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Progress Report

ELECTRICAL BREAKING OF SHOCK-TUBE DIAPHRAGMS

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ABSTRACT

A new method is described for breaking shock-tube diaphragms by means of electrical discharge. The total time required for the discharge to occur and for the diaphragm to be effectively broken depended on the diaphragm material and thickness, and on the differential pressure across it; the time ranged from 300 to 700 microsec. The repeatability with which the resulting shock could be placed in our viewing section was such that the mean deviation of the total diaphragm-breaking time was generally < 70 microsec. This permitted the entire process to be timed with respect to another shock with sufficient accuracy that photographic studies of shock collisions in the shock tube were practicable. Thus far, shocks in N_2 of strengths from $y=2$ to $y=4$ have been produced. The detailed mechanism of the rupturing process is studied. Some preliminary results are reported of work directed toward improving the repeatability of the generating process and the uniformity of the flow behind the shock.

INTRODUCTION AND BACKGROUND

This progress report describes the development of a technique for breaking a shock-tube diaphragm in such a way that the process started by a trigger pulse, is completed quickly and in a suitably repeatable fashion. The need for this development arose in connection with a study of head-on collisions of oppositely facing plane shocks in the 1-dimensional shock tube. The basic theory for this wave interaction was given by Courant;[1] additional theoretical details and early experimental work by the Toronto group were reported by Gould.[2] In generating two shocks of which the relative timing is to be controlled so that collision occurs within the viewing section of the shock tube, one has the choice of either programming the triggering of both diaphragm-breaking processes to obtain appropriately timed shocks or of triggering one diaphragm-breaking process by a signal obtained from an already generated shock.

The Toronto group chose the first approach: in their system there were two strongly spring-loaded electrically released mechanical plungers, each aimed obliquely at its diaphragm and both triggered simultaneously. The time between the generation of the two shocks was varied by changing the distances of travel of the plungers to their respective diaphragms. The evident disadvantages of this method include the following: 1) because the desired time interval is sought by relative adjustment of two independent diaphragm-breaking processes, the mean deviation in the location of the shock collision is the combination of the mean deviations of both processes; 2) the mean deviation of each process is large because the setting of a mechanical spring stop is by its nature relatively inaccurate and unrepeatable; 3) because of this large deviation, the Toronto group noted that, even for moderate shock velocities, corresponding to shock strengths in air of $5 \leqq y \leqq 10$, the shock collision occurred within the 12-in. viewing window only three times in five, indicating a combined mean deviation in the relative timing of the two shocks of the order of ± 150 microsec.

The only other previously developed fast-acting shock-generating mechanism we have found is a solenoid-operated quick-release valve of unspecified design that was described by Condit.[3] With this device the mean deviation in the time interval between triggering and effective shock formation was suitably small, but the valve apparently badly perturbed the flow behind the shock so that the advancing shock more closely resembled a sawtooth than a step. Thus it could not be considered for our purpose.

Our approach was to initiate the first shock (usually the stronger one) by a mechanical prod, then to start the second diaphragm-breaking process by using a trigger pulse derived either from the already formed shock or from the diaphragm-tearing process. In order for most of the shock collisions to be located within the 9-in.-diameter-test-section windows of our 2-in.-by-7-in. shock tube, the total mean deviation in the time interval between the two effective times of shock generation was to be limited to

$$\frac{1}{2} \times \frac{\text{diameter of viewing window}}{\text{maximum shock velocity to be used}} .$$

The window diameter was 225 mm. The maximum shock strength planned for this experiment was $y=6$ in N_2, for which the shock velocity is 0.8 mm/microsec. Thus the total allowable mean deviation in the time interval between shocks was

$$\frac{1}{2} \times \frac{225 \text{ mm}}{0.8 \text{ mm/microsec}} = 140 \text{ microsec} = \pm 70 \text{ microsec} .$$

For our experimental arrangement the total mean deviation in the time interval between shocks was the resultant of at least the following component deviations: the mean time deviations in the process by which the trigger for starting the second shock was obtained from the first shock or from the associated diaphragm-tearing process; time deviation in the further development of the first shock after the trigger was derived from it; and the deviation in the formation process for the second shock after it was triggered. We found that the first two component deviations were small compared to the third; therefore we were able to assign the entire allowed mean deviation of ± 70 microsec to the formation process of the second shock and thus to the shock-formation time, as it is later defined.

It was proposed that a high-voltage capacitor discharge, triggered by a series spark gap and coupled in some unspecified manner to a pressure-stressed diaphragm could add enough additional energy to it (presumably by joule heating) to cause it to rupture and break, and also that this would happen sufficiently quickly and reproducibly. The experimental work to which this proposal led is described here; briefly, the first round of experiments showed that the usable varieties of materials and the ranges of usable pressure differentials for these materials were sharply limited. This prompted a close study of the mechanism of electrical diaphragm-rupturing and ultimately made possible the use of a wider variety of diaphragm materials and of a much broader range of pressure differentials.

So far as we could determine, there has been very little previous work on electrical diaphragm-breaking; the only reference we found was an article by Campbell.[4] The diaphragm in a spherical sector shock tube was suddenly heated intensely around its periphery, presumably by an electrically heated wire, to insure a clean consistent diaphragm break. No indication was given of the total time required to produce rupture or even that the use of the electrical heating was to achieve quick, time-reproducible breaking.

DETAILS OF THE APPARATUS AND THE EXPERIMENTAL ARRANGEMENT

Figure 1 is a schematic diagram of the basic arrangement of the experimental equipment. Many of the conventional details of our shock tube and its associated apparatus are omitted; for these details, Geiger's work[5] is still essentially correct. Another basic reference on shock-tube construction and operation is Glass.[6] The main diaphragm at the left was ruptured by a mechanical plunger (not shown). Downstream from and lightly contacting the pressure-distended diaphragm was a bare No. 40 copper wire that spanned the tube opening centrally from top to bottom and which was insulated from the shock tube at both its ends (see Fig. 2, a schematic of the breaking-wire trigger generator, and Fig. 3, a sketch of the breaking wire at the end of the shock-tube expansion chamber). When this wire was broken during the rupturing of the diaphragm, a d-c current that flowed through the wire and through a series coil was interrupted, causing a voltage transient across the coil. This pulse started the phantastron delay generator (Fig. 5), which in turn produced a thyratron discharge pulse after an interval that had been pre-set so that eventually the two shocks would collide at the test section. The delay generator circuit was modified from Rahm;[7] the thyratron output stage was originally from Greif.[8] The delayed pulse was amplified, and then was used to trigger a second thyratron discharge circuit, shown in Fig. 4. This circuit could also be triggered manually, which was the usual mode of starting in these experiments, as only the electrical diaphragm process was of interest; details of deriving a trigger from the main shock are given to show the equipment as it will be used in shock-collision studies. The output thyratron discharged through an automotive spark coil primary; the voltage pulse in the secondary triggered the coaxial third electrode in the 3-electrode spark-gap switch, as is shown in Fig. 6. The spark gap design closely followed Cullington's.[9] The remaining elements of the electrical discharge apparatus, shown in Fig. 7, were conventional. The construction of the shock-tube breech at which the electrical diaphragm burning occurred is shown in Fig. 8.

