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A 3-INCH COMBUSTION DRIVE SHOCK TUBE FOR STUDYING CHEMICAL KINETICS

by

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INTRODUCTION

The Ames Research Center has recently placed in operation a combustion driven shock tube designed primarily for studying chemical kinetics. Velocities as high as 20,000 fps, equilibrium temperatures of 7,500° K, pressures between 1/2 and 5 atm, and testing times of 100 to 150 μsec are available in gas samples behind the incident shock wave. The principal features of this apparatus and its associated equipment, the pertinent operating procedures, the operating ranges available, and some results thus far obtained are described in the ensuing sections of this report.

SYMBOLS

a speed of sound

a radius of unsupported area of diaphragm (ref. 5); one-half diagonal of unsupported area of diaphragm for this shock tube

E modulus of elasticity of diaphragm material

h specific enthalpy

l maximum length of test gas sample

M Mach number

p pressure

t thickness of diaphragm before grooving

T absolute temperature

u velocity of test gas relative to shock tube

w velocity of incident shock wave relative to shock tube

ϵ_{au} apparent ultimate strength of diaphragm (ref. 5)

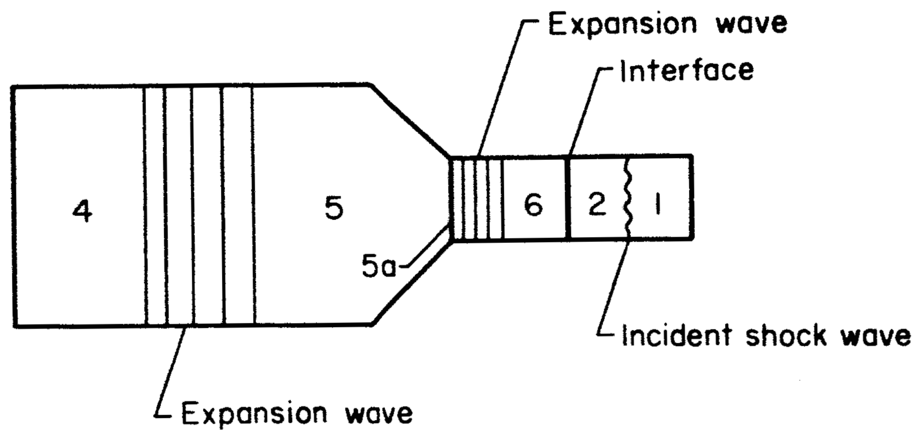
γ ratio of specific heats

ρ density

τ testing time

[redacted]

Subscripts



o condition at 273° K at 1 atm pressure

$\left.\begin{matrix}1,2\\4,5\end{matrix}\right\}$ regions in shock tube as shown in sketch

Note: Units used are either stated at time symbol is used, or chosen to be self-consistent.

THE SHOCK TUBE

Tube Assembly

The shock tube assembly, consisting of the driving tube, diaphragm section, driven tube, working section, and dump tank conforms in general with conventional arrangements. A line drawing of the installation is shown in figure 1 and pictures of various portions of the installation appear in figures 2, 3, 4, and 5. Pertinent data for these components are tabulated in tables I, II, and III.

Driving and Driven Tubes

The dimensions, materials of construction, and auxiliary equipment for the shock tube were chosen to provide test gas samples behind the incident shock wave having high temperatures at moderate pressures, as free from contamination as possible, and testing times of usable duration. Reliability, freedom from maintenance, and preparation time per shot were also important factors, but decidedly secondary considerations to these major objectives.

Quantitative design values for temperature and pressure were derived from analysis of the equilibrium thermodynamic characteristics of nitrogen. Nitrogen was used because (a) it is of immediate interest for earth atmosphere entry problems, and (b) since it dissociates at higher temperatures than most other gases, a shock tube suitable for nitrogen tests would be useful for chemical kinetic investigations in general. After some consideration the minimum design goal was somewhat arbitrarily fixed at 20 percent dissociation for 1 atm pressure. The equilibrium temperature corresponding to this state is 6400° K and the required shock wave velocity is 18,000 fps. It was also decided to exceed these minimum requirements by as wide a margin as a balance design would permit.

The shortest useful test time for chemical kinetic studies depends upon the time required for the reaction behind the shock wave to reach equilibrium, and the velocity of the test gas as it passes the observation ports in the working section. These two quantities determine the minimum length of the slug of test gas, which must equal or exceed the length of the reaction zone. A preliminary investigation indicated that a reaction zone length of the order of 2-1/2 feet should be sufficient for most work. This dimension corresponds to test times of 100 to 150 μsec, depending upon the test gas velocity.

Helium heated by the combustion of hydrogen and oxygen was chosen as the driving gas. This choice was made because the characteristics of the gas were well known and the performance, although sharply limited, appeared capable of meeting research requirements.

With these factors in mind a parametric study was made to evaluate the effects upon shock tube performance of (a) the sound speed of the driving gas at the moment of diaphragm rupture, (b) the area ratio of driving to driven tube, and (c) the pressure ratio of driving to driven gas. The analysis utilized tabulated values of the thermodynamic properties of nitrogen essentially the same as those of reference 1. Results initially were computed by hand in the manner described in appendix A; subsequently they were extended by use of an IBM 704 digital computer. Quantities computed included the thermodynamic properties of the test gas, that is, temperature, degree of dissociation, pressure, specific enthalpy, etc., as well as shock velocity, velocity of the test gas behind the shock wave, test time, and length of test gas sample. Although no attempt was made to account for effects of the boundary layer on the wall of the driven tube, the theoretical predictions agreed well with actual performance data (as will be shown subsequently).

The results indicated that the minimum conditions specified above could be attained, and in all probability, exceeded. Temperatures (in nitrogen) as high as 7500° K seemed possible:

Temperature, $^{\circ}K$	Dissociation, percent	Pressure, psi	Shock velocity, fps
7000	61.4	5.85	25,800
7300	40.4	36.9	22,600
7500	29.6	116.7	20,800

In addition it was determined that the driving gas sound speed had the greatest effect upon performance. Area ratio was next in importance. Finally, to realize significant gains with higher pressure, very large increases in pressure ratio were found to be necessary.

This study also provided most of the data needed to fix the major dimension and proportions of the shock tube. For the combustible mixture of hydrogen and oxygen in helium, an area ratio of 4:1 (driving to driven tube) would provide temperatures between 6500° K and 7500° K (nitrogen at 1 atm). The velocities calculated indicated that a driven tube 30 to 40 feet long would be needed for testing times of 100 to 150 μsec (35 feet was the length chosen).

The minimum diameter of the driven tube was chosen from information provided in the literature (see, e.g., ref. 2) which indicated that a rapid loss of shock wave velocity could be expected for length to diameter ratios above 100 to 120. However, a value of 140 (resulting in 3-inch i.d.) was used and provision made to shorten or lengthen the tube as experience dictated. The driving tube was made longer than necessary to provide for future rearrangements not then completely formulated.

Increased temperatures and enthalpies in the test gas would have been obtained with a larger diameter driving tube. The increase, however, is relatively small as the area ratio rises above 4 (ref. 2), and introduces a number of disadvantages. In particular the frequency and violence of detonation increase, the cost of the driving gas goes up roughly as the square of the bore, as does also the gas consumed per shot and therefore the capacities and sizes of the principal components of the combustion gas supply system. It is also true that longer testing times would have been provided by a scaled-up shock tube of the same proportions as those chosen. Increasing testing time in this manner, however, very quickly becomes prohibitively expensive - the increase is directly proportional to size, but the over-all cost, as just mentioned, increases quadratically.

As noted in table I, the design pressure for the driven tube was 50,000 psi, with 30,000 psi being the maximum expected working pressure. The selection of outside to inside diameter ratio was based primarily on the empirical formulas of reference 3 together with the test results reported in reference 4. Little weight was attached to values computed from the Lamé formula, although the calculation was made as a matter of interest. The physical properties used in the various calculations are included in table I.

The driving tube supplied by the vendor was above the hardness limit specified (Rockwell C-38). In addition, on the basis of information later obtained from a manufacturer specializing in the design and testing of high pressure apparatus, it is felt that even the hardness specified is a little too great. In spite of these conclusions the cylinder was not hydrostatically tested, the reasons for this being that (1) the unit is well barricaded; operating personnel are protected by a reinforced concrete wall 24 inches thick, (2) a hydrostatic test, if successful, at best would provide only approximate assurance against failure under dynamic loading. If on the other hand, the vessel should fail, the damage would probably be little less than would be experienced otherwise.[1] (3) Leaks have never been a problem, and any that may occur can be located far more quickly and safely at a low charging pressure with a helium leak detector.

The driven tube (see figs. 1 and 2, table III) has two features worth noting: (a) It is constructed of a group of demountable sections, and (b) the material from which it is fabricated is type 316 stainless steel. Demountable sections provide flexibility in experimental setups; the tube not only can be shortened, it can be lengthened by as much as 20 feet if conditions warrant. Type 316 stainless steel was chosen because it appeared to be the ferrous alloy least likely to contaminate test gases.

The stress calculations for selecting the driven tube diameter ratio were identical in method to those used for the combustion chamber, a design pressure of 30,000 psi being used. There was the additional problem of fixing the size of the flanges and choosing the method of attachment to the tube proper. Screw threads were used for attachment. In spite of the high design pressure, flange stresses were computed from the practical equations commonly used for this type of problem.

