500 to 3600	320 to 650
↓	↓	12	2	1800 to 2600	325 to 675
↓	↓	12	1	3300 to 3500	540 to 620
↓	↓	24	3	1800 to 2200	485 to 720
↓	↓	24	2	1800 to 2600	325 to 675
1.143	17	6	2	1400 to 2200	195 to 485
↓	↓	6	1	2200 to 2500	235 to 320
.813	20	6	2	1400 to 1800	195 to 325
↓	↓	6	1	2000 to 2300	200 to 265

Upon completion of bench tests, the diaphragm opener was installed in the expansion tube at the tertiary diaphragm location (fig. 1) and the seven-probe pitot-pressure rake was installed at the nozzle entrance station (33 cm downstream of the tertiary diaphragm location). Test gases used in this study were air and CO_2. The acceleration gas was the same as the test gas in each case. Initial pressures were 3447 Pa for the test gases, 3.1 Pa for the CO_2 acceleration gas, 6.7 Pa for the air acceleration gas, and 0.01 Pa in the nozzle. Unheated helium was used as the driver gas, and a driver pressure of 33 MPa produced test gas velocities of approximately 5 km/sec in the acceleration section.

With the opener installed in the facility, statistical data were obtained on the opening characteristics of the diaphragm under evacuated static (no-flow) conditions. The acceleration tube and the nozzle tank were evacuated to approximately 20 and 0.1 Pa, respectively. During the course of these statistical tests, the method of bonding the wire to the diaphragm was changed. Both the first bonding method, described previously, and the second bonding method are shown in sketch (a).

Sketch (a)

In the first method of bonding, the cement added strength to the diaphragm between the wires and thereby increased the force necessary to separate the wires. In addition, some of the cement was not pulled out of the flow path, but remained to add contamination to the flow. In the second method, the diaphragm was preglued, and then the wire was placed on the diaphragm and cement applied along the outer edge of the wire. Care was exercised to minimize the amount of cement used and to restrict the cement to the region along the outer edge of the wire.

RESULTS AND DISCUSSION

Diaphragm opening times for the bench tests were determined from photographs of each opening, one example of which is shown in figure 6. Figure 8 illustrates the variation in opening time with changes in both initial energy of the energy storage source and wire diameter. For these data, the diaphragm thickness was 6 μm and the wire was cemented to the diaphragm by the first method. (See "Test Conditions.") For 17 and 20 AWG wires, the forces involved caused breakage of the wires when a certain energy level was exceeded. Determination of the energy level at which breakage occurs is important, since such a failure during operation of the tunnel could prove harmful. The wires would probably be swept downstream with the flow and cause damage to both the nozzle entrance and the model in the nozzle test section.

The data of figure 8 are replotted in figure 9, where the diaphragm opening time is shown as a function of energy per unit of wire cross-sectional area. A second-order curve fit to the data of figure 9 gives the relation

$$t_o = 1952.7 - 3990.1\epsilon + 3249.4\epsilon^2 \tag{1}$$

where t_o is in microseconds and ϵ is in kilojoules per millimeter squared. The data of figure 9 show that the maximum value of energy per unit area that the 17 and 20 AWG wires could absorb is approximately 0.3 to 0.4 kJ/mm^2. The energy was not increased sufficiently to cause breakage of the 15 AWG wire. In this energy range, opening times were 800 to 1000 μs.

Not all of the energy stored in the capacitors is delivered to the wire, since a portion goes into heat losses due to Joule heating of the resistive components in the circuit. To determine what portion of the initial energy stored in the capacitors is delivered to the wire, two methods were used to analyze a particular test for which good photographs and good oscilloscope records were obtained. In the first method measurements made of the current and the voltage during the test were used. (Typical oscilloscope records of current and voltage traces were shown previously in fig. 7.) For the particular test studied, the test conditions were the 15 AWG wire, the 6-μm-thick diaphragm, and two capacitors giving an initial energy of 485 J each. The effective values of inductance and resistance of the circuit were determined from the measured values of current and voltage, in conjunction with the relations

$$\omega = \left(\frac{1}{LC} - \frac{R^2}{4L^2}\right)^{1/2} \tag{2}$$

and

$$\frac{R}{2L} = \frac{1}{t_2 - t_1} \ln \frac{I_2}{I_1} \tag{3}$$

The subscripts 1 and 2 indicate successive maximums in measured current from time histories of the current. (For example, see fig. 7.) The values of resistance and inductance determined from these relations were approximately 30 mΩ and 1 μH, respectively. The resistance of the 15 AWG wire was measured as 6 mΩ. Resistances of the other wires were 9 mΩ for the 17 AWG wire and 18 mΩ for the 20 AWG wire. These resistances were measured with a millivoltmeter, a precision ammeter, and a current source. The remainder of the resistance in the circuit was in the components and the connections of the various components. By the first method, the Joule heating (I^2R value) was computed to be about 86 percent of the energy stored in the capacitor.

In the second method, the displacement of the wires with time was measured by use of the photographs of the diaphragm opening. For this test, the velocity of the wire reached a constant value of 168 m/s in approximately 30 μs. At this velocity, the kinetic energy for the complete wire opener was computed to be about 13 percent of the energy stored in the capacitor, which was in good agreement with the available energy determined by the first method.

The various thicknesses of diaphragm material tested had little observable effect on opening time. However, the 24-μm-thick diaphragm was stiffer and ruptured into many small pieces, rather than opening cleanly with the wire. This effect is illustrated in figure 10(a), which shows that the diaphragm has become unglued from the retracted wire in places, leaving a triangular tab of diaphragm in the opening of the tube and pieces of diaphragm missing. In figure 10(b), the thinner diaphragm has remained attached to the wire; however, it has retracted into a roughly triangular pattern formed by the folding of the three segments. Thus, although the thinner diaphragm material showed opening characteristics superior to those of the thicker material, folds of the diaphragm usually remained in the flow path near the wall and represented an obstacle to the flow.

For the wire diameters examined, the 15 AWG wire was easier to mold into the desired shape, adhered to the diaphragm somewhat better than the smaller wires, and could absorb more energy before failure than could the smaller wires. This latter property allowed slightly shorter opening times for the 15 AWG wire than for the 17 or 20 AWG wire. Hence, for the parameters tested, best opening characteristics (opening time and cleanness of opened area) may be realized with the 6-μm-thick diaphragm and the 15 AWG wire.

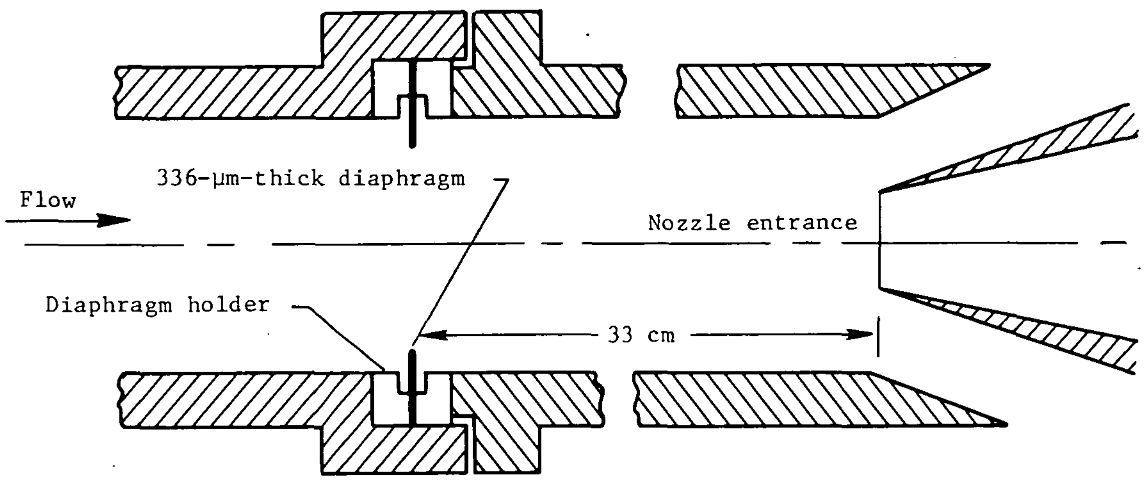
The diaphragm opener was installed in the expansion tube, but before expansion tube tests were undertaken, a number of diaphragm openings were performed under evacuated, no-flow conditions. The diaphragm thickness was 6 μm, the wire was 15 AWG, and the first method of bonding was used. (See "Test Conditions.") These no-flow tests revealed that in approximately one-half of the openings the wire removed the diaphragm from the center core of the tube and left a triangular pattern at the tube walls as in figure 10(b). In the other half of the openings, the wire separated from the diaphragm and left triangular-shaped tabs of the diaphragm within the tube as in figure 10(a). This led to the development of the second method of bonding the wire to the diaphragm, described previously in "Test Conditions." Although the second method improved the probability of obtaining a "clean" opening, roughly one of every three openings was characterized by tabs of the diaphragm remaining in the tube.

The effect of a flow-opened diaphragm on the pitot pressure in CO_2 test gas at the nozzle entrance station, 33 cm downstream of the diaphragm location, is shown in figure 11. In figure 11(a), the diaphragm holder was replaced by a steel ring with the same inside diameter as the tube so as to provide continuity in the tube diameter; in figure 11(b), a 6-μm-thick diaphragm (no wires) was installed at the tertiary diaphragm station. As observed from figure 11, both the magnitude and the time variation of the pitot pressure have been altered adversely by the use of a flow-opened diaphragm. This detrimental effect on pitot pressure for the flow-opened diaphragm is attributed to the reflection of the second incident shock from the diaphragm. The effect of this reflected shock was observed on the wall static pressure just upstream of the diaphragm in the present study and also in the study of reference 5. The results of figure 11 demonstrate the need to open the tertiary diaphragm prior to flow arrival.