After the diaphragm had been electrically ruptured and the auxiliary shock formed, the shock transit time (the velocity time VT) between two conventional schlieren detector stations (see Ref. 5, pp. 43-49, 56-57; changes in the pulse amplifying and shaping circuits are detailed in Fig. 10) was measured by a 1-Mc counter chronograph patterned after the Potter 1.6-Mc chronograph. In a similar fashion the total travel time of the shock (the shock arrival time) was measured from the initial manual trigger pulse to the shock arrival at the second detector station. The formation time SFT, intended to be a rough measure of the duration of the diaphragm-breaking and shock-starting processes, is defined as

$$\begin{pmatrix}\text{Shock}\\ \text{Arrival}\\ \text{Time}\end{pmatrix} - \frac{\text{distance from diaphragm to second detector station}}{\text{distance between the two detector stations}} \times \begin{pmatrix}\text{Velocity}\\ \text{Time}\end{pmatrix} .$$

For each shot VT and SFT were tabulated; when more than one shot was taken with a particular set of experimental conditions, the mean deviations in both VT and SFT were calculated for each set of shots.

For all these experiments the initial common expansion-chamber pressure p_0 was kept constant at 7 cm Hg of N_2, so the independent variable was either the initial auxiliary compression-chamber pressure p_2' or $\Delta p = p_2' - p_0$ or $z' = p_2'/p_0$. For each kind and thickness of diaphragm material, the self-bursting pressure differential was determined; then the pressure differential was reduced progressively until the diaphragm could no longer be ruptured reliably by a single electrical discharge. Except as specifically noted later, the presence or absence of not-yet-caught-up trailing waves behind the shocks produced under various experimental conditions was largely neglected as a criterion for suitable diaphragm materials; the chief criteria were the mean deviation in the SFT, and also the extent of the range of pressures over which the material could readily be ruptured electrically.

Good grounding from the shock tube to the discharge capacitors was needed to prevent inductive coupling to and pretriggering of the schlieren detectors by the electrical discharge. Along the same line, visible light emitted by the discharge, both directly down the tube and also out into the laboratory via the plastic breech plates, was scattered into the optical path of the schlieren detectors and pretriggered them. While the light sent down the tube could not be eliminated, improvement of the external shielding between the discharge and the detectors was sufficient to reduce optical pickup to a workable level.

PRELIMINARY RESULTS

Using this experimental arrangement, some simple methods for coupling the discharge to the stressed diaphragm were tried first: conductive paint was applied in various configurations to regular plastic diaphragms; strips of thin aluminum foil were glued to diaphragms. At this point the discharge could not cause rupture with either method. A thin copper wire was placed in contact with a diaphragm under pressure: when the wire was too thin, the discharge exploded it without sufficiently heating the diaphragm; if it was heavy enough not to be broken by the discharge, it could cause rupture, but only after delays of several milliseconds and with mean deviations of the order of a millisecond. A point-to-plane discharge was tried as a diaphragm-breaking device: the tip of a sharp-pointed prod that was coaxial with and extended the length of the auxiliary compression chamber was set at various distances from a regular plastic diaphragm with a grounded aluminum coating. It was again found that the SFT was quite long and that its mean deviation was much greater than our requirement.

The method finally chosen for diaphragm-rupturing was the passage of the discharge directly across regular plastic diaphragms each having one side that was thinly and uniformly coated with aluminum. The diaphragm materials used were as follows: 1/4 and 1/2 mil Mylar; 1, 2, 3, and 5 mil cellulose acetate (the usual diaphragm material for the 2-in.-by-7-in. tube); 5 mil polystyrene. The aluminum coatings were found to be in the range of 0.5 to 2 ohms/square, corresponding to coating thicknesses of 0.05 to 0.01 microns. Some of the coated materials were produced commercially (see acknowledgments) by unspecified means, others were vacuum-coated locally using regular diaphragm material. In both types, adhesion and uniformity of the coating were adequate for our needs, which were not great in these respects. The surface resistivities of the coatings were measured but not controlled, and, as noted, were subject to wide variation. From an oversimplified view, the rupture was caused by essentially uniform joule heating of the entire diaphragm surface by the discharge. Thus the surface resistivity of the coating should have been an important factor in determining the breakability of a diaphragm and therefore its SFT; actually variations of resistivity were not found to have any discernible influence on the nature of the rupturing. This was later understood when the actual rupturing mechanism was determined.

The qualitative results of the first round of tests with plain unmodified aluminum-coated diaphragms are given below. Quantitative details are not given separately for this portion of the testing. It was found that $\Delta p_{\text{self-burst}}$ for most of our diaphragm materials showed a mean deviation of 5-10%. For both these and later test results, when the SFT for each material was plotted as a function of the ratio of Δp to the average $\Delta p_{\text{self-burst}}$, the curves for the various materials appeared fairly well superimposed. The chief conclusion from this first testing was that electrical diaphragm-rupturing was feasible but that in most cases it provided only a narrow range of Δp's and therefore of shock strengths.

More detailed study was made of the diaphragm-rupturing process, prompted by interest in the causes of this limited range and of the differences in difficulty of rupturing different diaphragm materials. For this purpose the auxiliary compression chamber was removed; the diaphragms were clamped in place between the plastic insulating breech plates (see Fig. 8); 1 atm was used as $p_{\frac{1}{2}}$; a view camera, protected from the strong expansion wave by a thick sheet of transparent plastic, was set up a few feet back of the breech and focused on the diaphragm; the shutter was opened just before each shot and the luminosity produced by the electrical discharge was photographed. The patterns of luminosity were correlated closely with traces of the paths of current arcs that were left on the burned diaphragms by the discharges.

An effort was made to obtain a time sequence of pictures of the rupturing process by using a delayed photographic spark to illuminate the diaphragm, presumably after the discharge was no longer self-luminous. The diaphragm was made visible by a grid work of white lines painted on it. It was found that severe electromagnetic pickup of the electrical discharge by the photo-spark triggering circuit invariably pre-fired the spark; since by the time that this was realized the chief aim of these experiments—the understanding of the rupturing process—was already achieved, no additional effort was made to shield against this pickup.

Material	Reproducibility (Smallness of Mean Deviation of SFT)	Minimum Δp for Reliable Diaphragm Rupture (% of $\Delta p_{self\text{-}burst}$)	Comments
1/4 1/2 mil Mylar	Good	~ 75%	
1 2 3 5 mil acetate	Good	~ 100%	Unrupturable except for Δp very close to $\Delta p_{self\text{-}burst}$, where untriggered bursts often occurred because of 5-10% variations in diaphragm strength
5 mil polystyrene	Good	40-50%	

For each shot in this series of tests, VT and shock arrival time were recorded in an effort to relate the mean deviation in SFT to the pattern of the electric discharge. It was found, however, that the basic discharge pattern was quite similar for most of the diaphragm materials. In the absence of a compression chamber in these experiments, the backward-traveling expansion wave was hemispherical; the values of VT and SFT for these shots showed that additional compression waves were following the shock and gradually overtaking it. This caused the VT to be too short relative to the case of the regular 1-dimensional shock tube, and the SFT to appear too long, since in the SFT calculation it was assumed that the shock velocity was constant at its measured value. Hence the values of VT and SFT for these shots were not included on the plots of the experimental data.

Correlation of the discharge luminosity photographs with the burned diaphragms showed that in each case of a ruptured diaphragm (with the exception of Mylar, which was a special case because of its unusual properties) the photographs showed a very bright spot near the lower edge of the tube opening; at the corresponding spot the burned diaphragm showed a deeply burned trace of a current arc that traveled along the diaphragm surface from the edge of the lower, high-voltage electrode to the lower edge of the shock tube opening on the downstream side. This discharge path is shown on Fig. 8.