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[1]The authors are acquainted with the results of one failure which took place during the hydrostatic test of a vessel quite similar in size and shape to the driving tube. The vessel failed at the relatively low pressure of 20,000 psi; the ensuing damage was impressive. Stuffing a second vessel, which also failed, with a close-fitting, solid metal cylinder did not noticeably reduce the damage of the second explosion. The hardness of the eighteen remaining vessels was then reduced from Rockwell C-40 to C-36. All of these were tested successfully. Test personnel noted that the first two vessels rang like bells when tapped with a hammer (as does the driving tube); in contrast, the remaining eighteen (hardness C-36) responded with a kind of dull thud.

The various ports and joints in the tube assembly are made gas tight with O-ring seals, care being taken that clearances are kept small enough to prevent extrusion between the mating surfaces. This type of seal has worked very well.

Diaphragm and Transition Section

The diaphragm separating the driving from the driven tube is illustrated in figures 3 and 6, and the retaining ring holding it in place is shown in figure 4. Figure 4 also illustrates the transition section. Pertinent physical data are tabulated in table II. The distinguishing features of the assembly are (a) the diaphragm is self-rupturing, and (b) the face of the transition section supporting it has a square, not round, opening which is intended to minimize tearing at the base of the petals. That this objective was achieved is quite apparent from inspection of the ruptured diaphragms displayed in figure 3. With any type of combustion, including relatively severe detonations, no petal has ever been lost. The diaphragms are not bulged by preloading before use.

In selecting this design the primary concern, aside from retaining the petals, was assurance that premature ruptures inducing detonation would be avoided. The general arrangement considered most promising in this respect was the self-rupturing diaphragm of the type described in reference 5.

With a self-rupturing diaphram it is imperative to know accurately the bursting pressure before it is used in the shock tube; assurance is also necessary that bursting pressure for any given design will be repeatable within narrow limits. Arrangements were therefore made to test designs outside the tube. A hydraulic test apparatus (fig. 7) - despite the fact that it produces low rates of loading, and that bursting pressures measured under such conditions might differ markedly from those encountered in the shock tube - was assembled for this purpose. The accuracy with which it predicts results proved to be much better than expected. A comparison is shown in figure 8.

The diaphragms conformed closely enough to the design reported in reference 5 to permit valid comparison of the present results with the design charts of the reference. The only difference possibly vitiating such a comparison was the use of a square instead of round exit port. Four points covering the range of local experience, taken from the faired curve for shock tube results, are plotted in figure 9, which is a reproduction of figure 5 of the reference. The agreement is considered excellent.

Working Section

The working section consists simply of a 5-foot tube attached to the end of the driven tube having the same bore but an 8-inch o.d. The upstream portion of this unit can be seen in the center of figure 2(b). It is ported as necessary to accommodate the instrumentation. Attached immediately to the downstream end is a conical diffuser connecting it to the dump tank. The driven tube and working section are isolated from the dump tank by a diaphragm of type A "mylar" polyester, 0.002 or 0.005 inch thick, installed at the downstream end of the working section. The thickness used depends upon the pressure to be obtained in the test gas behind the incident shock wave. The 0.002-inch diaphragm is used for pressures up to 1 atm; 0.005 inch for higher values. Experience has shown that these diaphragms are inexpensive, easily installed, and free from operating problems. However, when test gas pressures behind the shock wave are substantially less than 1 atm, diaphragms 0.001 thick are sometimes used to reduce the strength of the reflected shock wave to levels not interfering with test results. This arrangement requires close attention during the evacuation of the dump tank and driven tube to avoid premature rupture.

Combustion Gas and Ignition Systems

Detonation is unquestionably the major problem encountered in the operation of a combustion drive shock tube. The necessity of minimizing its occurrence governs decisively the choice of every important design feature of the systems for mixing, loading, and igniting the driver gas. It cannot be said that the present equipment has been entirely successful in this respect, but some aspects of the arrangements chosen appear to have been helpful.

In designing the gas mixing system the principal objectives sought in the effort to control detonation were: (1) precise control of mixtures used and (2) uniform distribution of all constituents throughout the combustion chamber before ignition. Other objectives considered equally important, but having no bearing on detonation, were safety of operating personnel and flexibility in usage. A schematic drawing of the system is shown in figure 10.

The relative proportions of the mixture are controlled by measurement of partial pressures. The gages on the mixing panel intended to control the $He:H_2$ ratio are graduated to read 1/750 full scale. For the most unfavorable proportion this results in errors slightly less than 1 percent in the hydrogen partial pressure. A series of four gages, each indicating 1/1000 full scale and having maximum ranges of 100 psia, 500 psia, 2,000 psia, and 10,000 psia control mixing in the combustion chamber. This combustion maintains errors of less than 1/2 percent over the entire useful range of mixtures and charging pressures.

Devising an effective arrangement that would ensure uniform distribution in the driving tube was more difficult. Calculations indicated that approximately one year would be required for one part hydrogen to diffuse into four parts of helium in the driving tube, the path length being 8 feet and the total pressure 15,000 psi. It was therefore decided to rely upon jet action to mix the constituents, and arrangements were made to introduce the helium-hydrogen mixture into the driving tube at sonic velocity. Since the maximum charging pressure was 5,000 psi, maintenance of sonic flow during the entire charging cycle required a high source pressure. The 15,000 psi value was selected partly because for that pressure the principal components required (compressor, large bore tubing, fittings, etc.) were readily obtainable.

Originally it was planned to premix the hydrogen and helium at 6000 psi in vertical tanks. The mixing was to be achieved by diffusion, it being thought, in spite of the results of the calculations for the combustion chamber, that two or three weeks should suffice. This procedure proved ineffectual; the extent to which it failed is discussed in appendix B. Present charging practice consists of filling the combustion chamber directly with oxygen, hydrogen, and helium, in that order, the latter two gases being introduced at sonic velocity.[2] More information concerning the procedure is contained in the section "Operating Experience."

The gas mixture is ignited with a hot wire. This method was first suggested in a personal communication to the authors[3] and subsequently described in reference 6. Pertinent data concerning the components used in the subject installation are included in table IV.

The electrical feed-through in the breech plug (fig. 5) is insulated by nylon, which has been found superior to the boron nitride first used in that it survives detonation. It also is markedly cheaper. Although the inside surface of the nylon vaporizes slightly on each firing, it is quite satisfactory as an insulator. The ignition wire itself is drawn taut to a specified tension and clamped directly to the downstream support. It has been found unnecessary to use springs or any supporting material to keep the wire from sagging against the combustion chamber during ignition. The wire remains intact during normal combustion, but it is replaced for each firing.

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[2]For 1000 psi charging pressure and the source pressures stated above the flow times for both the hydrogen and the helium are less than two seconds. To obtain accurate proportions with these very short flow times a timing device which automatically controls the inlet valve was developed. This device ordinarily holds errors in hydrogen content below 5 percent and in helium below 1 percent.

[3]Mr. K. C. Hendershot, Convair Hypersonics Laboratory, San Diego, California.

Miscellaneous Equipment

The remainder of the peripheral equipment, excepting some of the instrumentation, is conventional. As indicated in the piping schematic (fig. 10) the driving tube and dump tank are evacuated by a two-stage vacuum pump, composed of an air ballasted vane-type forepump connected in tandem with a Roots-type blower forming the first stage. Valves and piping are arranged so that each vessel may be evacuated independently, or the two simultaneously. A single stage mechanical pump is used to evacuate the driven tube. The ports for evacuating and charging the driven tube were machined in a spacer 2-5/8 inches long of the same o.d. as the tube flanges and an i.d. equal to the tube bore. This spacer is installed between the first and second sections of the driven tube.

At present the lowest practical pressure to which the driven tube can be evacuated is 3 μ. At this pressure the leak rate is 5 μ per hour and is stable over periods up to 72 hours. Although the leak rate is acceptable, the minimum pressure is too high for precise tests. At least one purging with the test gas is therefore necessary. Charging pressure of the test gas is measured with McLeod or Bourdon tube gages, depending upon the magnitude involved.

INSTRUMENTATION

The instrumentation for obtaining performance data measures (a) combustion chamber pressures as a function of time, (b) shock wave velocity, and (c) test gas density as a function of time. Combustion chamber pressure is measured from photographs of the oscilloscope trace of a pressure cell signal. A drawing of the pressure cell and its installation appears in figure 11. It is to be noted that the cell is mounted in a removable liner instead of directly in the port of the driving tube. This arrangement greatly facilitates repair of the erosion encountered when the seal for the pressure cell piston fails.

Shock wave velocity is determined from time histories of pressure in the shock tube at five accurately located ports. The time intervals between the pressure rise at each port is measured to the nearest 0.1 μsec by commercial counters. An oscilloscope with raster sweep also monitors this information, but with somewhat less accuracy. The pressure sensing elements for these measurements are barium titanate cells. By mounting them in rubber it has been found possible to suppress sufficiently the signal from the pressure wave traversing the walls of the driven tube so that it is seldom a source of trouble.

Test gas density is measured with a pulsed X-ray densitometer in combination with an oscilloscope and camera assembly. Wavelength of the X-rays can be adjusted between 5 and 8 Å. The signal fed to the oscilloscope is derived from a photomultiplier tube which, in turn, is driven by a scintillator upon which the X-rays impinge. The error of measurement of a single point is about 5 percent; the error of points taken from a continuous record of density versus time is somewhat less.