The effect of the electromagnetically opened diaphragm on the pitot pressure in air as a test gas at the nozzle entrance location is shown in figure 12. As in figure 11(a), the results of figure 12(a) were obtained with no discontinuity in tube diameter at the tertiary station; the results of figure 12(b) were obtained with the self-opening diaphragm. Comparison of figures 12(a) and 12(b) shows that the magnitude of the pitot pressure, particularly near the center line, has been altered (increased), but that the time variation of pitot pressure has been only moderately affected. The increase in pitot pressure was assumed to be caused by a disturbance at the wall resulting from the diaphragm opening into a triangular pattern. This disturbance most probably results in a complex oblique shock system being formed upstream of the pitot-pressure probe and affects the pitot pressure near the center line at a distance 33 cm downstream of the disturbance.

The pitot pressures shown in figures 11(a) and 12(a), with no diaphragm and a smooth wall at the diaphragm station, were considered the standard against which other pitot-pressure time histories were judged.

A series of tests was run to determine whether the disturbed pitot pressure could be attributed to incomplete diaphragm opening. Partial blockage at the diaphragm station was simulated by a ring of diaphragm material mounted in the diaphragm holder. Specimens 336 μm thick with different diameter center portions removed (see sketch (b)) were tested under the same conditions as those for air as the test gas. Figure 13 shows the



Sketch (b)

effect on the pitot pressure at the nozzle entrance when a 13.97-cm-diameter disk is removed from the center of the diaphragm to leave a 0.635-cm protuberance on the radius of the tube wall. The magnitude of the pitot-pressure disturbance near the center is very similar to that for the electromagnetically opened diaphragm. The results of this test and the statistical no-flow tests support the assumption that under flow conditions the electromagnetically opened diaphragm leaves material protruding into the flow and thus results in degradation of nozzle-entrance flow quality.

The results of the tests reported herein led to the redesign of a diaphragm opener for future use in the expansion tunnel. A sketch of this diaphragm opener is shown in figure 14. The diaphragm diameter (unsupported) has been increased from 17.84 to 26.64 cm, and the diaphragm has been relocated very close to the nozzle entrance. Both these modifications are expected to reduce the possibility of the diaphragm and holder causing disturbances that will influence the test gas flow entering the nozzle. The entrance to the cavity has been rounded and widened to increase the probability of the wire entering the cavity.

CONCLUDING REMARKS

An experimental study was made to determine the opening characteristics of an electromagnetically opened diaphragm for the Langley expansion tunnel. This diaphragm consisted of a polyester film bonded to a preformed wire and was opened by passing a current pulse (capacitor discharge) through the wire. Tests were performed in which the opening times of the 15.24-cm-diameter diaphragm were determined from photographs taken with a high-speed framing camera. Both sides of the diaphragm were at atmospheric pressure for these tests. The effects of diaphragm thickness, wire diameter, wire bonding technique, and voltage and energy level on the opening characteristics were examined. Cleanness of the opened area was studied not only during bench tests, but also when the diaphragm was installed in the expansion tube and placed under vacuum.

For both bench tests and tests under a vacuum, the diaphragm opened into a triangular pattern at the periphery of the tube. The bench tests indicated that there was no detectable effect of diaphragm thickness on the opening time for the thickness range tested. However, the thinner diaphragms opened cleaner than the thickest diaphragm. Best opening characteristics were obtained for values of energy per unit cross-sectional area of the wire from 0.3 to 0.4 kJ/mm^2. The bench tests showed that the minimum opening time for the range of variables tested was approximately 800 to 1000 μs. The reliability of operation of the electrical discharge was increased considerably by the use of a very reliable circuit developed for triggering air gaps at low voltages.

Pitot-pressure time histories measured at the nozzle entrance station, 33 cm downstream of the diaphragm location, showed that pitot pressures were unacceptable for the condition in which the diaphragm was opened by the flow. Although the flow quality with the electromagnetically opened diaphragm was greatly improved over that with the flow-opened diaphragm, the pitot-pressure surveys indicated some disturbance which was not present for the no-diaphragm tests. The reasons for this are believed to be primarily the nature of the opening (into a triangular pattern within the tube diameter) and the distance of the diaphragm upstream of the nozzle entrance. Therefore, a redesigned opener is proposed which allows the triangular pattern of the diaphragm to retract clear of the tube opening, and places the diaphragm as close as possible to the nozzle entrance.

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June 21, 1976

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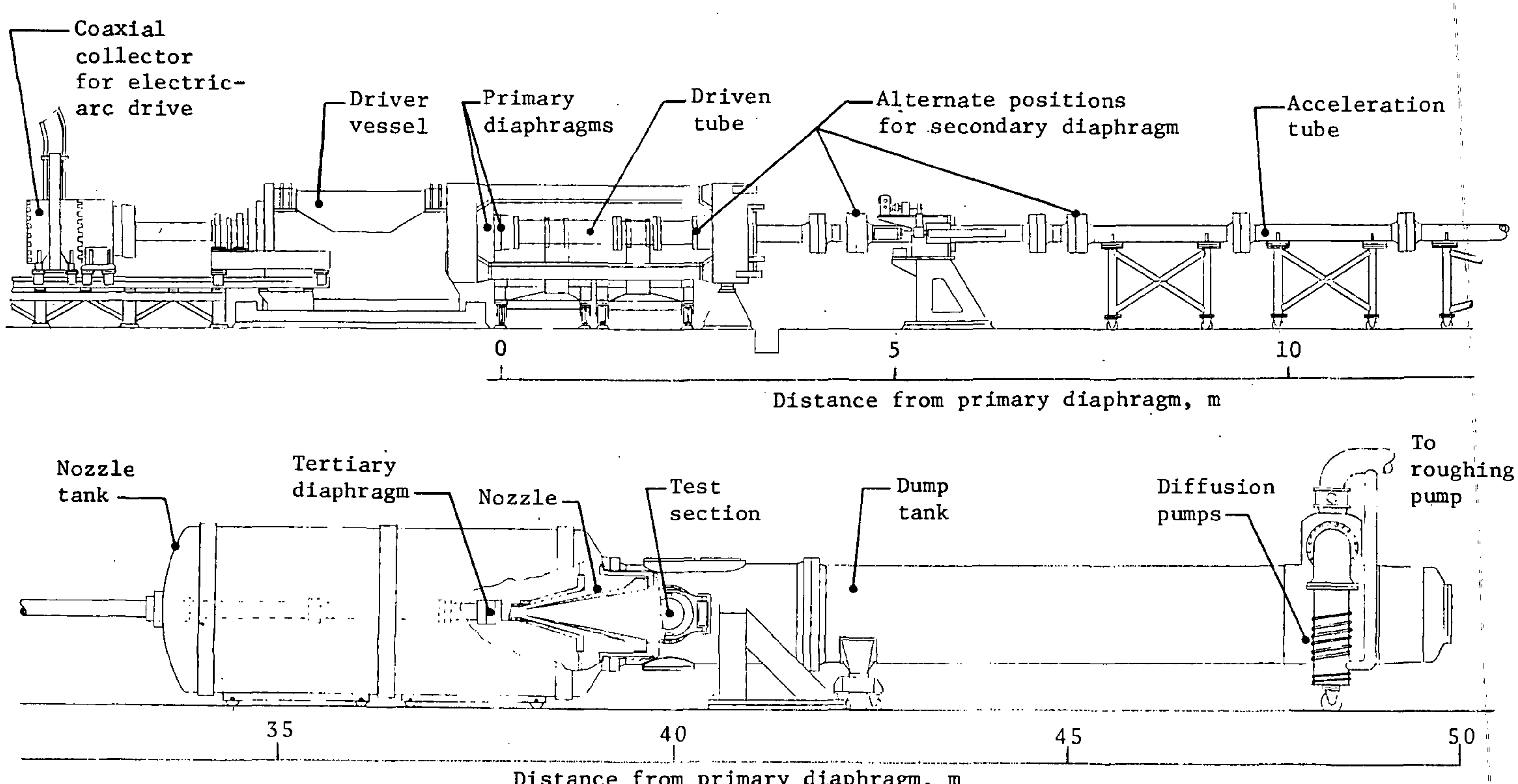


Figure 1.- Sketch of Langley expansion tunnel.