Some tests were run with the diaphragm coating reversed to face upstream. Here the arc traces were not nearly so deep, and in most of these cases the discharge would not rupture the diaphragm even when the Δp was close to $\Delta p_{\text{self-burst}}$. In the few cases in which the diaphragm was broken, presumably by the arc discharge finding its way around the end of the diaphragm to the downstream side, the SFT was highly erratic.

In the special case of 1/4 and 1/2 mil Mylar, it was found that good breaking could be obtained with less intense arc-discharge traces on the burst diaphragms and in the absence of any points of concentrated luminosity. Mylar film deformed very much before it ruptured, i.e., it was much more plastic than the other plastic diaphragm materials. It was also very tough and could be torn only with relative difficulty. A Mylar diaphragm under pressure distended much farther into the expansion chamber; if its coating faced downstream, the shortest path from the coating to the lower edge of the grounded shock tube was via a point on the diaphragm considerably above the bottom of the tube opening, as can be seen in Fig. 9. When the coating faced upstream, the discharge and the point of rupture occurred at the lower edge of the diaphragm; in this case the break was cleaner and the resulting SFT much less erratic.

In the course of some shots with 5-mil polystyrene (a relatively brittle material), we found that even though there was no Δp across the diaphragm, passage of a discharge caused breaks in the lower corners of the diaphragm where the discharge arcs were located. Evidently substantial electromechanical force was being exerted by the magnetic field of the current on the diaphragm as a part of the current-carrying loop. In a related experiment, again without any Δp, a diaphragm was used that was only a little wider than the tube opening, and hence was clamped effectively only at the top and bottom. After discharge, the central part of the diaphragm was found bowed out into and stuck in the compression chamber; this direction of displacement was appropriate for the geometry of our discharge current loop.

This detailed study seemed to indicate that most of the discharge current traveled only a relatively short distance on the unclamped part of the diaphragm on its way from the high-voltage electrode to the nearest ground, i.e., the lower edge of the expansion chamber. The concentrated heating at the point on the diaphragm coating where the air arc ended appeared to be the chief cause of rupture.

An effort was made to increase the resistance of the diaphragm coating to increase the fraction of the discharge energy that was delivered to the diaphragm, and also to utilize more efficiently that part of the current that did not flow through the arc. For this purpose, horizontal gaps, generally extending the entire width of the diaphragm, were introduced in the coating. The gaps were made by daubing the coated diaphragms with strong caustic soda solution, and then quickly washing it off; this removed the coating to make the gaps without affecting the diaphragm material. Various shapes and locations of the gaps were tried, as well as various combinations of gaps on a single diaphragm. As was expected, only gaps near the lower edge of the diaphragm (in the lower quarter of the unclamped part of the diaphragm) were found effective in extending the range of usable Δp's. Neither the gap width and shape nor the number of gaps per diaphragm were found to have any significant effect, so we fixed upon a single straight-edged gap 1/16 in. wide, as is shown in Fig. 13.

It was concluded that the presence of a gap was effective only in extending downward the fractional range of usable Δp's and was effective in this only for those diaphragm materials that were difficult to break without gaps. These included Mylar, which is tough and very hard to break, and cellulose acetate, which is moderately so. No improvement was found for polystyrene, which is so brittle that even without gaps a broad range of Δp's had been found usable. In no case where similar diaphragms, gapped and ungapped, could be tested under the same conditions was any significant difference found in SFT or in VT. Hence on the plots of experimental values of SFT and VT no distinction was made between data taken with gapped and ungapped diaphragm coatings. On these plots mean deviation flags are included for those points for which there were enough test data, usually at least four or five shots apiece, to give some meaning to the mean deviation. The intervals between flags represent twice the mean deviation of the test data from the average value for each point.

The plot of SFT (Fig. 11) shows that in all cases SFT decreased with increasing $\Delta p/\Delta p_{SB}$ (SB = self-burst). Those component processes of the overall SF process that varied with diaphragm thickness and especially with self-bursting pressure were as follows: heating of some small area of the diaphragm to the point where the softening of the pressure-stressed diaphragm causes local rupture; propagation of the rupture by progressive strain relief; and work by the high-pressure gas against inertial forces to remove the diaphragm pieces from the breech aperture. Thus the SFT plot seems to show that at least these processes are accelerated as Δp approaches Δp_{SB}. The experimental points on the SFT plot covered a range of 20 to 1 in diaphragm thickness, of 12 to 1 in self-burst pressure. Also there were data for two diaphragms of the same thickness but of different materials so that the Δp_{SB} differed by as much as 4 to 1. Thus the relatively close superposition of the SFT data points for the entire range of diaphragm materials indicated that the speeds of those component processes in the shock-formation process that varied with the diaphragm material varied chiefly with changes in $\Delta p/\Delta p_{SB}$. Hence it appears that those component processes that depend on the relative stress in the diaphragm, i.e., the process of local heating to rupture and of diaphragm-tearing after initial rupture, were the most important of the variable processes contributing to the SFT, while other components, dependent on the material thickness but not on the relative stress in the diaphragm, especially the process of overcoming the inertia of the diaphragm pieces and removing them from the path of the flow, were not so important.

The order of magnitude of the mean deviations shown on the SFT plot indicates that the electrical diaphragm-breaking technique, with present materials and equipment, in general satisfied the initial requirement that the mean deviation of the SFT be less than ± 70 microsec. From this standpoint the least satisfactory diaphragm material was polystyrene, which showed relatively large deviations, probably because of its extreme brittleness and of its very erratic patterns of breaking after initial rupture.

On the plot of the VT (Fig. 12), the close agreement of the experimental points with the ideal theoretical curve showed that, for all the modes of diaphragm-breaking that were used, the trailing waves had completely overtaken the shock and the shock had been completely formed by the time both had reached the detector stations. In all cases the points are above the ideal curve; their deviation from the curve tended to increase with increasing z' and thus y'. The chief cause of these deviations was believed to be shock attenuation. An order-of-magnitude calculation, based on the theory of Hollyer,[10] appeared to verify this.

In addition, part of the SFT was also due to attenuation. As is shown in Fig. 15, the effect of attenuation on the shock velocity was opposite to its effect on the location of the shock as a function of time, so far as their effects on the SFT were concerned. A similar calculation here showed that the net contribution to the SFT was of the order of 10%. On the plot of SFT vs. $\Delta p/\Delta p_{SB}$, points were superposed for which the values of p_2' varied by as much as 12 to 1. The attenuation was only a relatively weak function of p_2'; the contribution of the attenuation to the SFT was small. Thus of the deviation between two experimental SFT points with the same value of $\Delta p/\Delta p_{SB}$, the part caused by the variation in the attenuation component of the SFT with changes in Δp_{SB} and thus in p_2' was negligible in comparison with the experimental mean deviation.

Pictures taken at the test section with the electrically generated shock in the window showed that directly behind this shock was a relatively strong trailing wave which progressively overtook it. The slope and curvature of this wave indicated that it originated from either the top or bottom of the shock tube channel at a point near the breech. It was thus reasonable to assume that this wave was caused by the rupturing of the diaphragm first at the floor of the channel and, in many cases, its subsequent incomplete tearing and folding back. This produced a highly asymmetrical constriction at the breech. Efforts were made to insulate the neighboring portions of the shock tube from the electrical discharge; this was to make possible putting the gap in the coating, and thus the point of initial rupture, at the center of the channel. Preliminary results showed that when such insulation was effective, i.e., when the diaphragm ruptured at its center, the strong asymmetrical trailing wave was no longer visible at the test section, but was replaced by a relatively weaker symmetrical trailing wave. It was also noted that this change had little effect on the measured VT, since both before and after the change the entire trailing wave had overtaken the primary shock before it arrived at the velocity detector stations; but it had a substantial effect on the SFT, reducing it, in the experiments tried thus far, by roughly 200 microsec. The cause of this reduction is made evident in Fig. 16, where we note that more rapid catchup of the trailing waves with a shock of a given strength reduced the apparent SFT.