PERFORMANCE

A good indication of the performance is furnished by the data of table V and the plot in figure 12(a). All of these data pertain to nitrogen as the test gas and represent conditions behind the incident shock wave. The reader should note that two sets of results appear in the table. The first set was obtained from calculations based upon the observed value of the driving and test gas pressures before diaphragm rupture; the second was derived from the measured velocity of the shock wave. Both calculations are based upon equilibrium properties of nitrogen and were computed as described in appendix A. The agreement between the results is excellent.

The shock tube has been designed so that it can be driven by cold gas mixtures at pressures up to 11,000 psi. Tests using cold helium drive have so far been made at pressures of 300 to 400 psi. An indication of the performance available is contained in figure 12(b). The curve of computed velocity in this figure is based both upon the equation of state of an ideal gas and the assumption that the enthalpy varies linearly with absolute temperature. It is apparent that the variation of calculated velocity with driver pressure is not greatly different from that of the experimental values, so that reasonably accurate predictions can be made with confidence.

OPERATING EXPERIENCE

The changes dictated by operating experience have been centered around but one problem - detonation. To develop a satisfactory operating procedure with a minimum risk of damage, the shakedown operating procedure followed three steps: (1) contained firings with the driving tube blanked off from the driven tube, (2) complete operation with a rough driven tube fabricated from heavy wall, low carbon, commercial tubing, and (3) final test firings with the stainless steel driven tube in place. By this procedure the experience needed to determine ignition characteristics, optimum proportions of the combustible gas mixture, diaphragm design, driving tube pressures, gas mixing procedure, and many other routine matters was obtained with the least possible risk to personnel and equipment.

A chronological account of the various steps taken to develop the combustible mixture currently used and the procedure for introducing it into the driving tube is summarized in table VI. Some typical oscilloscope traces of the pressure during combustion are presented in figure 13. The shots in which detonation occurred are also listed in the table.

The observations made during this series of tests may be summarized as follows:

1. If a mixture with a ratio of 7:2:1 (70-percent helium, fig. 14) is fired immediately after it enters the driving tube, without being allowed to mix, it burns very roughly. Increasing the helium content up to 13-2/3:2:1 (82-percent helium) improves matters, but some roughness is always present.

2. Zones of hot spots evidently occur at intervals along the axis of the driving tube during rough burning. This conclusion is based upon the fact that after firing, the tungsten ignition wire is brittle at various points along its length, retaining its ductility between such points. No such loss of ductility is observed with smooth burning.

3. Rough combustion invariably is noisy, the noise being anything between a light ping and a muffled shock. Smooth burning is too quiet to be heard outside the blast chamber (fig. 1).

4. Rough combustion leaves a puddle of water on the bottom of the driving tube. With smooth burning no such puddle is found. The water remaining in the tube is deposited in small drops uniformly distributed over the entire bore.

CONCLUDING REMARKS

The foregoing report has described a shock tube installation designed primarily for investigating the field of chemical kinetics at temperatures up to 7500° K and at pressures from 1/2 to 5 atm. There was no attempt to make this description complete; emphasis was placed principally upon those aspects of the design upon which opinions differ as to the best arrangement. Effort has been made to explain the reasoning followed in the choices for this apparatus. Wherever possible results measured with this shock tube and its appurtenances have been compared with calculated values, or with results reported for other installations. Agreement has in all cases been much better than originally expected.

APPENDIX A

The performance of the shock tube was computed directly from the properties of the combustible gas mixture and of the test gas at the instant of diaphragm rupture. These calculations assume the following conditions:

1. Isentropic, one-dimensional flow exists in the gas stream extending from the driving tube to the interface.

2. Ideal gas equations are representative of conditions throughout the region of item 1.

3. The free-stream static pressure is constant across the interface (i.e., $p_6 = p_2$).

4. The properties of the test gas across the shock wave may be related to each other by data such as those of reference 1 together with equations derived from the conservation of (a) mass, (b) momentum, and (c) energy.

5. The flow is everywhere adiabatic.

Using these assumptions, choosing the proper frame of reference for velocities, and rearranging some of equations of reference 7, we assembled the following equations for calculating conditions behind the incident shock wave:

$$\frac{u_2}{a_4} = \frac{2}{\gamma_4 - 1}\left[\left(\frac{\gamma_4 + 1}{2}\right)^{\frac{1}{2}} \frac{\left(1 + \frac{\gamma_4 - 1}{2} M_5{}^2\right)^{\frac{1}{2}}}{1 + \frac{\gamma_4 - 1}{2} M_5} - \left(\frac{p_2}{p_4}\right)^{\frac{\gamma_4 - 1}{2\gamma_4}}\right] \tag{1}$$

$$\frac{A_4}{A_1} = \left(\frac{2}{\gamma_4 + 1}\right)^{\frac{\gamma_4 + 1}{2(\gamma_4 - 1)}} \frac{1}{M_5}\left(1 + \frac{\gamma_4 - 1}{2} M_5{}^2\right)^{\frac{\gamma_4 + 1}{2(\gamma_4 - 1)}} \tag{2}$$

$$\frac{\rho_0}{\rho_2} = \frac{\rho_0}{\rho_1} - \frac{\gamma_0\left(\frac{a_4}{a_0}\right)^2 \left(\frac{u_2}{a_4}\right)^2}{\frac{p_2}{p_0} - \frac{p_1}{p_0}} \tag{3}$$

$$\frac{h_2}{h_1} = 1 + \frac{1}{2}\left(\frac{a_4{}^2}{h_1}\right)\left(\frac{u_2}{a_4}\right)^2 \frac{\frac{\rho_o}{\rho_1} + \frac{\rho_o}{\rho_2}}{\frac{\rho_o}{\rho_1} - \frac{\rho_o}{\rho_2}} \tag{4}$$

$$f(\rho_2, p_2, h_2) = 0 \tag{5}$$

Equation (5) is the equation of state, tabulated as in reference 1. It is used in the form seen in figure 15.

There are thus five equations available. For assumed values of A_4/A_1 and of p_4 there are also five unknowns; namely, p_2, ρ_2, h_2, u_2, and M_5. The procedure for calculating these unknown quantities consists of:

1. Computing M_5 from equation (2) for the assumed value of A_4/A_1.

2. Assuming a series of values for p_2 and computing u_2/a_4 from equation (1) for each value.

3. Computing corresponding values for ρ_2/ρ_o from equation (3).

4. Computing corresponding values for h_2 from equation (4).

Two curves are then drawn on figure 15(a). The first curve, $h_2 = f(\rho_2/\rho_o)$, results directly from steps 3 and 4. The second curve is obtained through the intermediary plot, figure 15(b), in the following manner:

1. From steps 2 and 3 plot a curve of $p_2/p_o = f(\rho_2/\rho_o)$.

2. For each point used to construct this curve (or for any other set of points lying on the curve) read the corresponding temperature.

3. With the values of temperature and of ρ_2/ρ_o thus obtained, plot a second curve on figure 15(a), which also represents $h_2 = f(\rho_2/\rho_o)$.

4. The point at which these curves intersect is the solution to the problem.

Some observations concerning this procedure follow:

1. Figures 15(a) and 15(b) can be replaced by any plot depicting the equilibrium properties of the gas, for example, a Mollier diagram.

2. For precise work, a tabulated form of equation (5) and an iteration process can be used to calculate the values of the unknown quantities numerically.

3. For undissociated ideal gases at high Mach numbers the ratios of pressure and temperature across the shock wave vary as M^2, but the density ratio tends to the limit $(\gamma + 1)/(\gamma - 1)$. Whenever, therefore, it can be arranged it is advantageous to use the density ratio rather than pressure as the independent variable.

4. A scheme similar to that outlined above can be used to compute equilibrium conditions across a normal shock wave. The work involved is much less than the computation of shock tube performance.

APPENDIX B

The tanks in which it was planned to premix the helium and hydrogen are cylindrical vessels approximately 13 inches in diameter, 16 feet long (inside dimensions) having a volume of 15 cubic feet. They are mounted vertically. The same port is used for charging both helium and hydrogen, and for withdrawing the contents. It is located approximately 1 foot above the bottom end.

To determine whether diffusion would effectively mix the gases within a reasonable time one tank was charged, first with hydrogen, then with helium. The $He:H_2$ ratio was 6.24 based on partial pressures. After being charged, the contents were allowed to stand 5 days, and were then removed. As the tank pressure fell, samples of the effluent were obtained at the pressures noted in figure 16, and the $He:H_2$ ratios were measured with a mass spectrometer. These ratios are also plotted on the figure.

Figure 16 shows that virtually no mixing took place during this 5-day period, and that thorough mixing could not be expected within any reasonable time. The accuracy of the data presented in the figure was confirmed by using them to calculate the $He:H_2$ ratio of the original contents of the tank. The value thus computed was 6.02, which agrees well with 6.24 ratio obtained from partial pressures.

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TABLE I.- DRIVING TUBE DATA

Material

Type: "Gun type steel"

Analysis:

Element	Specified (NASA), percent	Measured, percent
C	0.30-0.40	0.37
Mn	.20- .90	.56
Si	.10- .35	.21
P	.03 max	.015
S	.03 max	.016
Cr	.60-1.50	1.13
Ni	2.50-3.75	3.47
Mo	.30- .65	.61
Va	.20 max	.13

Method of manufacture: Forged from ingot, 3:1 minimum reduction. Ingot poured from basic electric furnace.