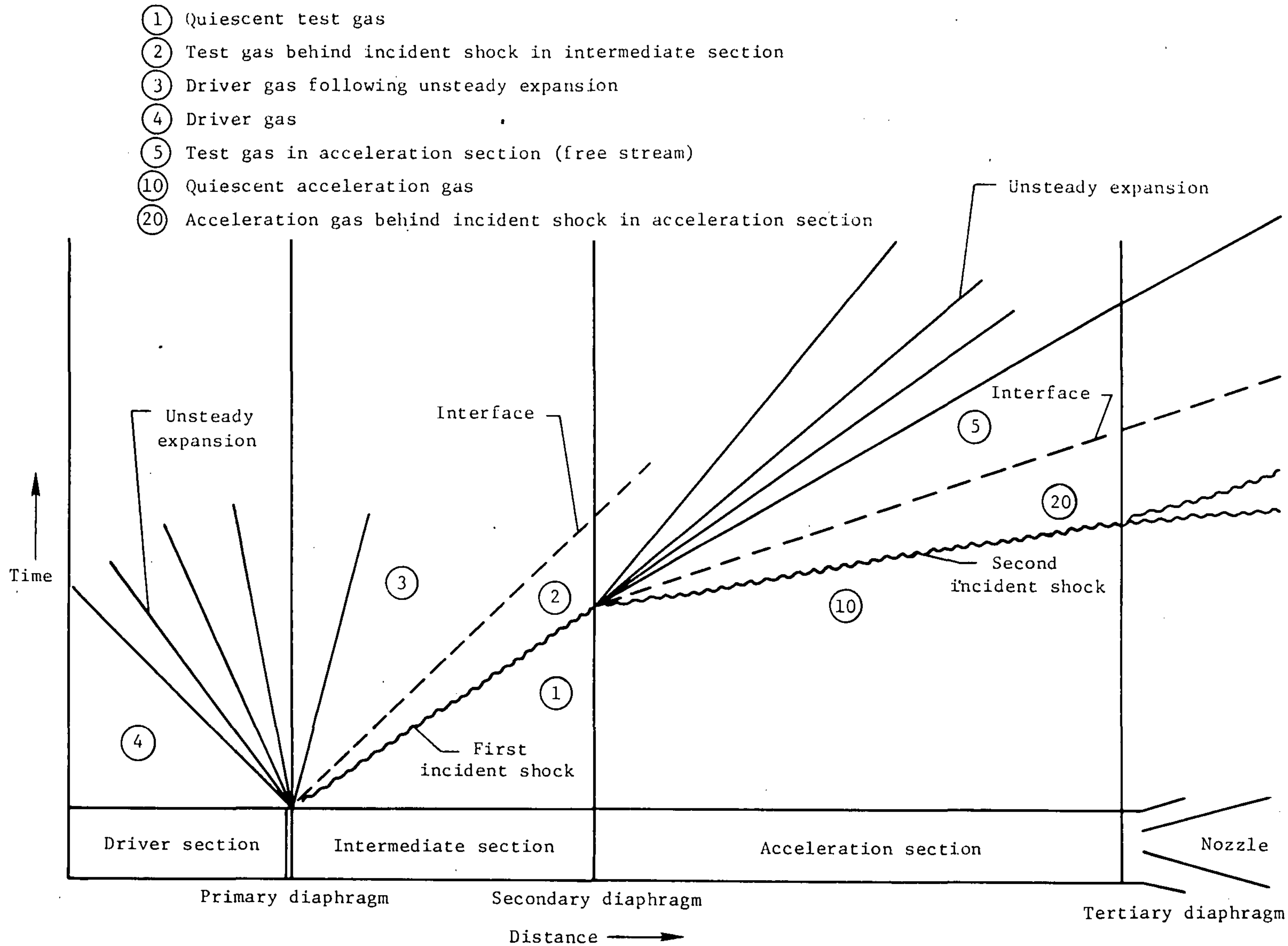
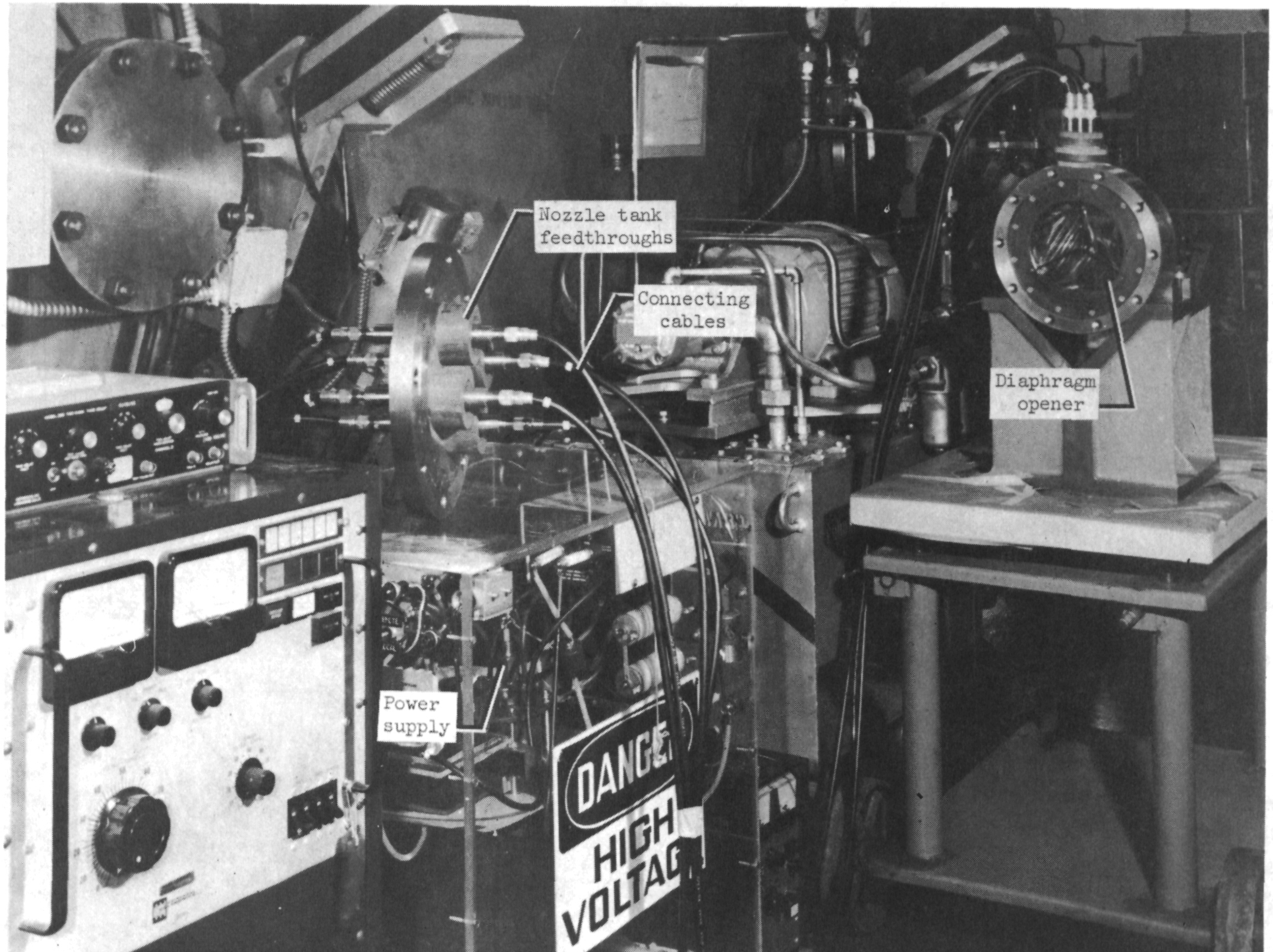


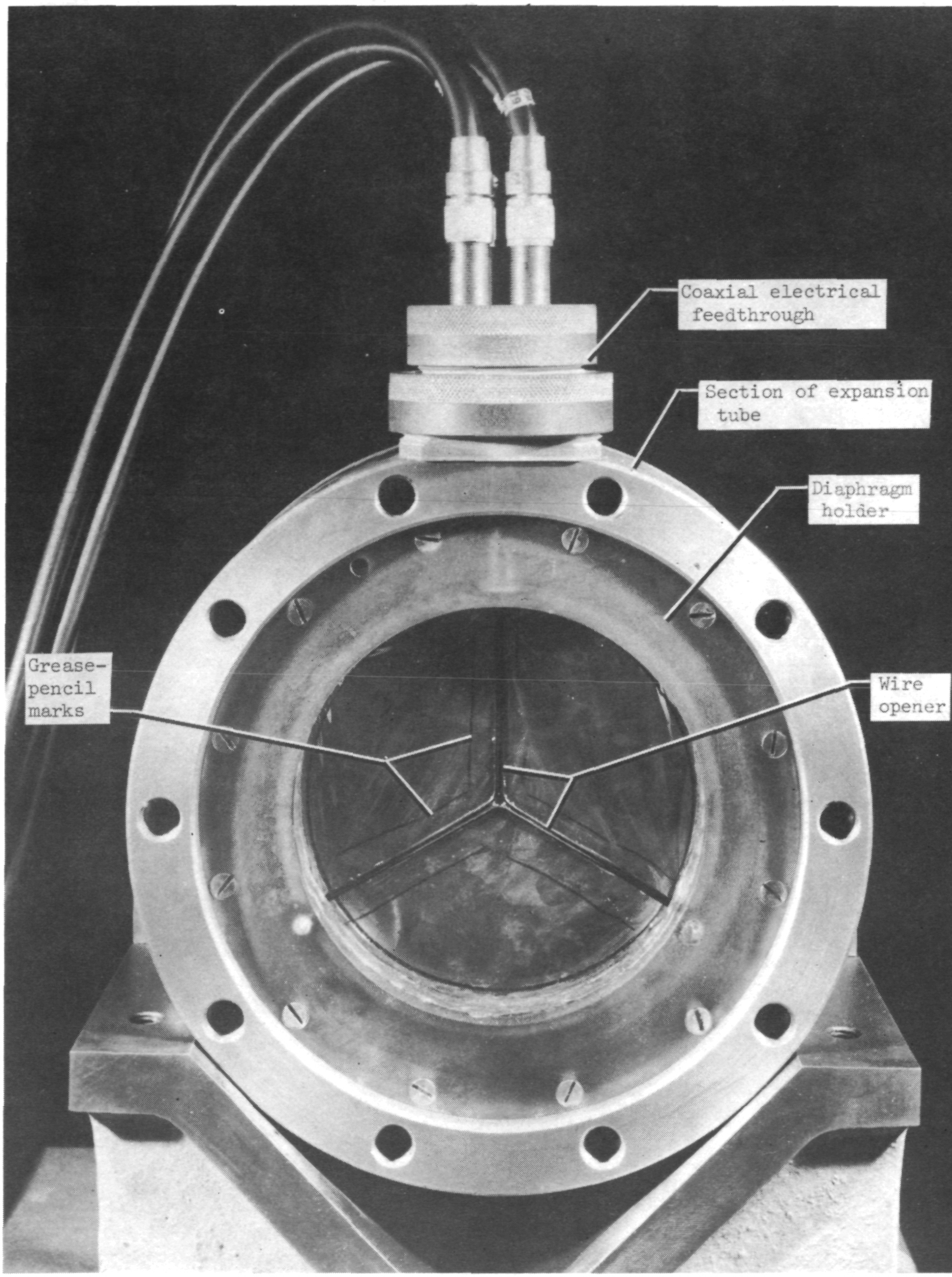
Figure 2.- Schematic diagram of expansion-tunnel flow sequence.