Even with the nieghboring shock-tube sections fully insulated from the discharge and with the coating gaps at the center of the diaphragm, it became evident that some of the current was not passing directly across the gap but was traveling over much longer paths in air from high to low potential points on the diaphragm. Thus, both to achieve cleaner and more consistent rupturing and breaking of the diaphragms and also to make use of our large supply of coated Mylar diaphragm material in combination with cleaner breaking cellulose acetate diaphragms, we adopted a two-layer diaphragm, consisting of a fuse-shaped strip of coated Mylar film attached by cellophane tape to an uncoated acetate diaphragm over only the narrow central part of the strip (see Fig. 14). The coating on the Mylar faced the acetate. The confinement of the discharge in this fashion evidently increased the efficiency of the coupling of the discharge to the diaphragm and gave very clean initial rupture at the center of the diaphragm.

It is hoped that the mean deviation of the SFT will be decreased substantially by having the electrical discharge determined not by a long erratic discharge path from the shock-tube walls to the diaphragm but solely by a short, well-defined gap in the diaphragm coating. Very recent experiments have also shown that, while the symmetric trailing waves overtook the shock sooner than did the asymmetrical ones, the process was still by no means completed by the time they passed the viewing windows together. This indicated that the diaphragm-to-test-section distance for our shock tube was not long enough; thus the potential usefulness of this equipment in shock-collision studies and in the various intended applications may well be more limited than had been anticipated.

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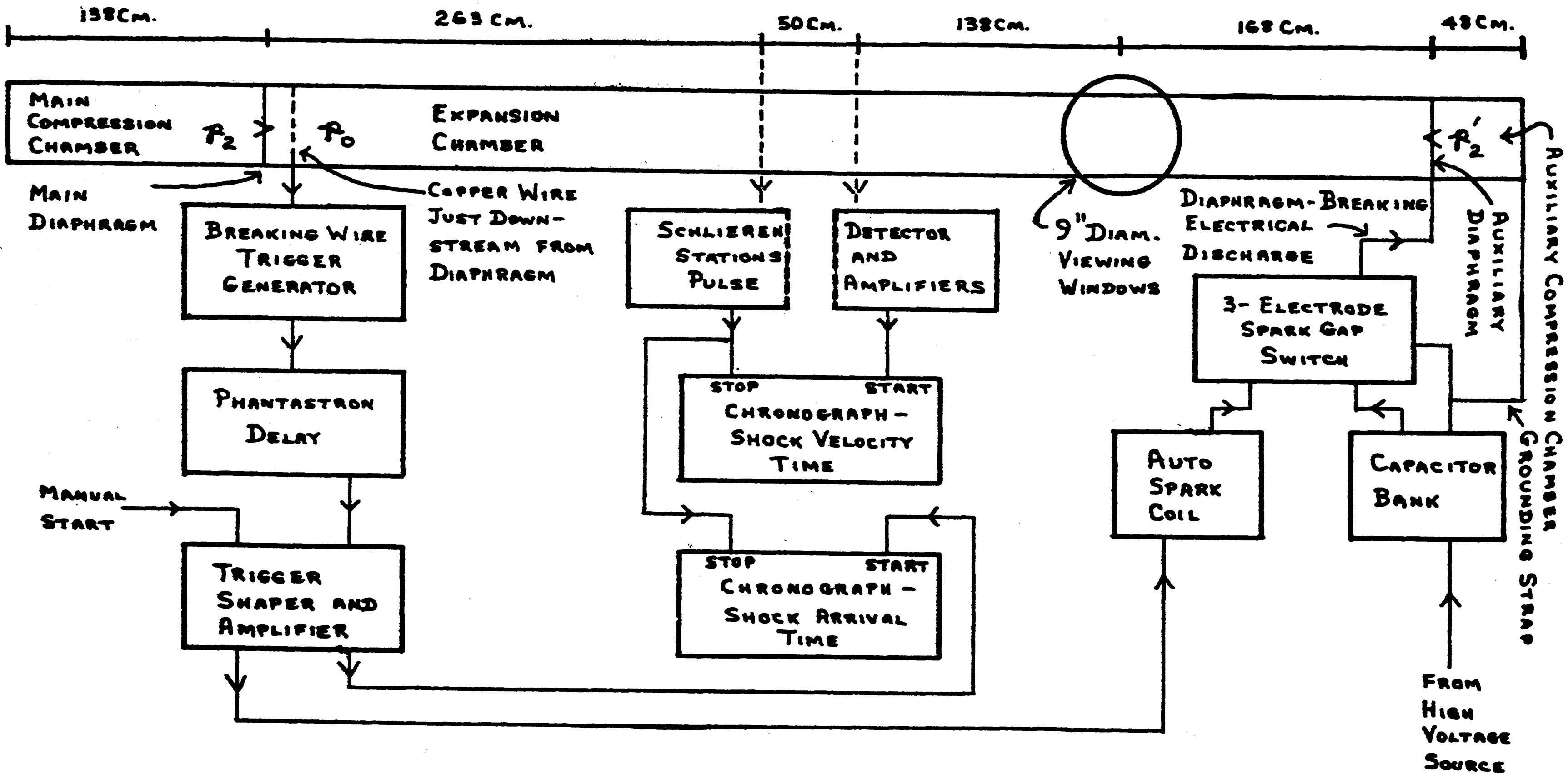


Fig. 1. Block Diagram of Experimental Equipment for Studying Electrical Diaphragm Breaking and for Using It in Producing Colliding Shocks