Physical properties*:

Specimen	Tensile Strength, psi	Yield 0.2% offset, psi	Elongation, percent	Reduction of area, percent
Specified	Not specified	145,000 min	10 min	18 min
1- Tangential	177,000	---	7.5	15.7
2- Tangential	187,000	172,000	8.85	23.3
3- Radial	189,000	174,000	10.7	27.4
4- Radial	189,000	175,000	10.6	27.4
5- Radial	189,500	176,000	9.7	18.7
6- Longitudinal	193,500	181,000	14.0	43.7
7- Longitudinal	193,000	180,000	16.2	45.4
8- Longitudinal	195,500	182,500	12.7	39.7

Hardness: Specified - Rockwell C-38 max
Measured - Rockwell C-36 to C-40

Charpy Impact: Specified - 13 ft lb
Measured - 14.5, 15.0 ft lb

Ultrasonic: Okay

Dye penetrant: Okay

*All values obtained from ASTM standard test bars 0.505d × 2 in. long fabricated from the inside 6-in. portion of a 12-in. long coupon forged integrally with the driving tube.

TABLE I.- DRIVING TUBE DATA - Concluded

Dimensions: o.d. 15 in.
i.d. 6 in.
length 17 ft

Ports: 8 total, 6 spaced at 33 in. and staggered at 90°, plus 1 additional port at each end located 120° from corresponding staggered port. Ports numbered 1 through 8 in direction of gas flow; used as follows:

No. 1	O_2 input
2	He/H_2 input*
3	Pressure cell (fig. 11)
4	Vacant
5	He/H_2 input**
6	Pressure cell (fig. 11)
7	He/H_2 input*
8	Charging pressure gage line

*One orifice 0.073 in. d
**Two orifices 0.096 in. d

TABLE II.- DIAPHRAGM DATA

Material

Type: 321 stainless steel

Analysis:

Element	Specified (ASM),%	Measured,%
C	0.08 max	0.040
Mn	2.00 max	1.56
P	.045 max	.023
S	.030 max	.009
Si	1.00 max	.77
Cr	17.00-19.00	17.85
Ni	8.00-11.00	9.60
Ti	5×C, min	.48

Physical properties, measured:

Tensile strength	86,300 psi
Yield	39,800 psi
Elongation	52%
Hardness	Rockwell B-81
Bend test	180° at 1x thickness, o.k.

TABLE III.- DRIVEN TUBE AND WORKING SECTION DATA

Material

Type: 316 stainless steel

Analysis:

Element	Specified (ASM), %	Measured, %
C	0.10 max	0.06
Mn	2.00 max	1.85
Si	1.00 max	.46
P	.045 max	.031
S	.03 max	.014
Cr	16.00-18.00	17.42
Ni	10.00-14.00	13.79
Mo	2.00-3.00	2.58

Method of manufacture: Forged from ingots, 3:1 minimum reduction. Ingots poured from basic electric furnace.

Physical properties:

Specimen	Tensile Strength, psi	Yield 0.2% offset, psi	Elongation, %	Reduction of area, %	Rockwell hardness
Specified	75,000 min	30,000 min	25 min	35 min	B-95 max
1- Tangential	77,750	37,500	37.5	46.6	82
2- Tangential	82,000	38,000	66.0	64.7	83
3- Tangential	80,000	38,000	32.0	48.6	84
4- Tangential	81,250	38,000	65.0	71.6	84
1- Longitudinal	82,500	39,500	71.0	80.2	84
2- Longitudinal	82,000	37,000	70.5	80.2	84
3- Longitudinal	82,000	37,500	72.0	79.4	84
4- Longitudinal	82,250	35,500	71.0	80.2	84

Ultrasonic: o.k.

Dye penetrant: o.k.

Dimensions:

Component	o.d.	i.d.	Length
Driven tube sections	6 in.	3 in.	10 ft
Working section	8 in.	3 in.	5 ft
Flanges	12-1/2 in.	---	2-1/2 in.

TABLE IV.- IGNITION EQUIPMENT AND COMBUSTION GAS DATA

Ignition

Type: Hot wire, heated by capacitor discharge

Wire: 0.015 d tungsten, preloaded with 10 lb tension

Electrical equipment: 6 capacitors at 7-1/2 μFd each (45 μFd total). Voltage 9 kv used, 20 kv maximum available.

Wire temperature: 975° C to 1000° C estimated with optical pyrometer

Combustion Gas

Mixture: $He:H_2:O_2 = 12:2:1$

Source pressures: H_2 2,200 psi to 2,800 psi

He 12,000 psi to 13,000 psi

Procedure:

a. O_2 to amount needed

b. H_2 to amount needed at source pressure

c. He to amount needed at source pressure

d. Mixing time wait before ignition

1. 500 psi charging pressure - 1 hr
2. 1000 psi charging pressure - 2 hr

TABLE V.- PERFORMANCE OF SHOCK TUBE

Initial conditions:

Test gas:

Kind	Nitrogen
Pressure	2 mm Hg
Temperature	525° R
Specific enthalpy	130.1 Btu/lb
Sonic velocity	1,142 ft/sec

Driving gas:

Mixture $He:H_2:O_2$	12:2:1
Charging pressure	505 psia

Test conditions:

Driving gas pressure	3,610 psia
Shock wave velocity	20,000 ft/sec

Computed results:

	Based on driving tube pressure	Based on shock wave velocity
p_2/p_1	426	406
ρ_2/ρ_1	14.21	13.52
T_2	$6,750^{\circ}$ K	$6,680^{\circ}$ K
h_2	8,600 Btu/lb	8,200 Btu/lb
w_1	20,640 ft/sec	20,000 ft/sec (observed)
M_1	18.07	17.51
u_2	19,180 ft/sec	18,520 ft/sec
τ	128.4 μsec	139.8 μsec
l_2	2.46 ft	2.59 ft
a_4	7,105 ft/sec	---
$p_4/p_{4,o}$	7.15	---
Combustion efficiency	96.2%*	---

*Based upon constant volume reaction

TABLE VI.- SUMMARY OF TEST FIRINGS

Shot	Mixture $He:H_2:O_2$	Charging pressure, psi	Mixing procedure	Contained firing	With diaphragm	Number of detonations	Object
1-15	8.8:2:1	500	He and H_2 premixed, charged at sonic velocity	X		2	Test choice of mixture and charging procedure
16-39	13-2/3:2:1 to 7:2:1 and 10-1/3:3-1/3:1, 9:3:1 to 6:3:1	500	All gases mixed in driving tube, O_2 first, then H_2, then He; the latter two at sonic velocity	X		0	Investigate mixing in driving tube and determining optimum proportions
40-44	12:2:1	500	Mixed in driving tube, mixture allowed to stand 20 to 30 minutes before ignition	X		0	Determining benefit, if any, of allowing mixture to stand in driving tube after charging
45-64	12:2:1 and 8-1/2:2:1	500 to 1000	Same as preceding but with 30 to 90 minutes standing time in driving tube	X		4	Choose settling time as pressure is increased
65-84	12:2:1	375 to 580	Same as preceding		X	0	Observe operating characteristics and investigate loading procedures with diaphragm in place
85-90	12:2:1	500 to 575	Same as preceding	X		1	Find method to reduce combustion roughness
91-100	12:2:1	500 to 960	Same as preceding, 30 minutes for 500 psi, 120 minutes for 960 psi		X	1	Determine standing time as function of charging pressure
101-111	12:2:1	500 to 1000	Same as preceding	X		1	Same as preceding
112-123	12:2:1	500 at 1000	Same as preceding		X	0	Final firings to fix all procedures