L-75-5326.1

(a) Opener, power supply, and connecting cables.

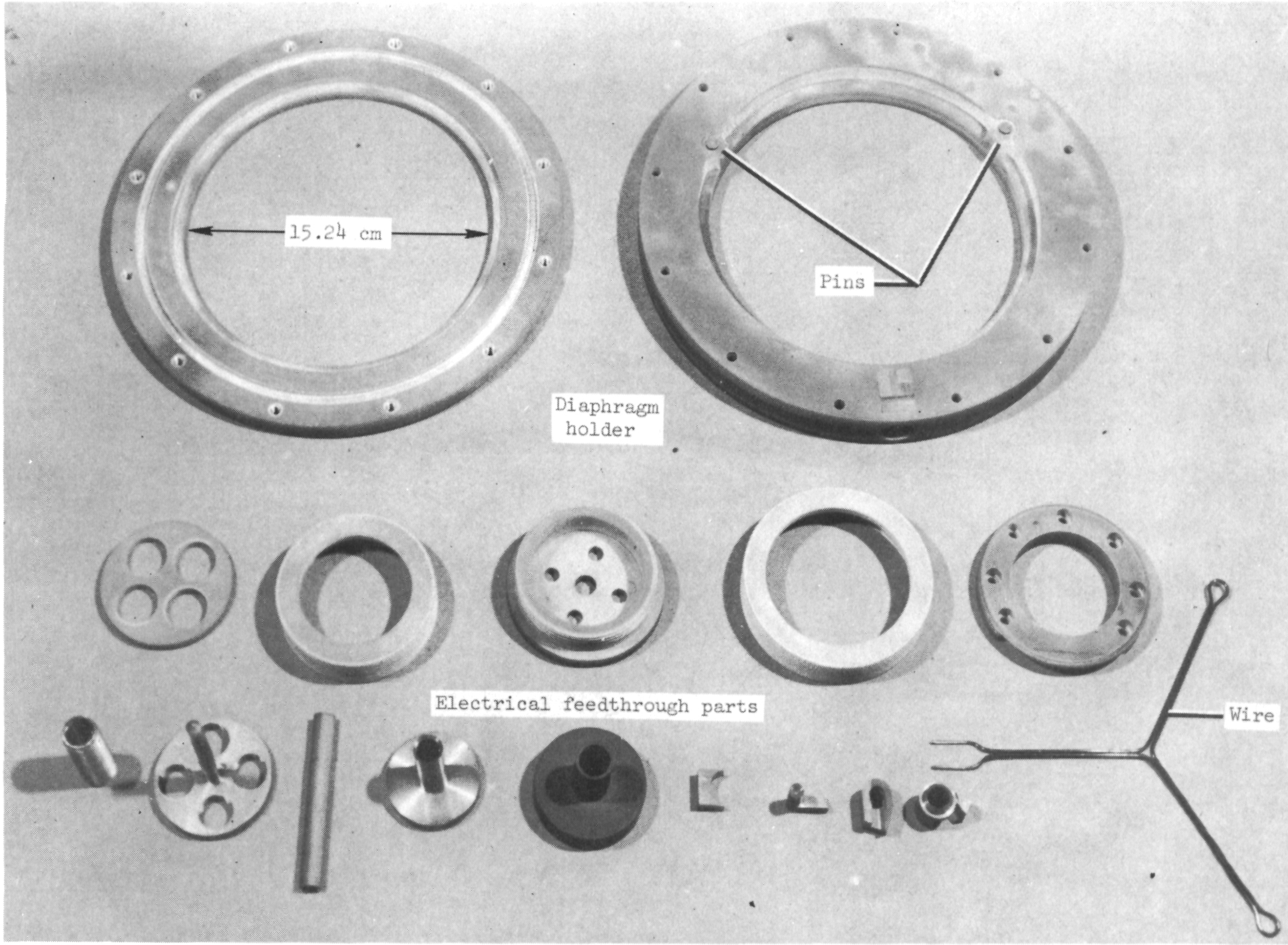
Figure 3.- Photographs of diaphragm opener.



L-75-5328.1

(b) Diaphragm opener installed in a section of expansion-tube wall.

Figure 3.- Continued.



L-75-5325.1

(c) Individual parts of diaphragm opener and electrical feedthrough.

Figure 3.- Concluded.

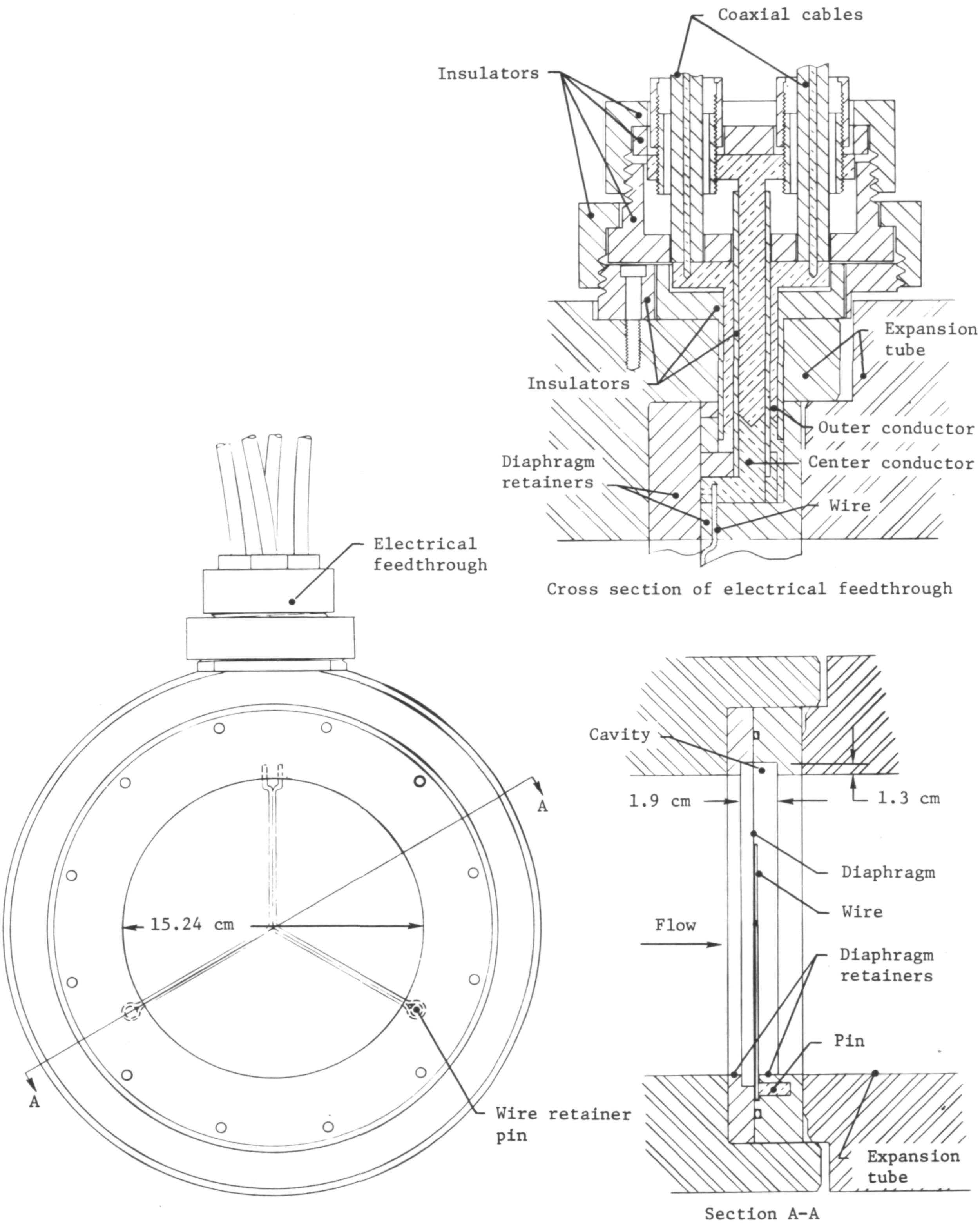


Figure 4.- Sketch of diaphragm opener.