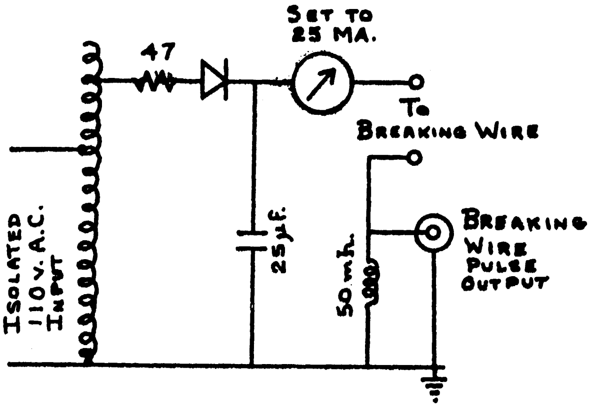


FIG.2. SCHEMATIC OF THE BREAKING WIRE TRIGGER GENERATOR

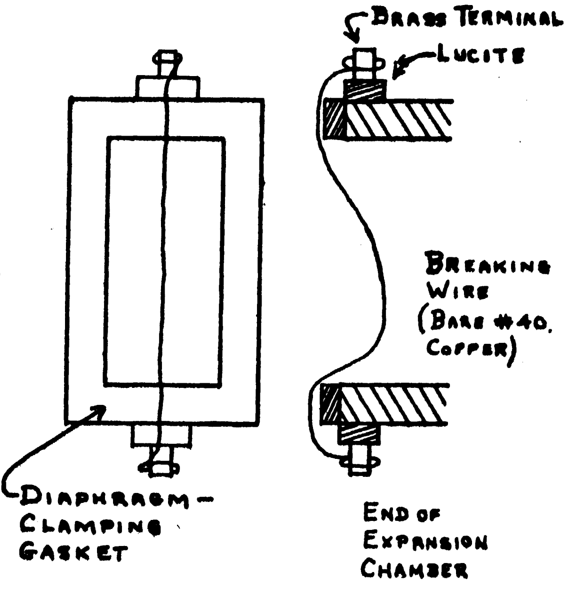


FIG.3. LOCATION AND MOUNTING OF THE BREAKING WIRE

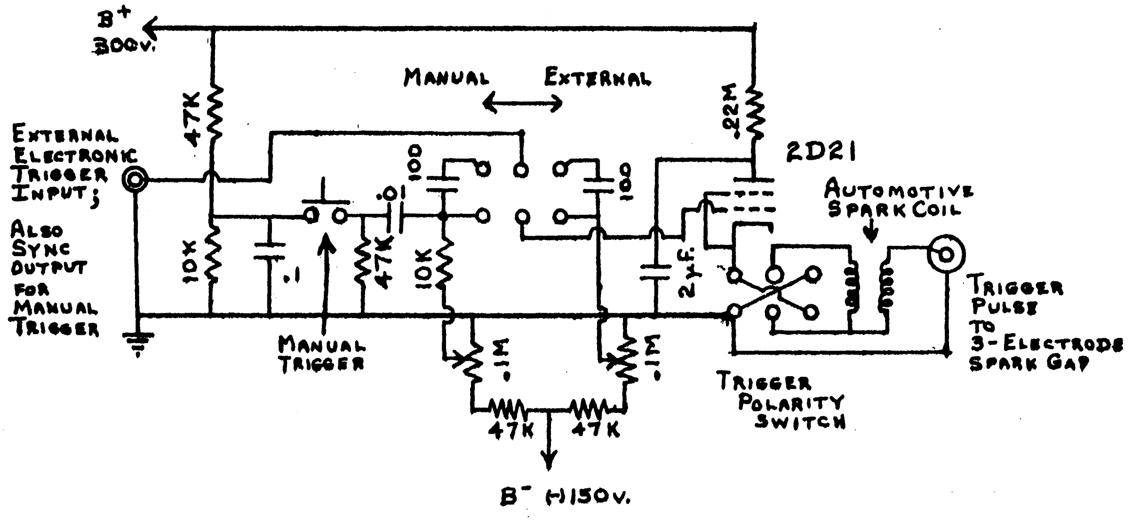
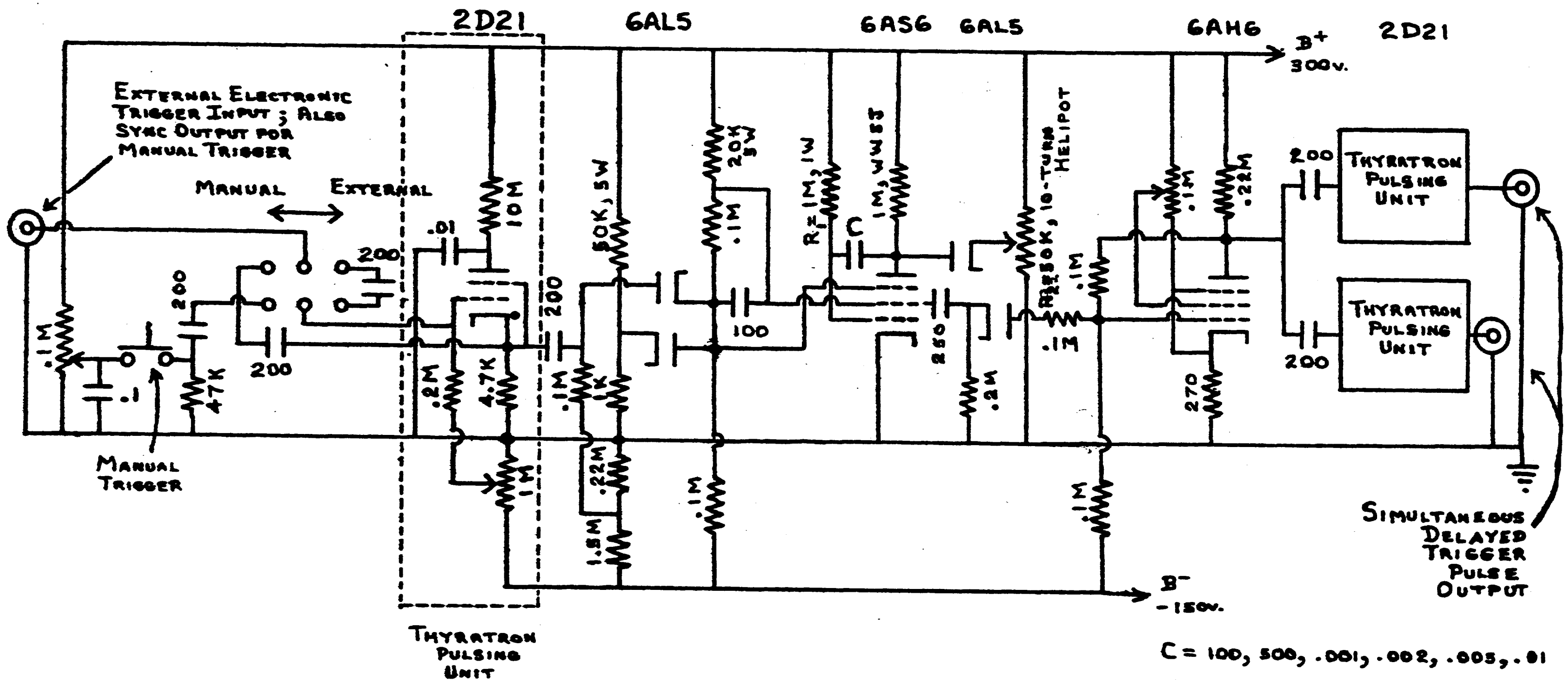