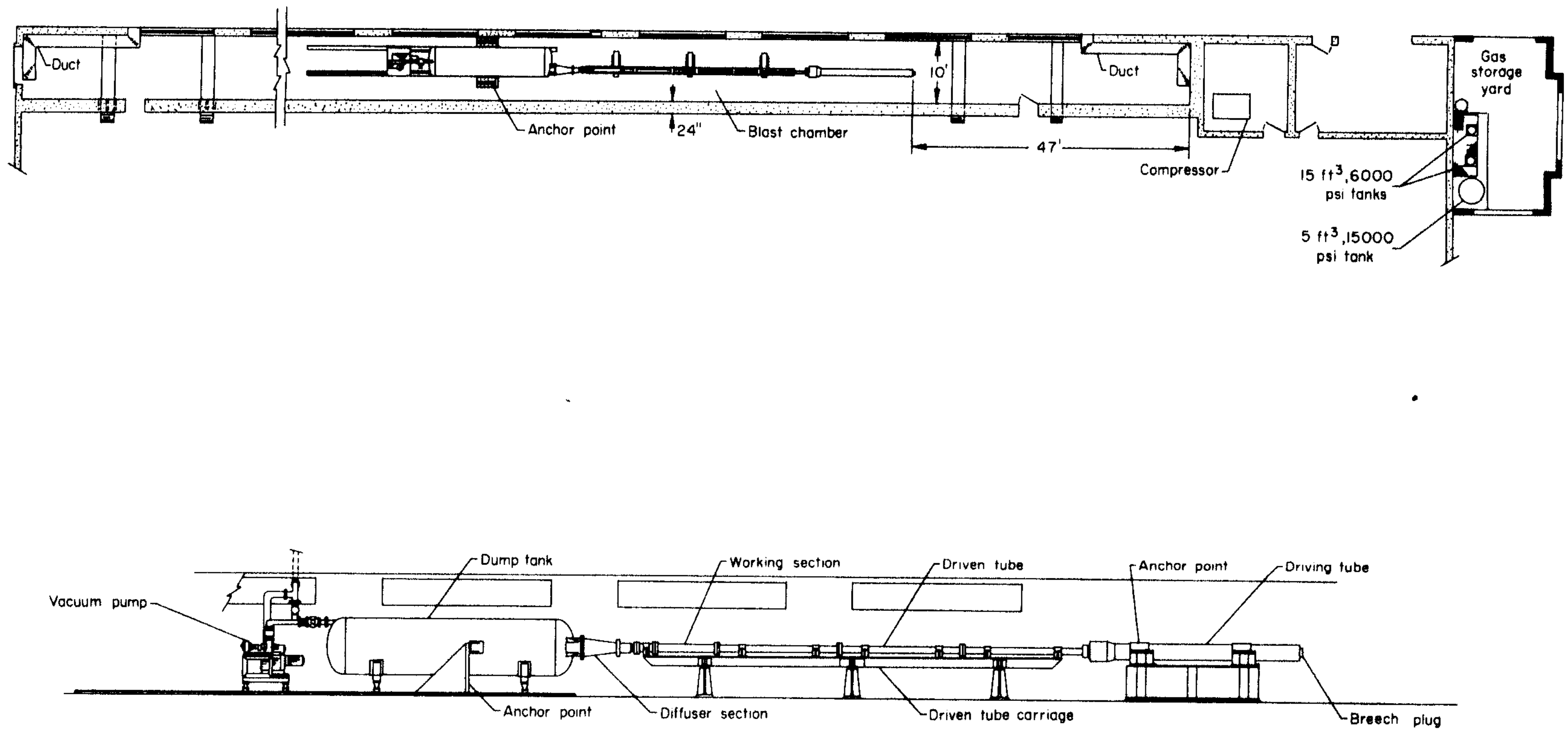
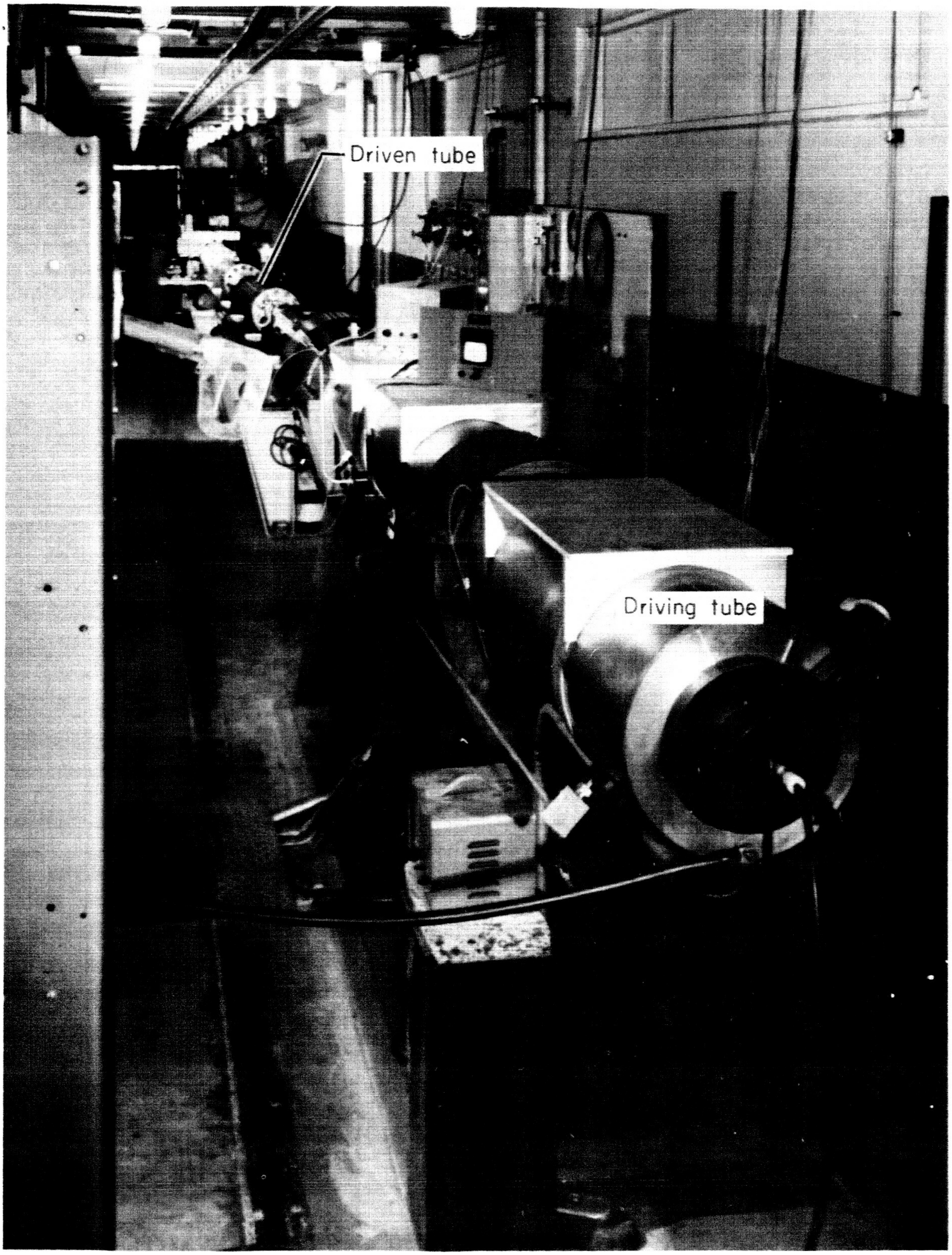


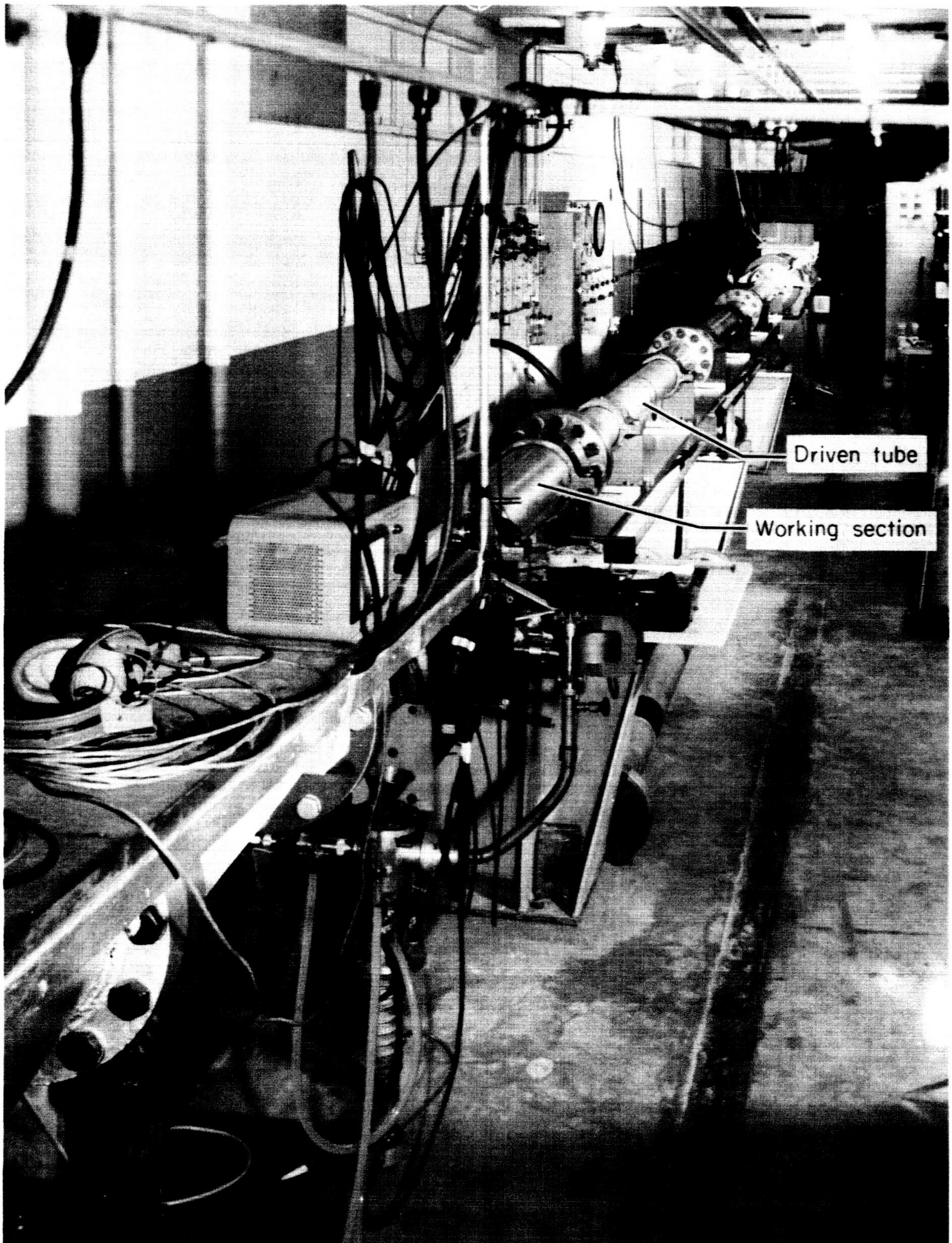
Fig. 1.- Drawing of shock tube assembly.