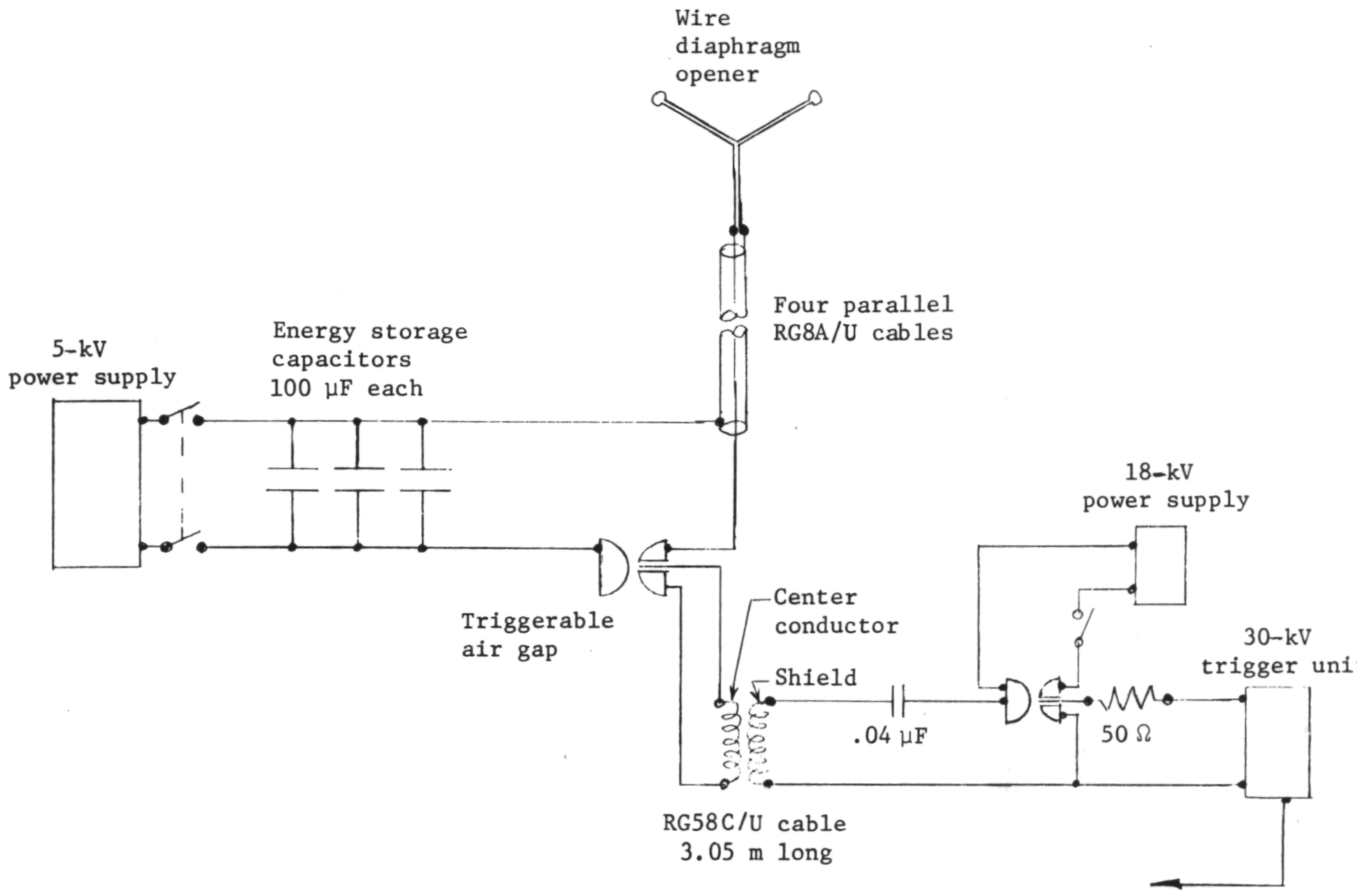
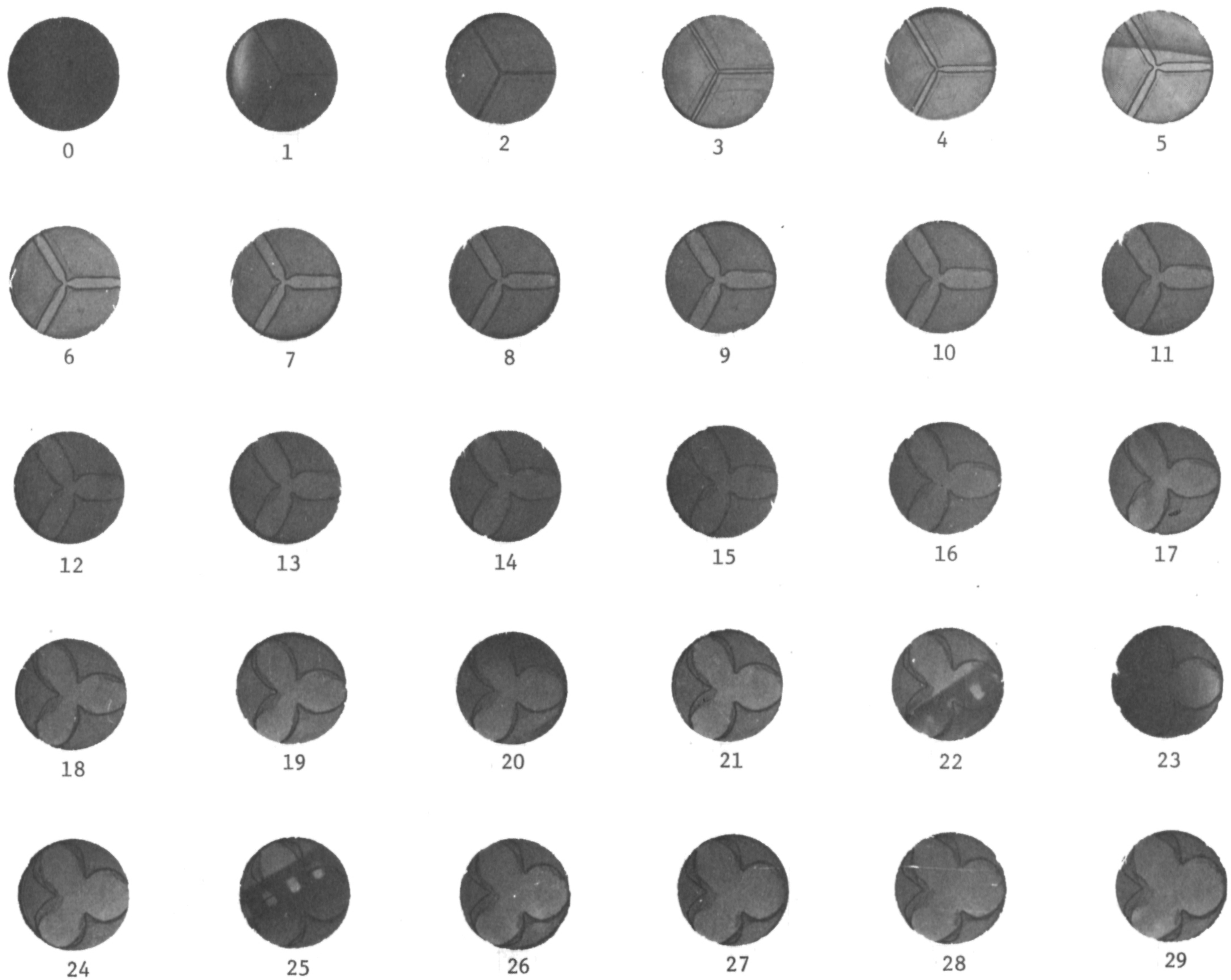


Figure 5.- Schematic diagram of electrical circuit for wire diaphragm opener.



L-76-224

Figure 6.- Photographs of typical diaphragm opening. 15 AWG wire; 12-μm-thick diaphragm; 0.44 kJ/mm^2; 14.6 μs between frames.