FIG. 4. THYRATRON DISCHARGE CIRCUIT FOR TRIGGERING THE SPARK GAP



C = 100, 500, .001, .002, .005, .01

R₁, R₂ and C Determine Generated Delay

Fig. 5. Phantastron Delay Generator

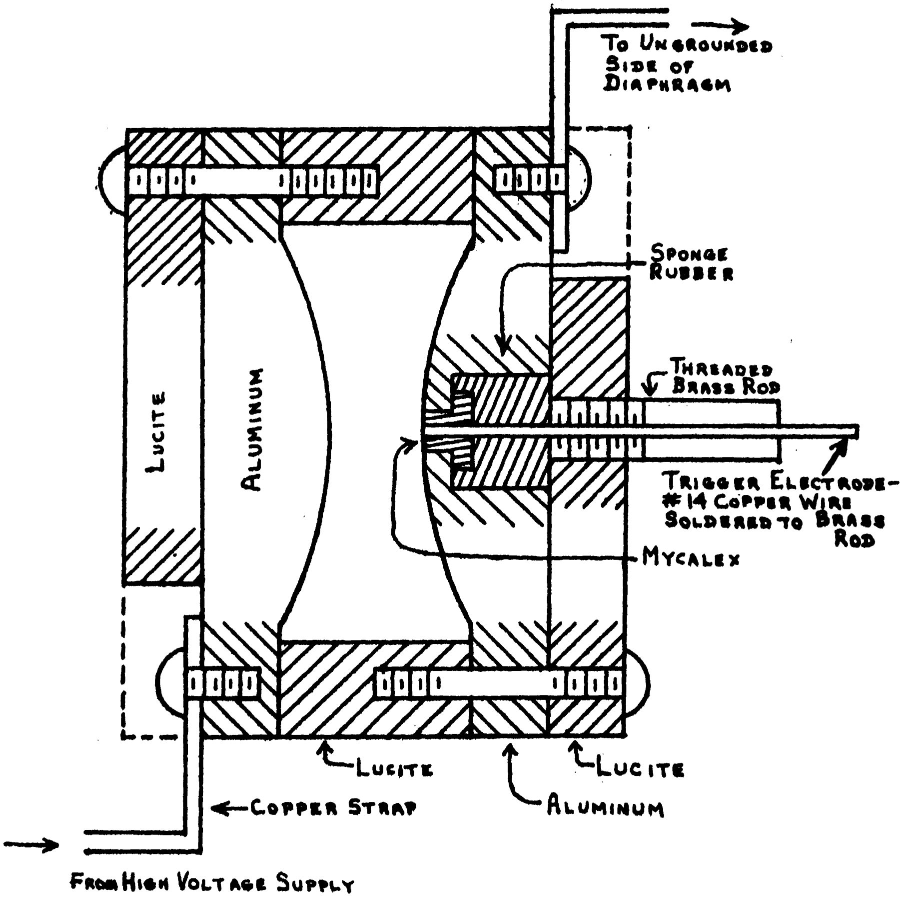


FIG. 6. THREE-ELECTRODE SPARK GAP SWITCH

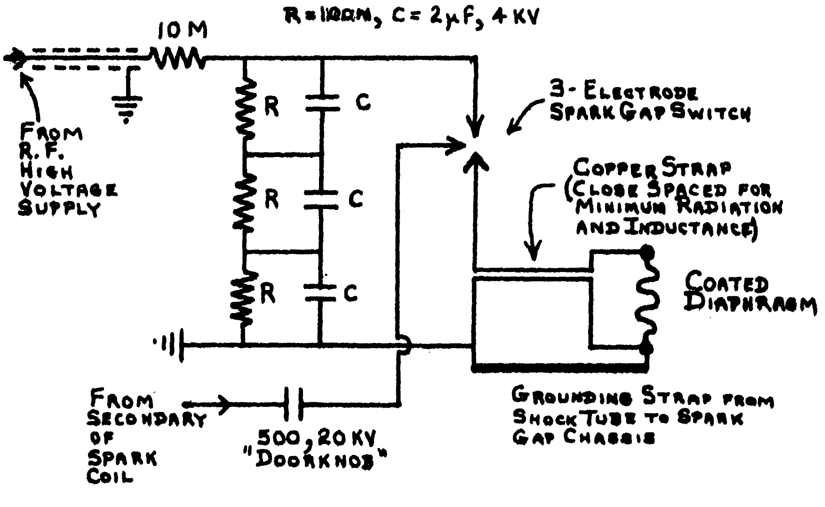


FIG. 7. SCHEMATIC OF THE DISCHARGE CIRCUIT

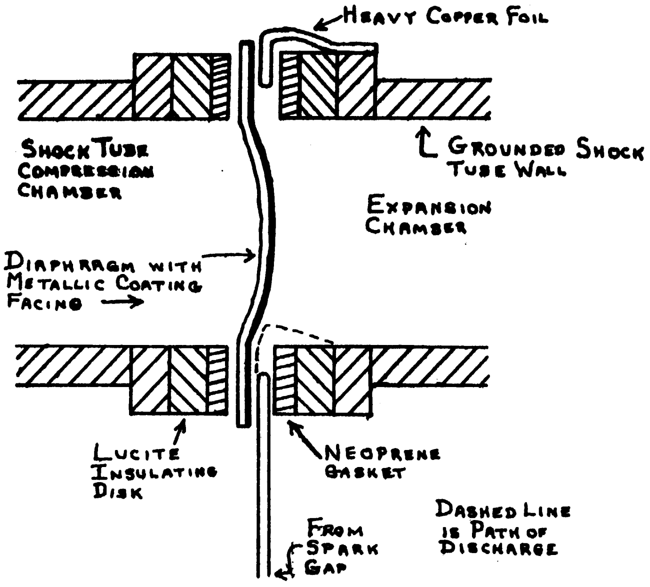


FIG. 8. CROSS SECTION OF SHOCK TUBE BREECH FOR DIAPHRAGM BURNING