(a) From driving tube end.

Fig. 2.- View of shock tube.

A-34159-1.1



(b) From working section end.

Fig. 2.- Concluded.

A-34159-2.1

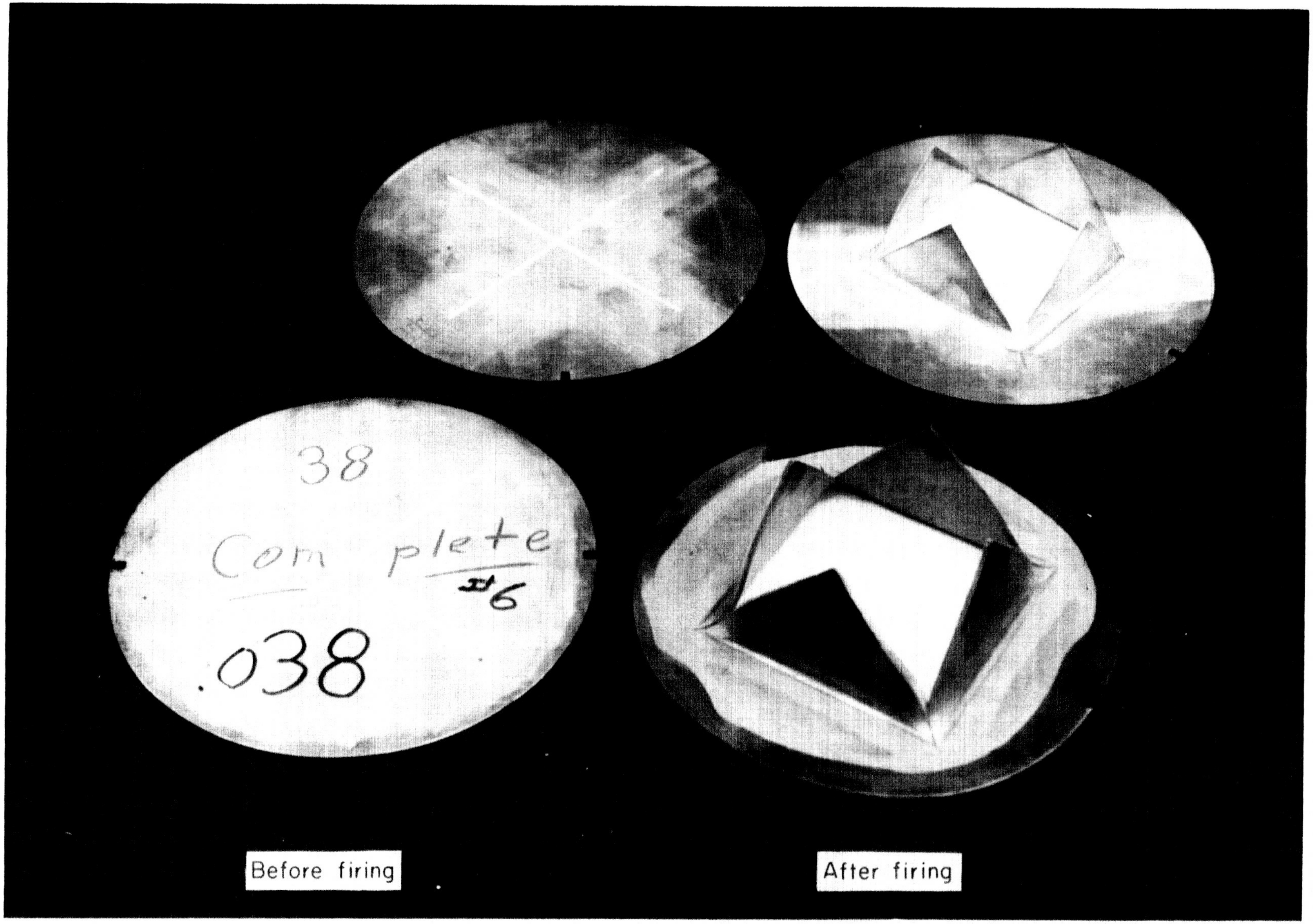


Fig. 3.- Diaphragms.

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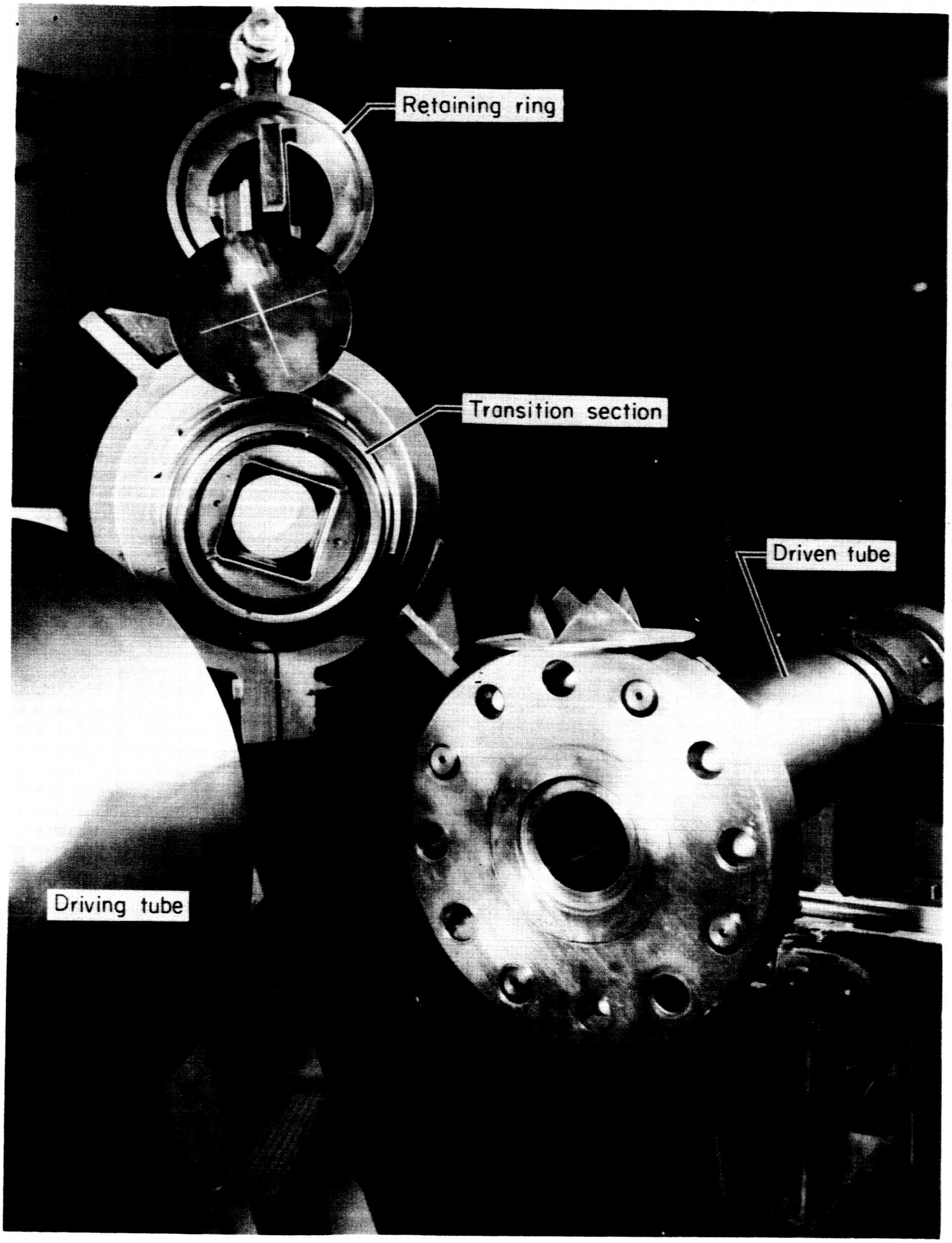

Figure 4.- Transition section and diaphragm components.