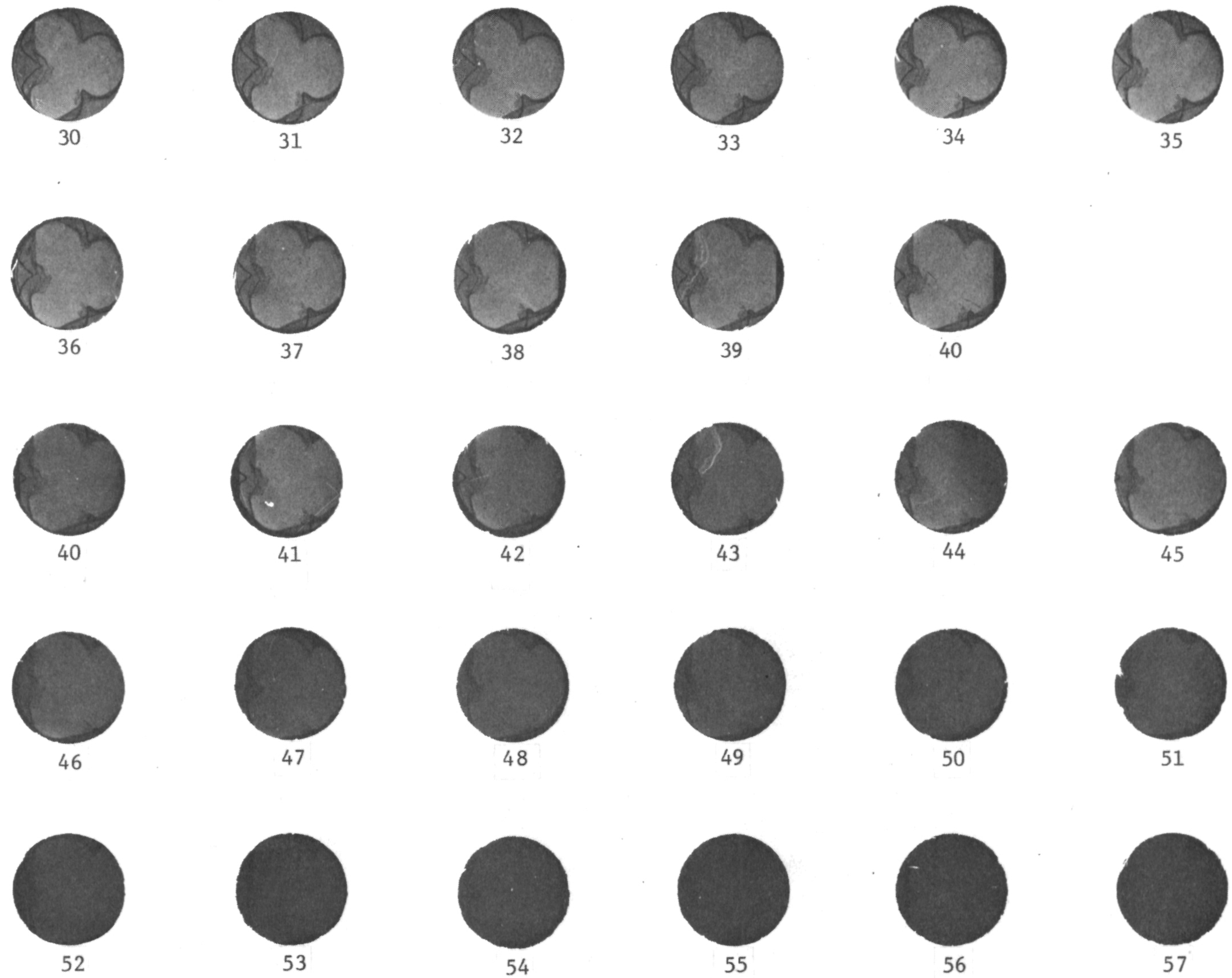
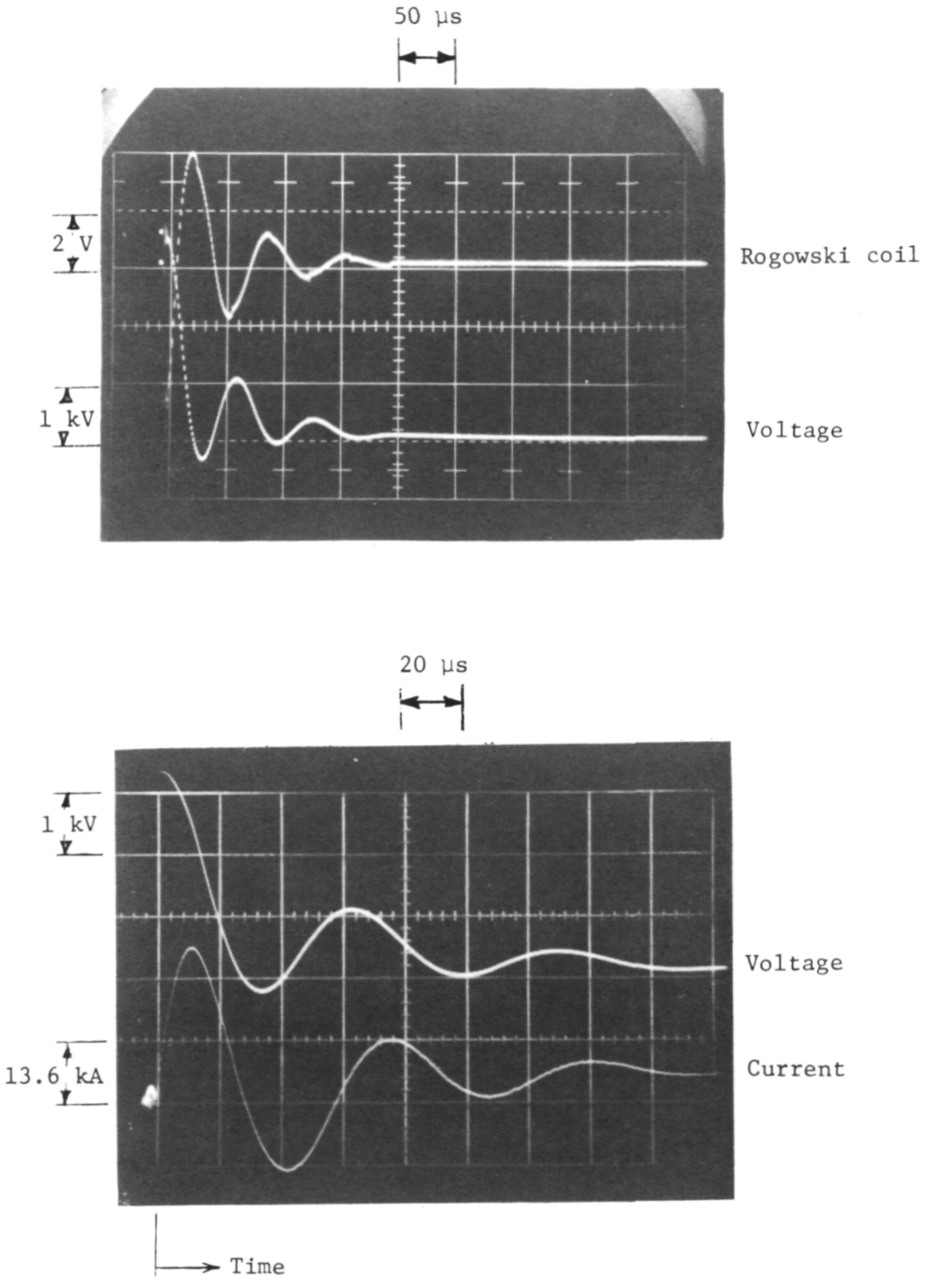


Figure 6.- Concluded.



L-76-226

Figure 7.- Oscilloscope records of voltage and current time histories. 15 AWG wire; E = 485 J; two capacitors.

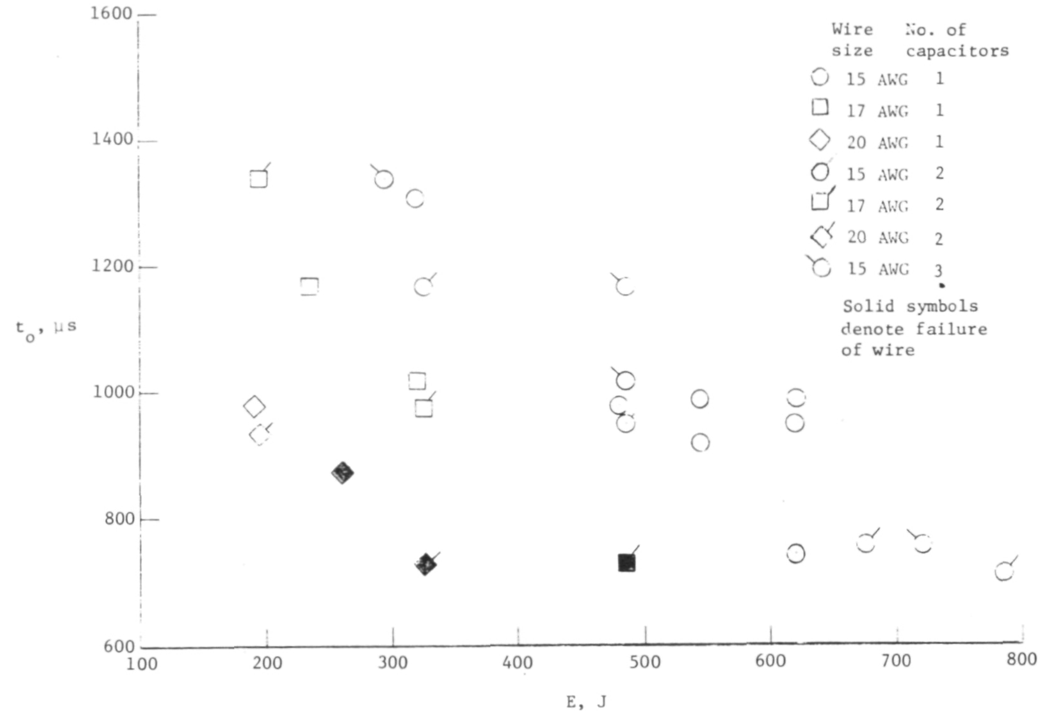


Figure 8.- Opening times as a function of initial energy of energy storage capacitors for 6-μm-thick diaphragm.