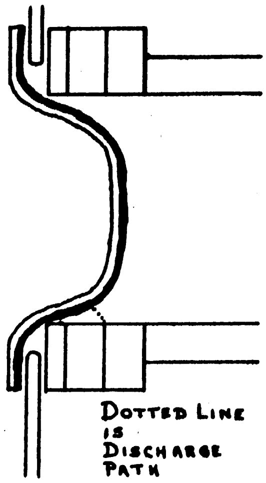


FIG. 9. PATH OF DISCHARGE FOR SPECIAL CASE OF MYLAR DIAPHRAGM

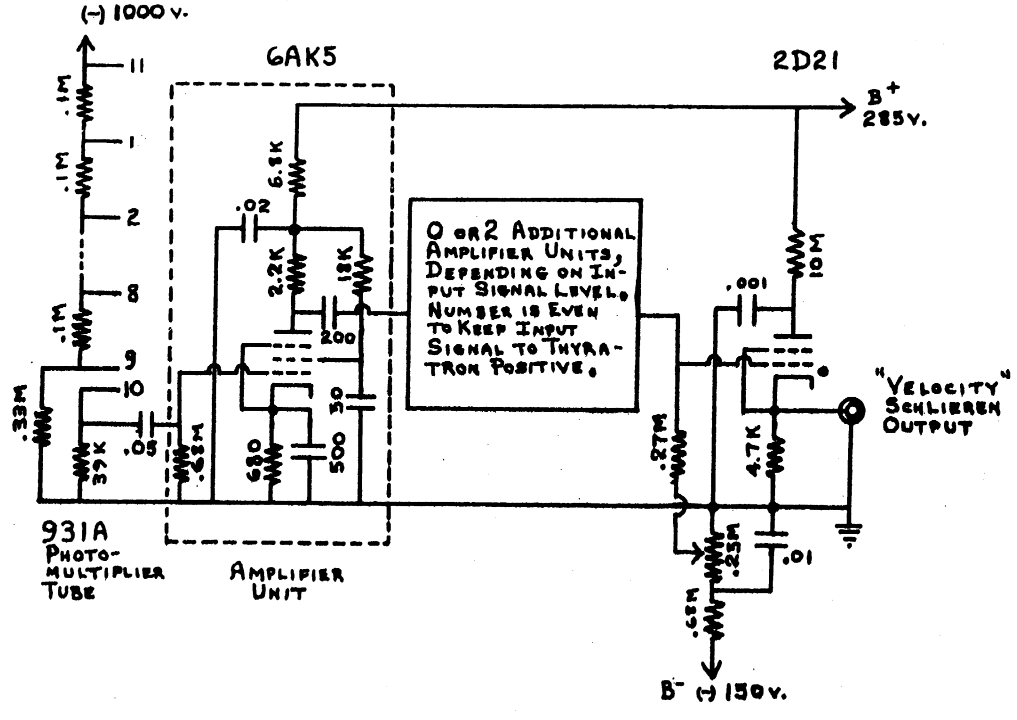


FIG. 10. AMPLIFIER AND SHAPER FOR PULSES FROM VELOCITY SCHLIEREN DETECTORS

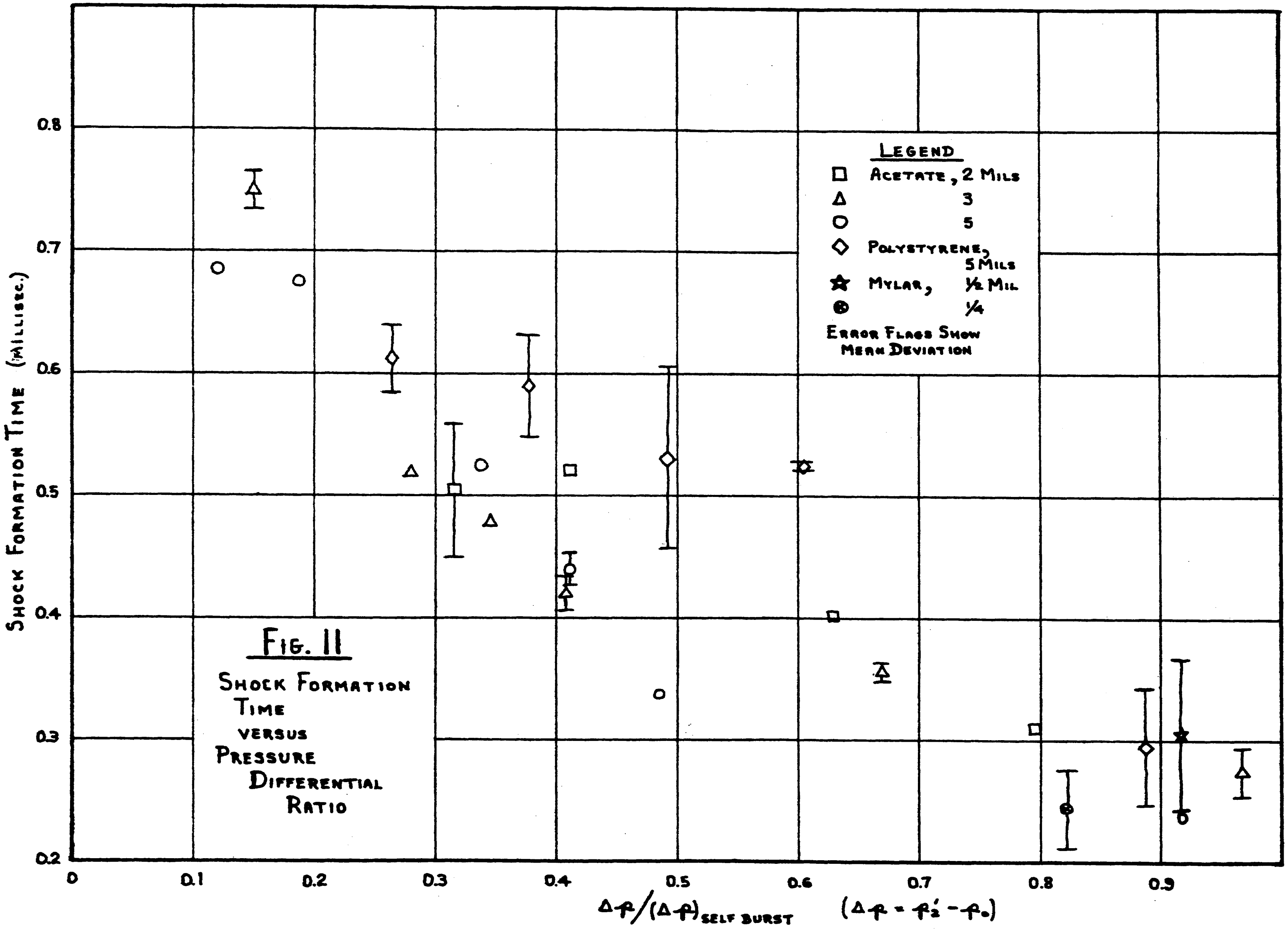


FIG. 11

SHOCK FORMATION TIME VERSUS PRESSURE DIFFERENTIAL RATIO

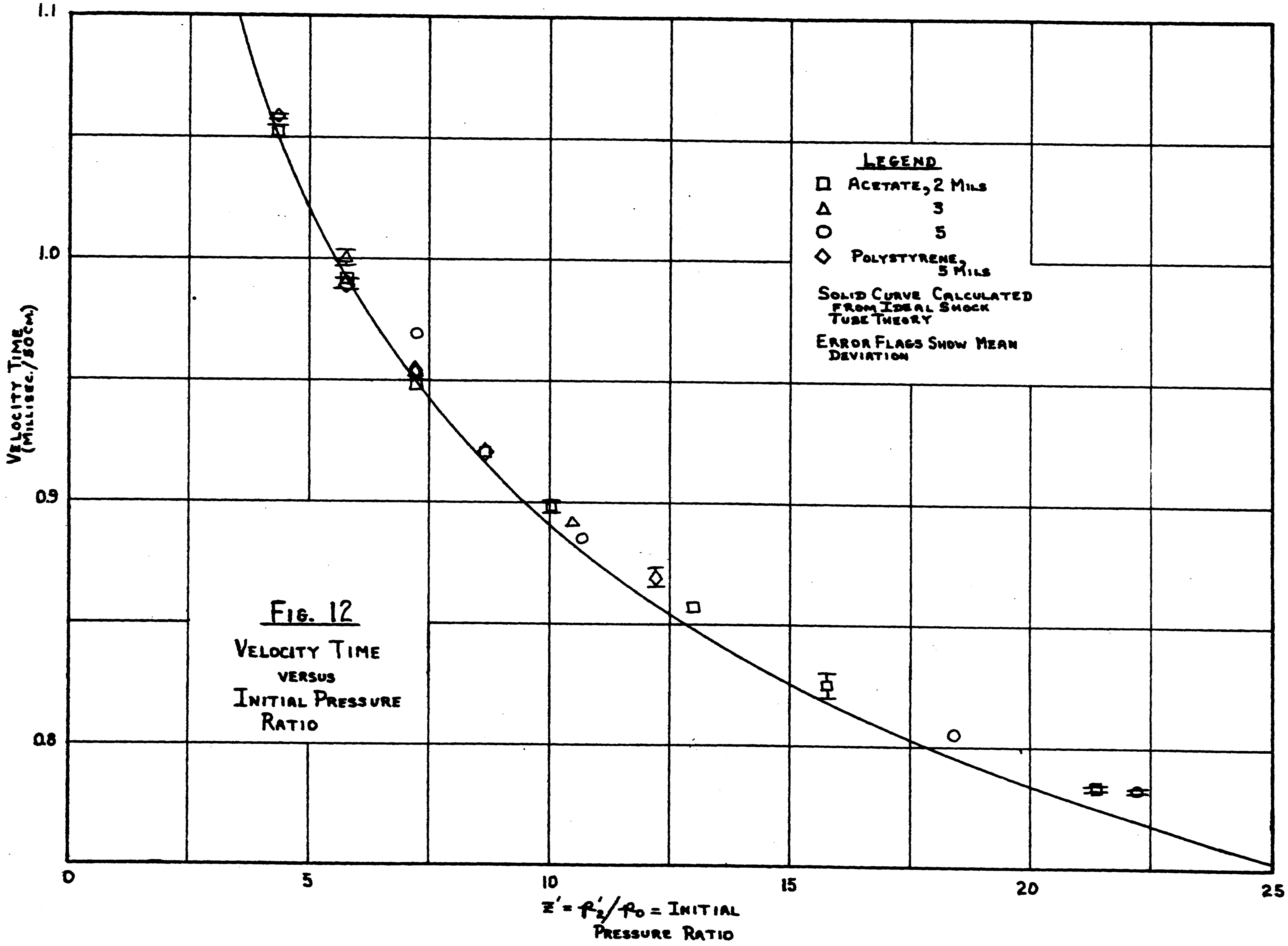
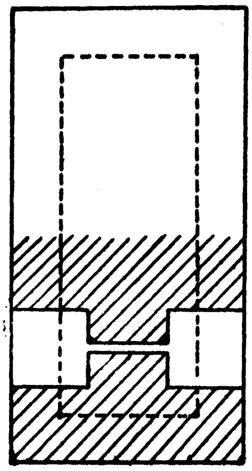