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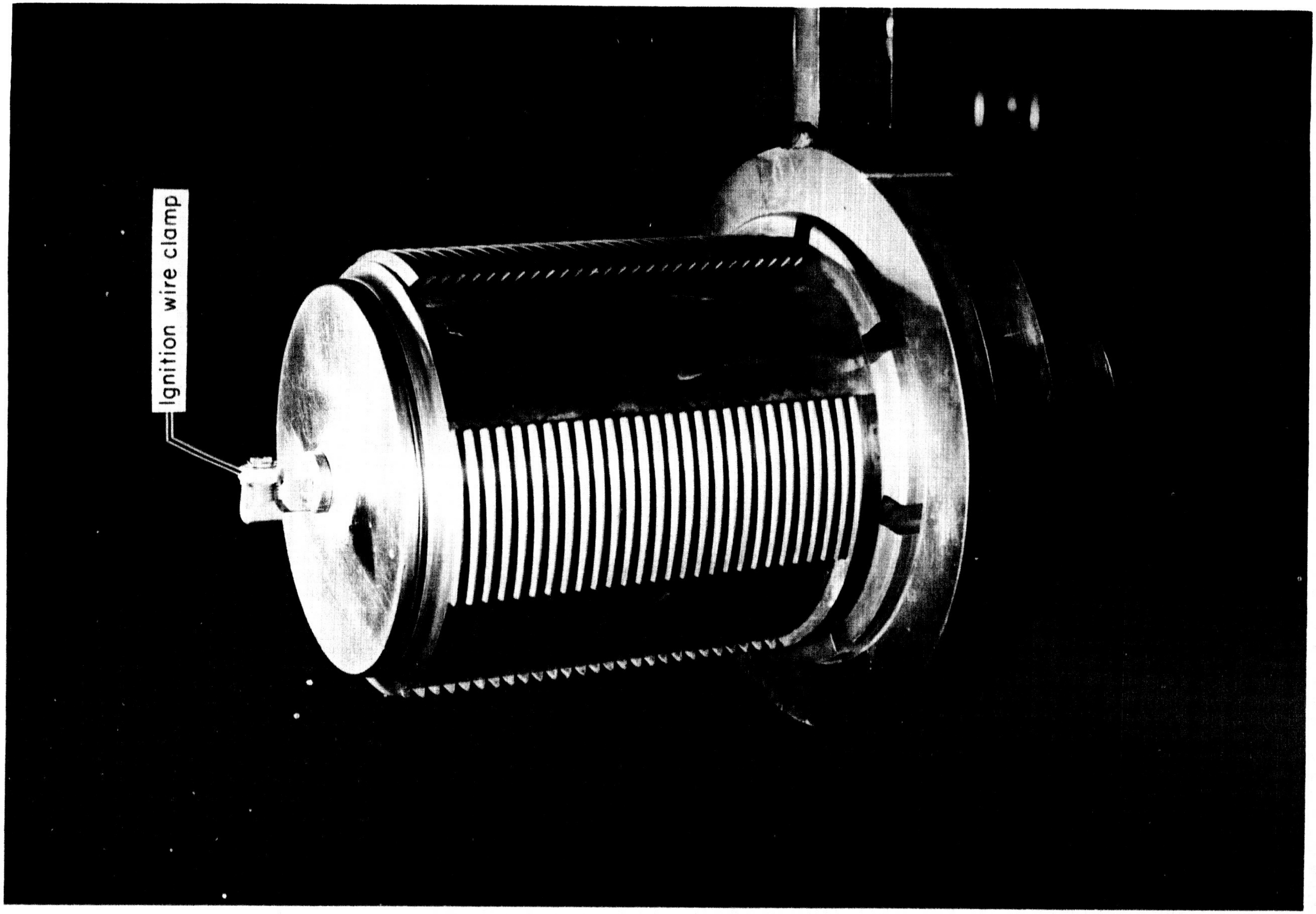

Fig. 5.- Breech plug.

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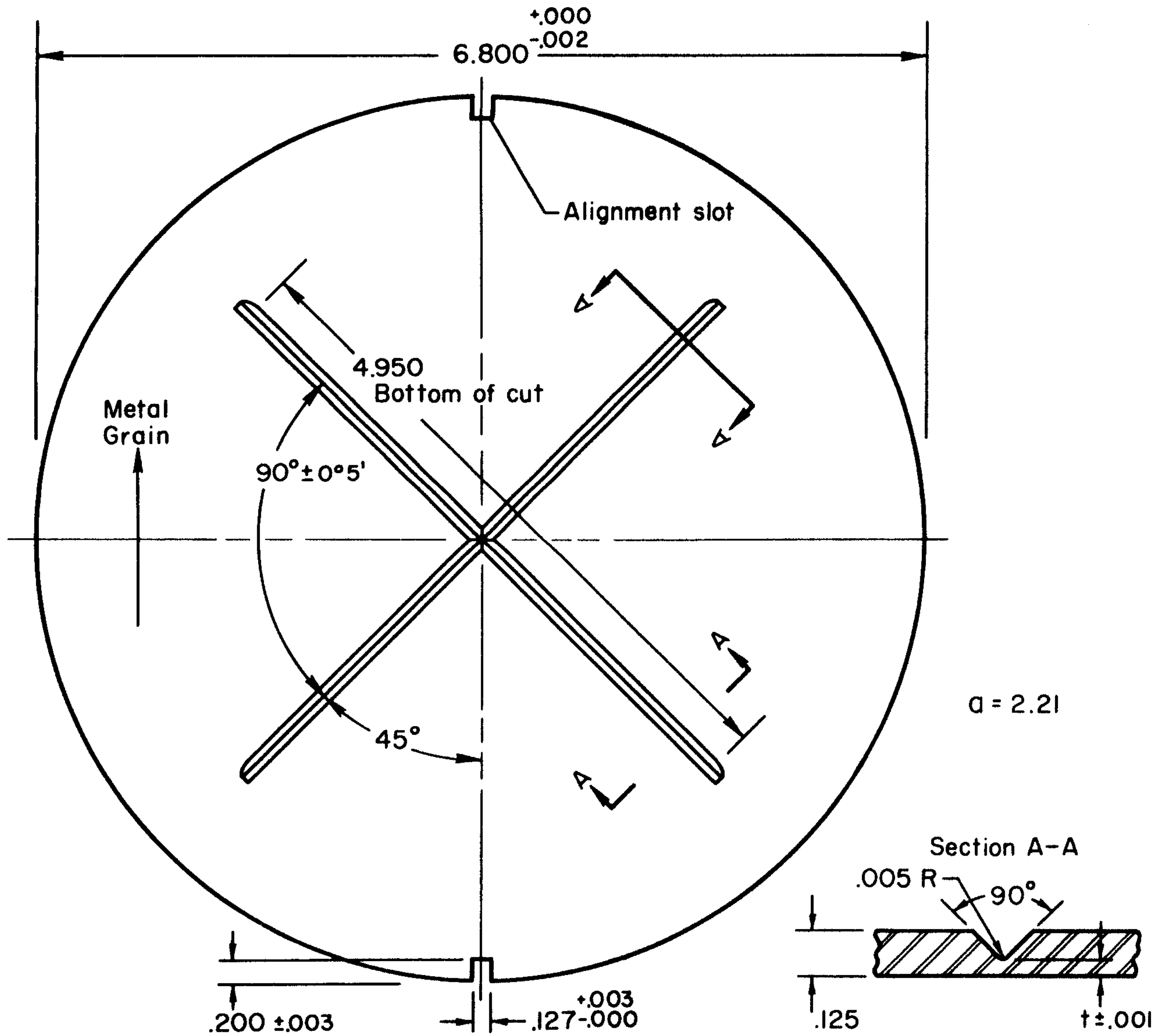

Fig. 6.- Diaphragm design details (all dimensions in inches).