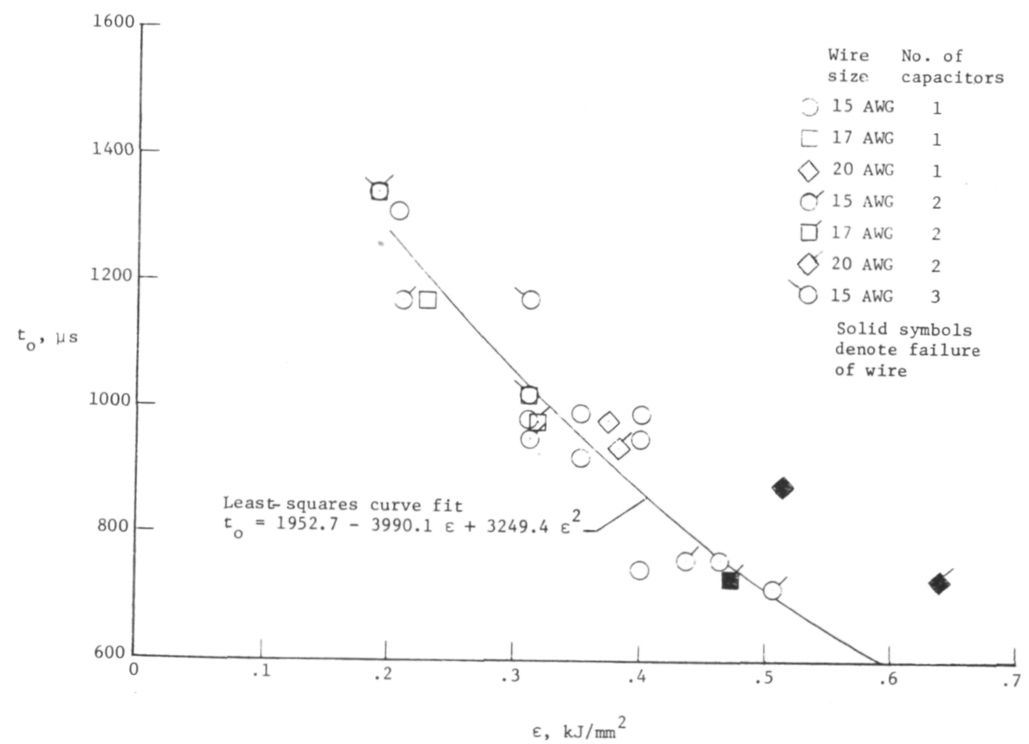
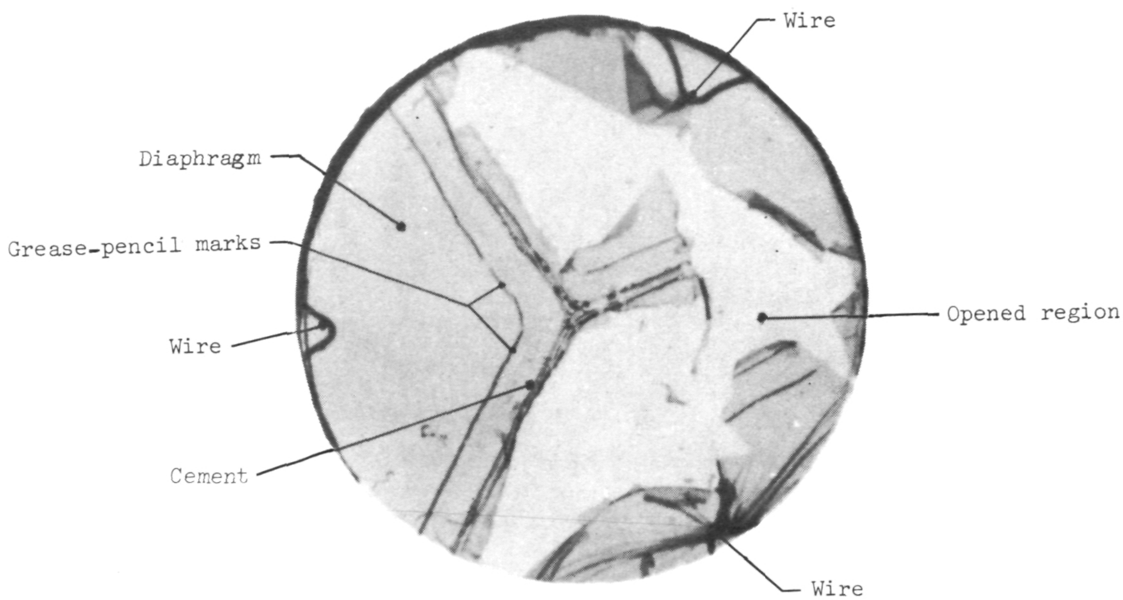
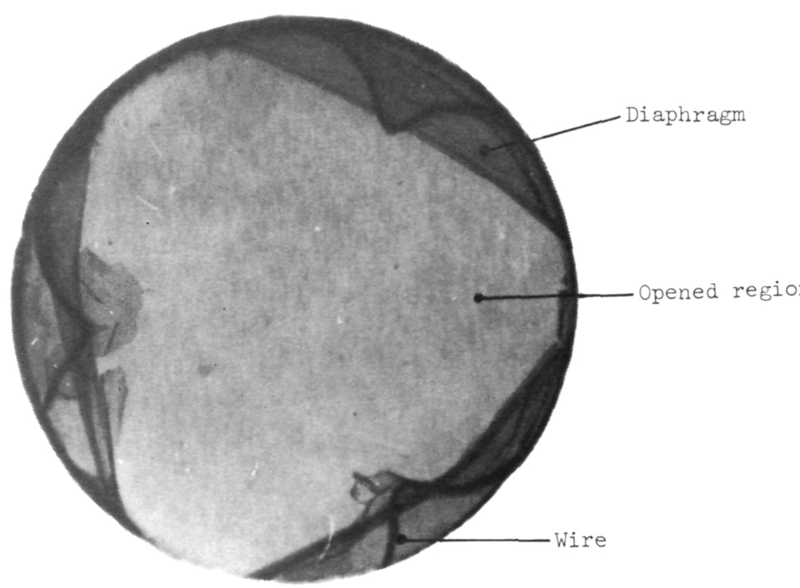


Figure 9.- Opening times as a function of initial energy of storage capacitors per unit cross-sectional area of wires for 6-μm-thick diaphragm.



(a) 24-μm-thick diaphragm. (Time of photograph: about 1300 μs from first frame.)



(b) 6-μm-thick diaphragm.

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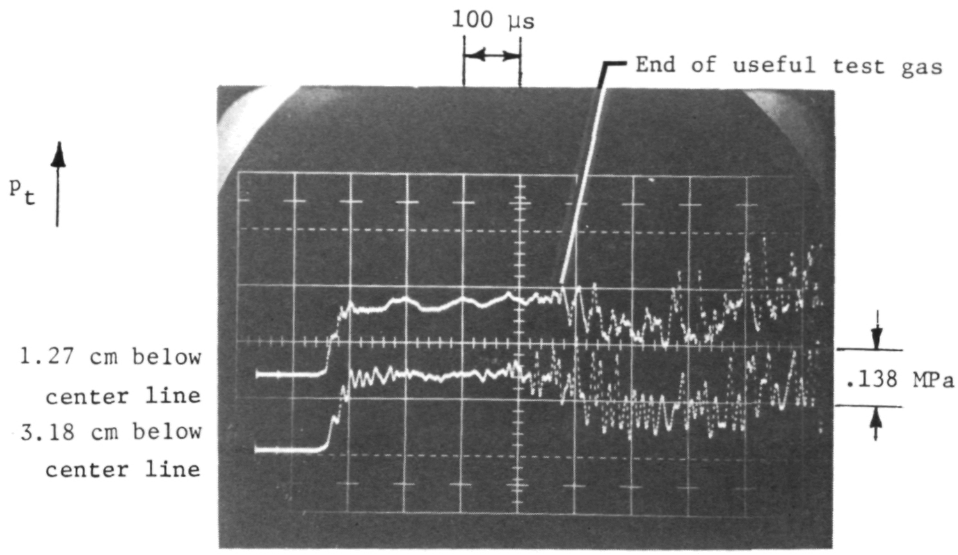
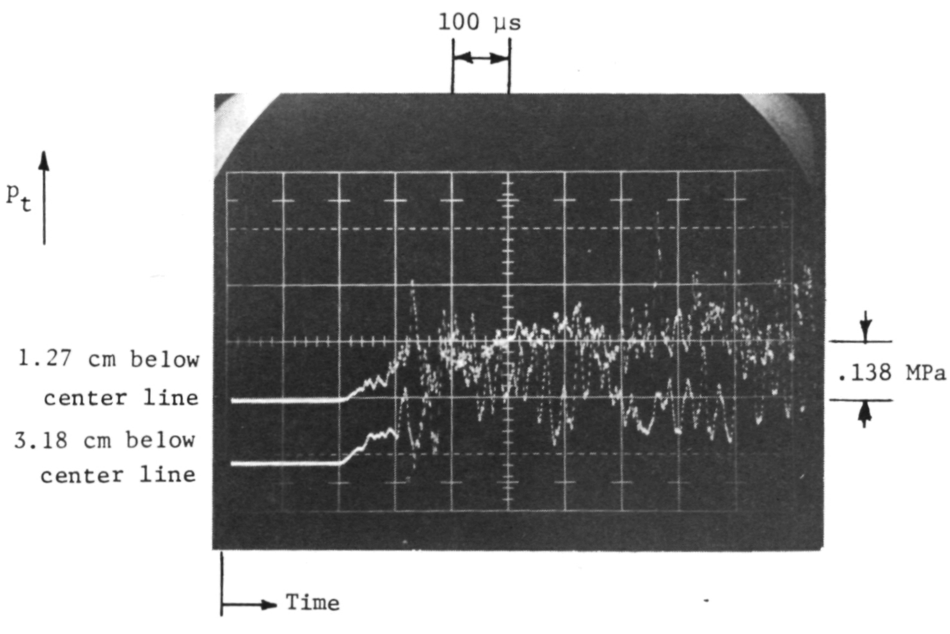
Figure 10.- Comparison of opening cleanness of 24-μm-thick and 6-μm-thick diaphragms.



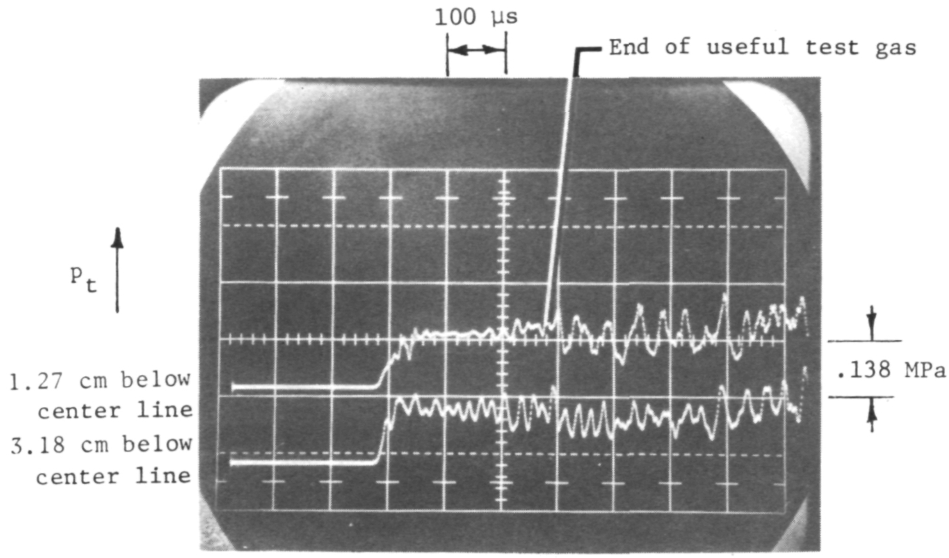
(a) No diaphragm.