Fig. 12

Velocity Time
versus
Initial Pressure
Ratio



Dotted Line is Outline of Shock Tube Aperture

Fig. 13. Sketch of Diaphragm with Gap in Coating

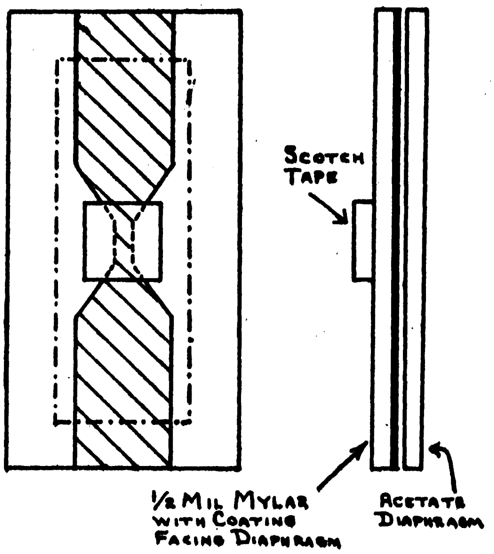
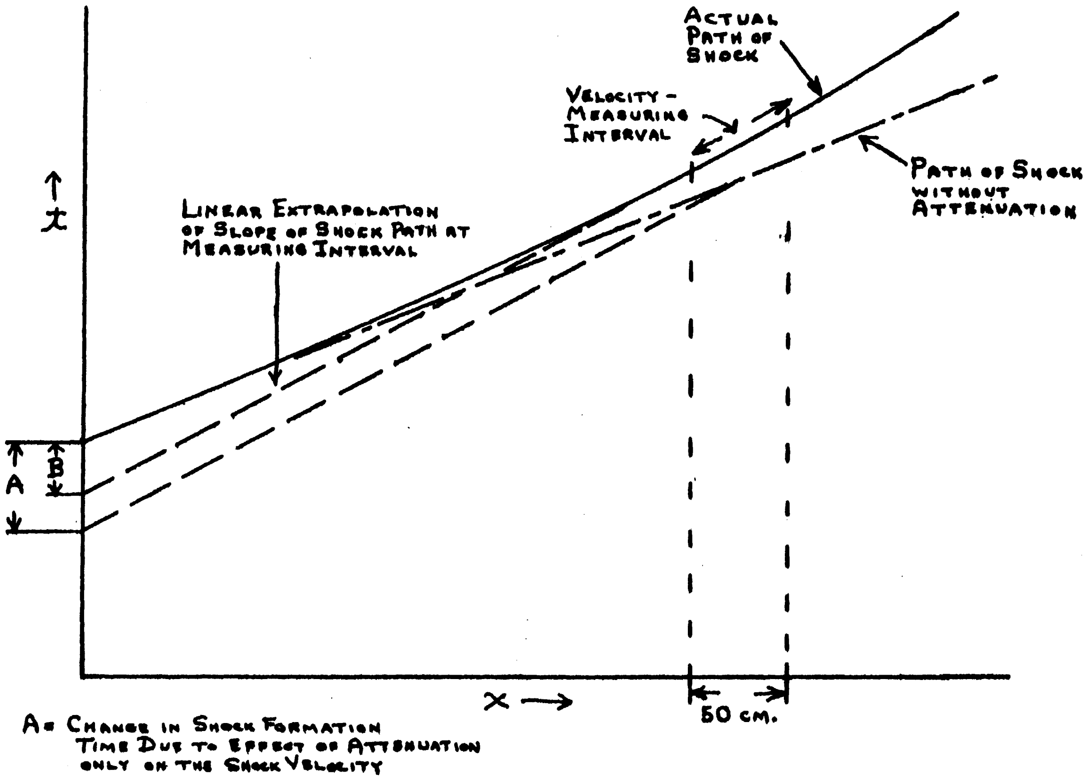


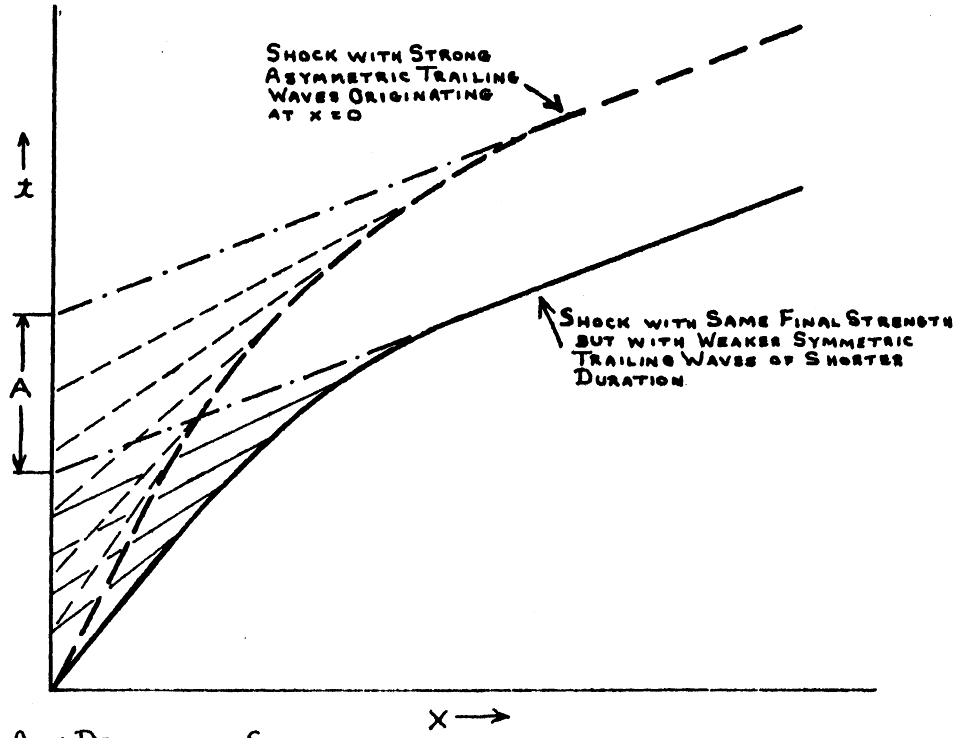
Fig. 14. Sketch of Later Version of Diaphragm with Gap



A = Change in Shock Formation Time Due to Effect of Attenuation only on the Shock Velocity

B = Change Due to Effect of Both Shock Velocity and Shock Position

Fig. 15. Effect of Attenuation on Shock Path and on Shock Formation Time



Shock with Strong Asymmetric Trailing Waves Originating at x = 0

Shock with Same Final Strength but with Weaker Symmetric Trailing Waves of Shorter Duration

A is Decrease in Shock Formation Time Associated with Shorter Duration of Trailing Waves

FIG. 16. EFFECT OF TRAILING WAVE DURATION ON SHOCK FORMATION TIME