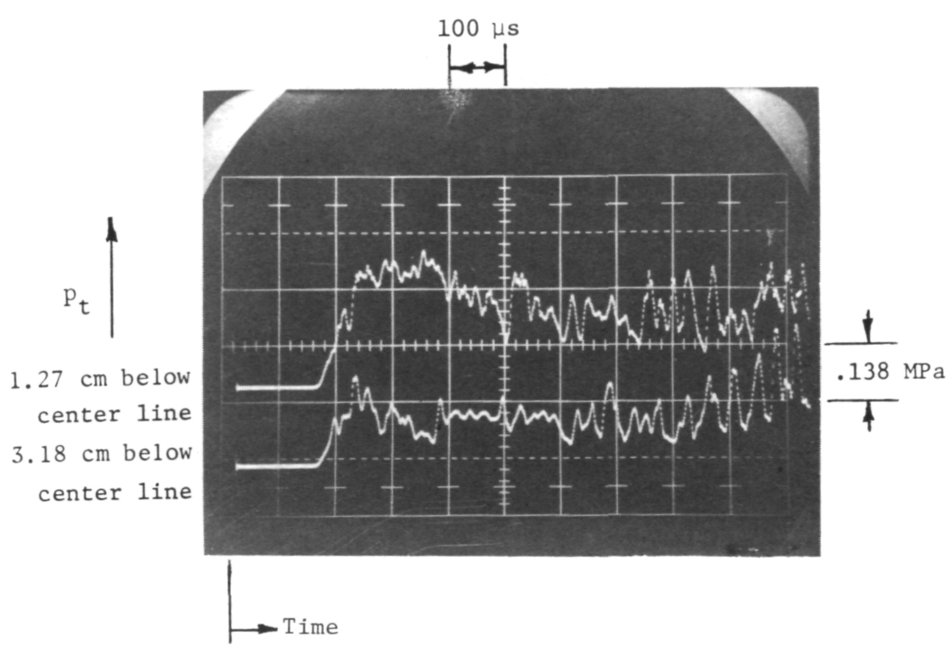
(b) Diaphragm opened by flow.

L-76-228

Figure 11.- Oscilloscope records of pitot-pressure probes located at nozzle entrance for tests with no tertiary diaphragm and with flow-opened tertiary diaphragm. Test gas is CO_2.



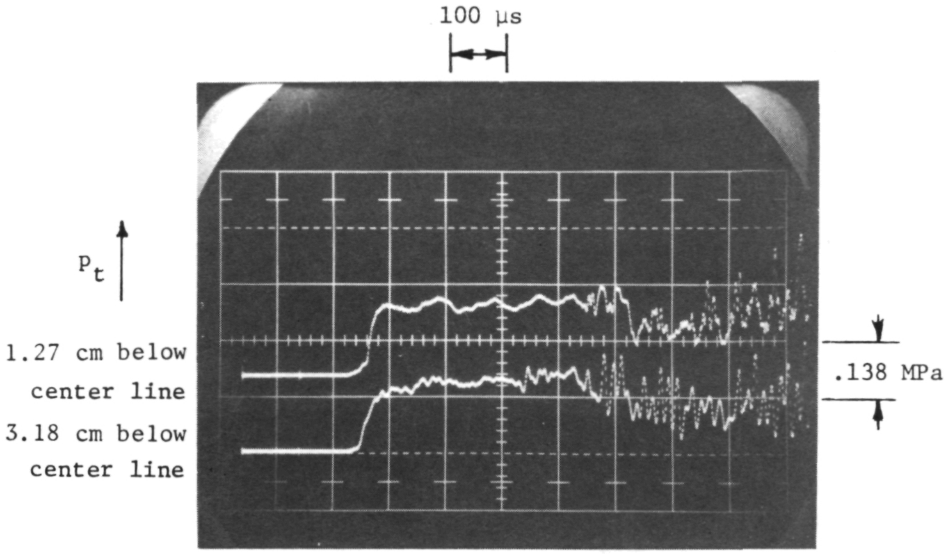
(a) No diaphragm.



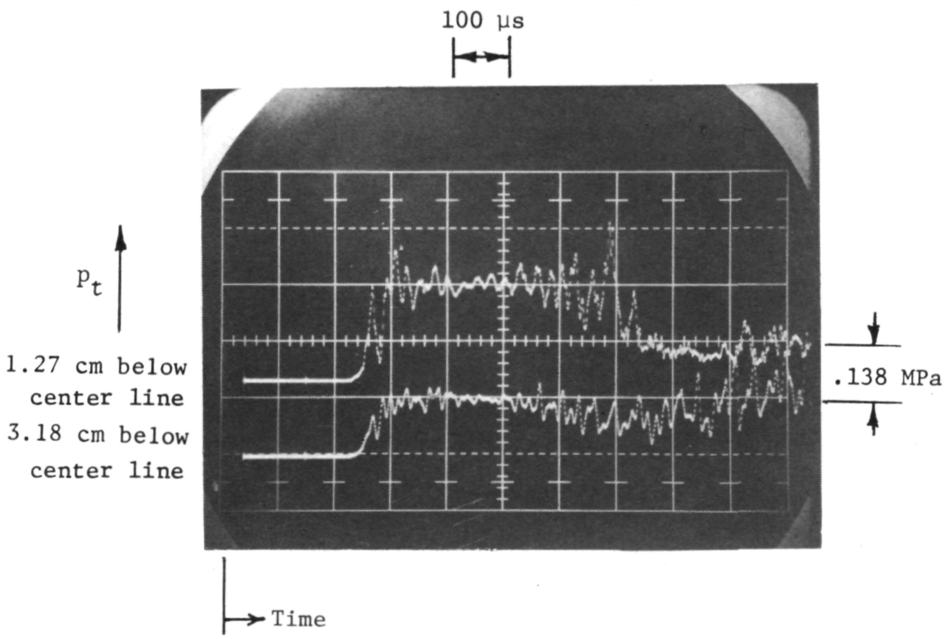
(b) Electromagnetically opened diaphragm.

L-76-229

Figure 12.- Effect of electromagnetically opened diaphragm on pitot pressure at nozzle-entrance station (33 cm downstream of tertiary diaphragm). Test gas is air.



(a) Diaphragm with 15.24-cm-diameter opening (no protuberance).



(b) Diaphragm with 13.97-cm-diameter opening (0.635-cm protuberance).

L-76-230

Figure 13.- Effect of protuberance at tertiary-diaphragm station on pitot pressure at nozzle-entrance station. Test gas is air.

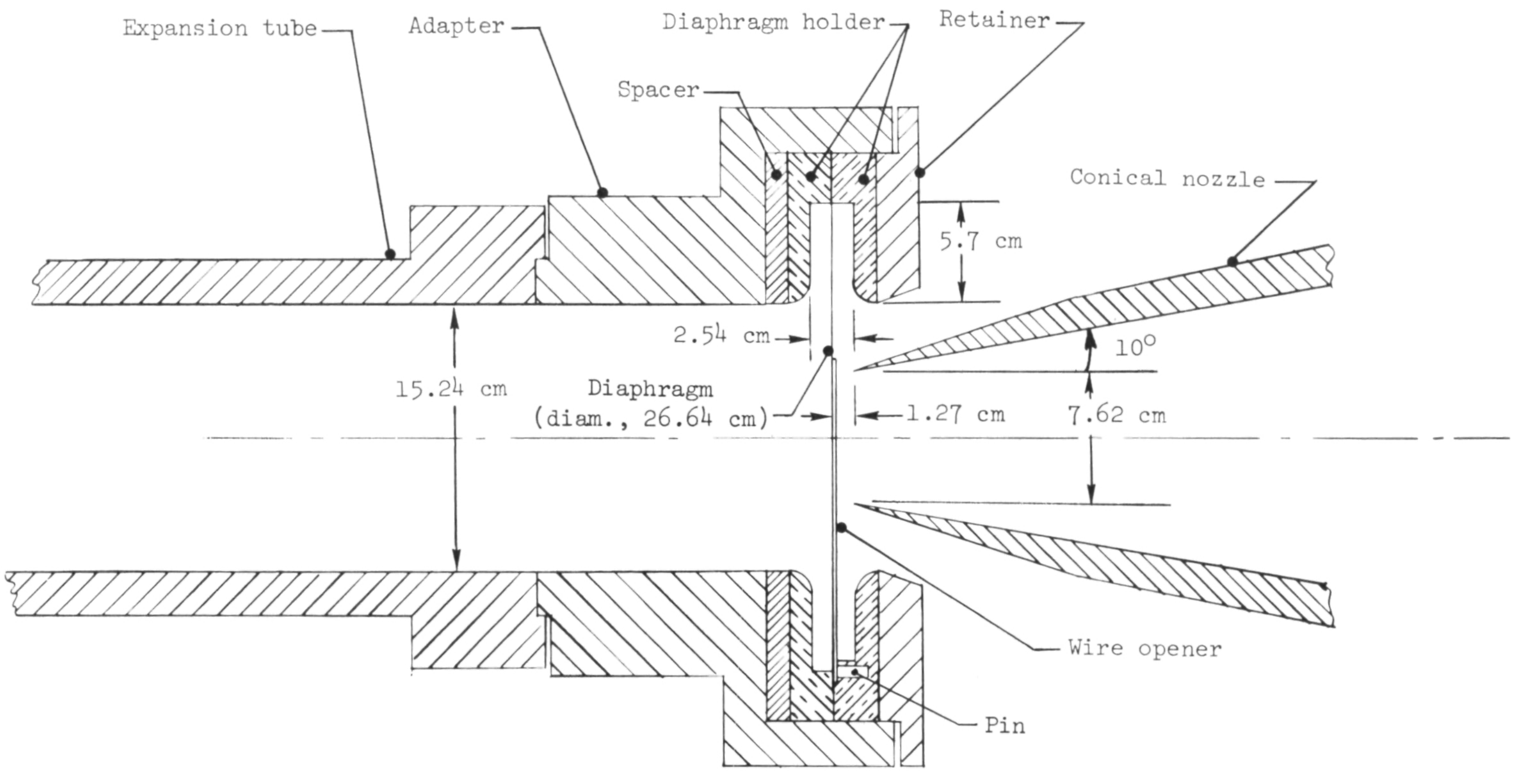


Figure 14.- Sketch of redesigned electromagnetically opened diaphragm.

NASA-Langley, 1976 L-10796

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