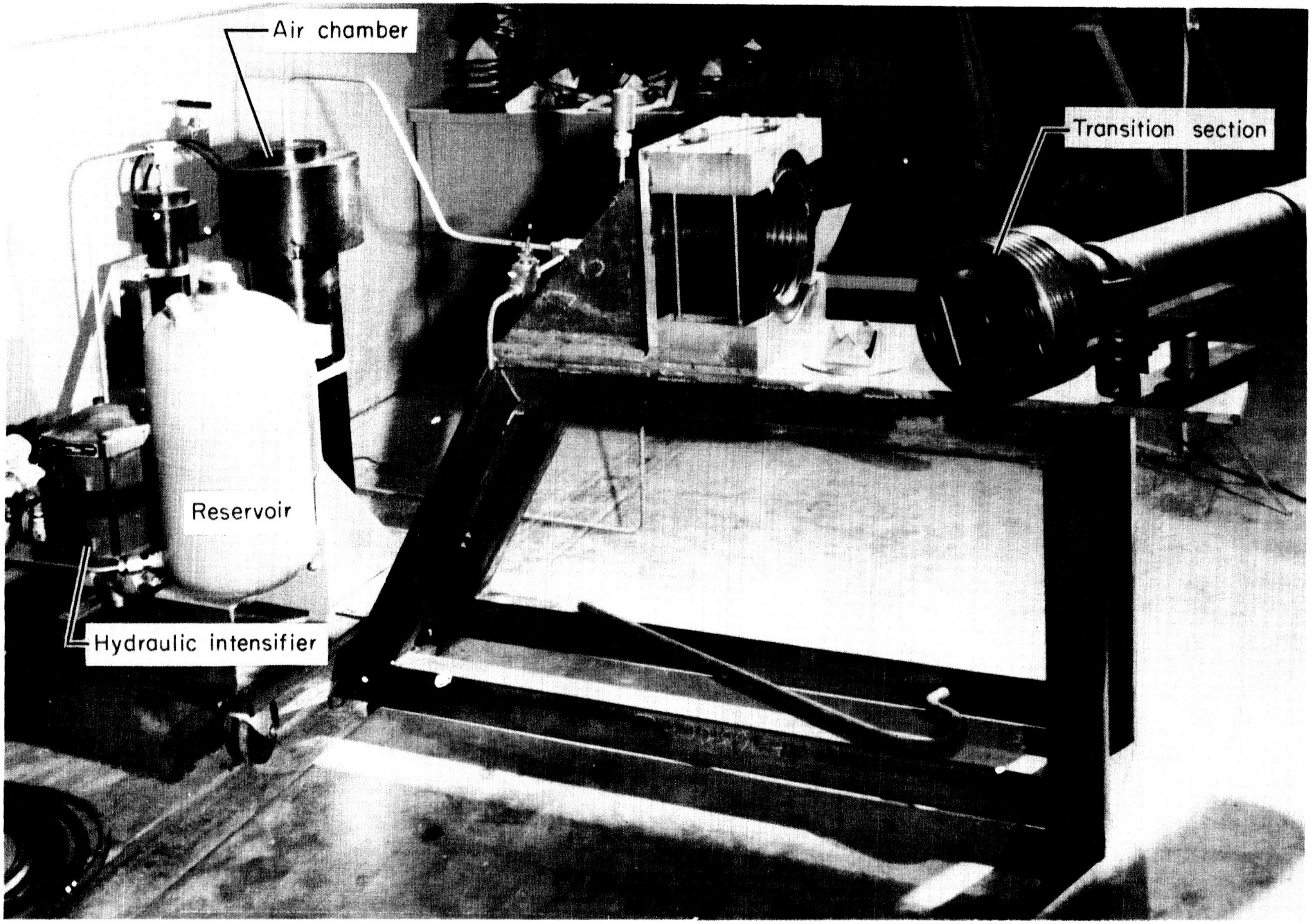

Fig. 7.- Diaphragm test apparatus.

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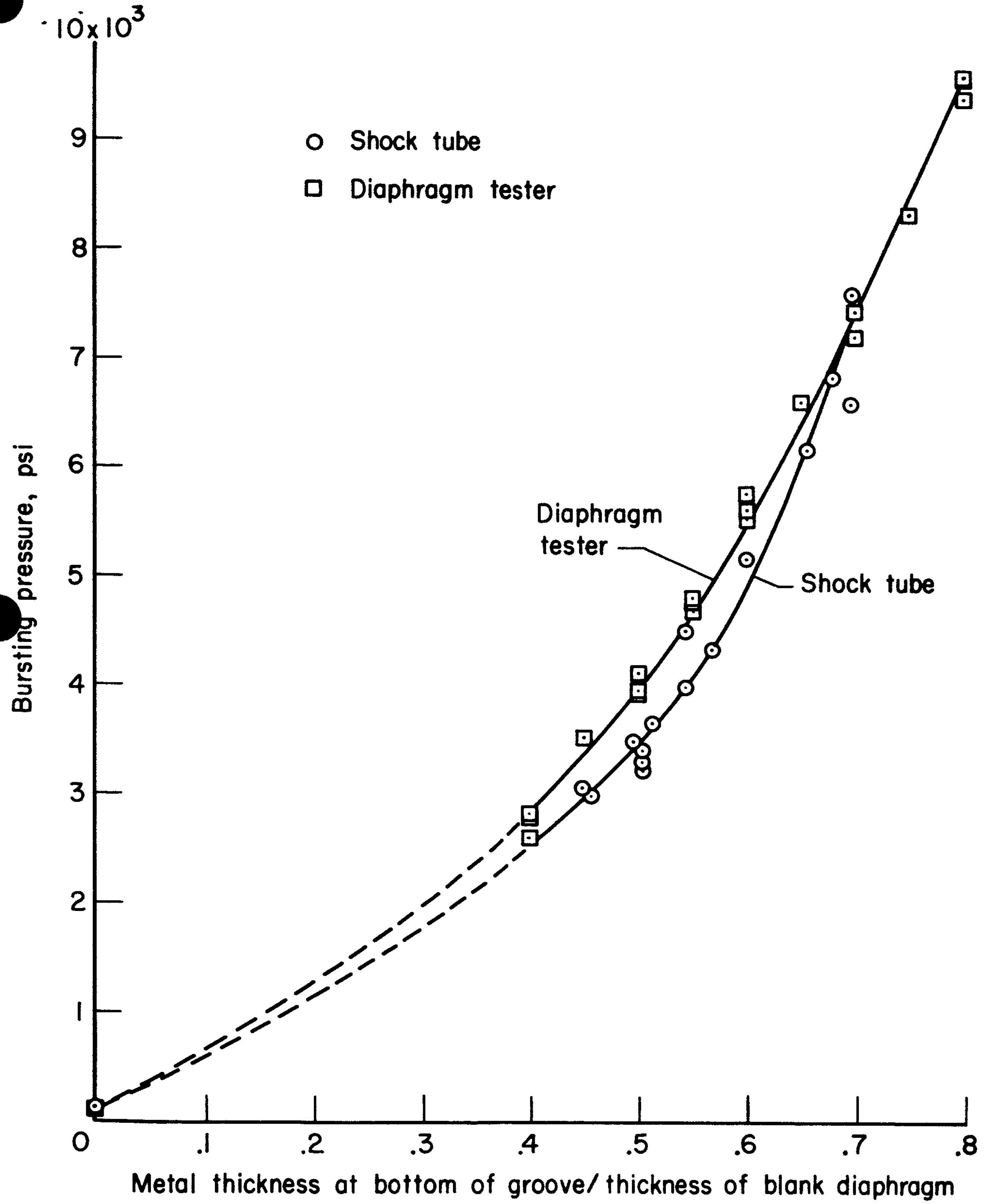

Fig. 8.- Diaphragm bursting pressures in test apparatus and in shock tube.

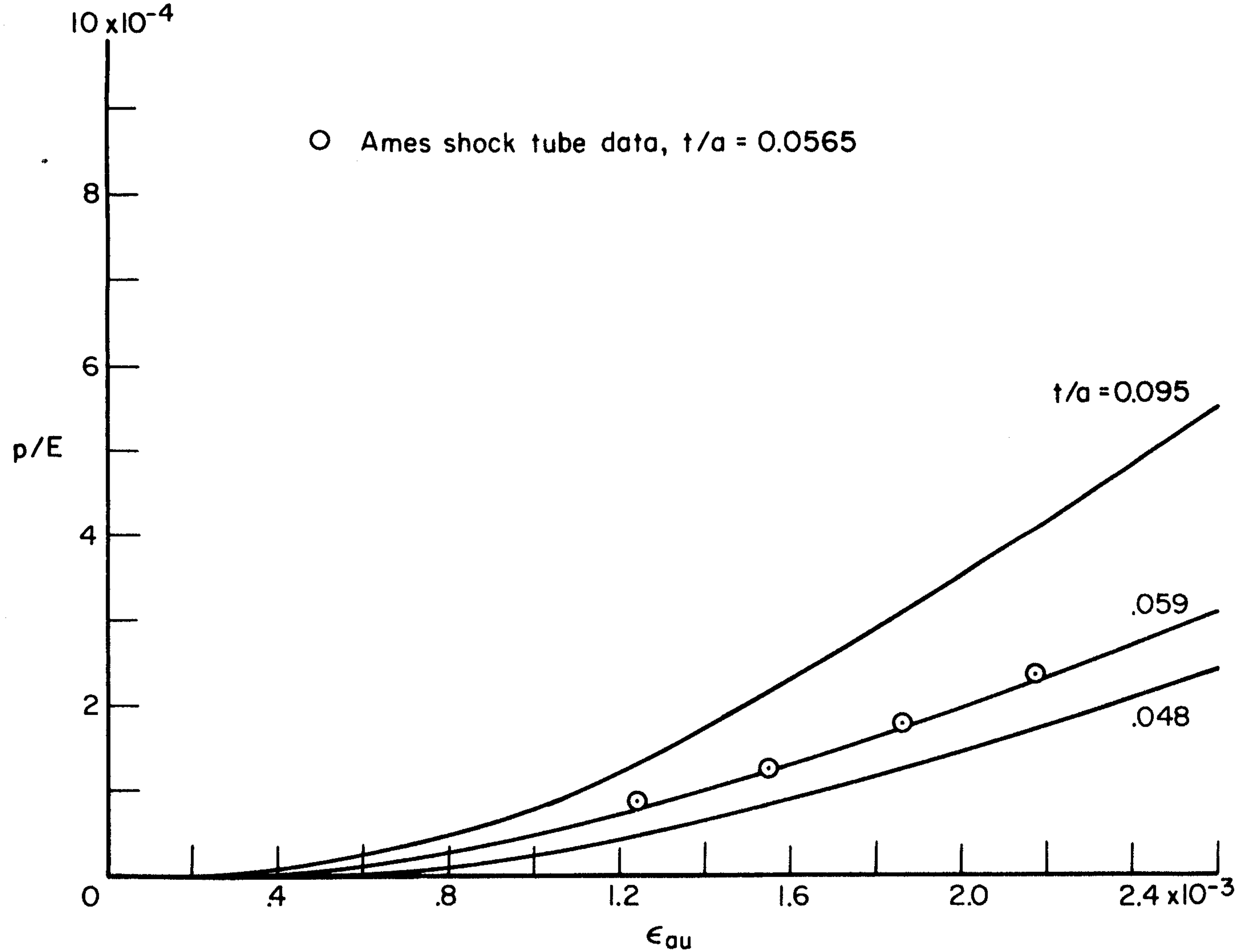

Fig. 9.- Results for Ames diaphragms compared to design curves of reference 5.

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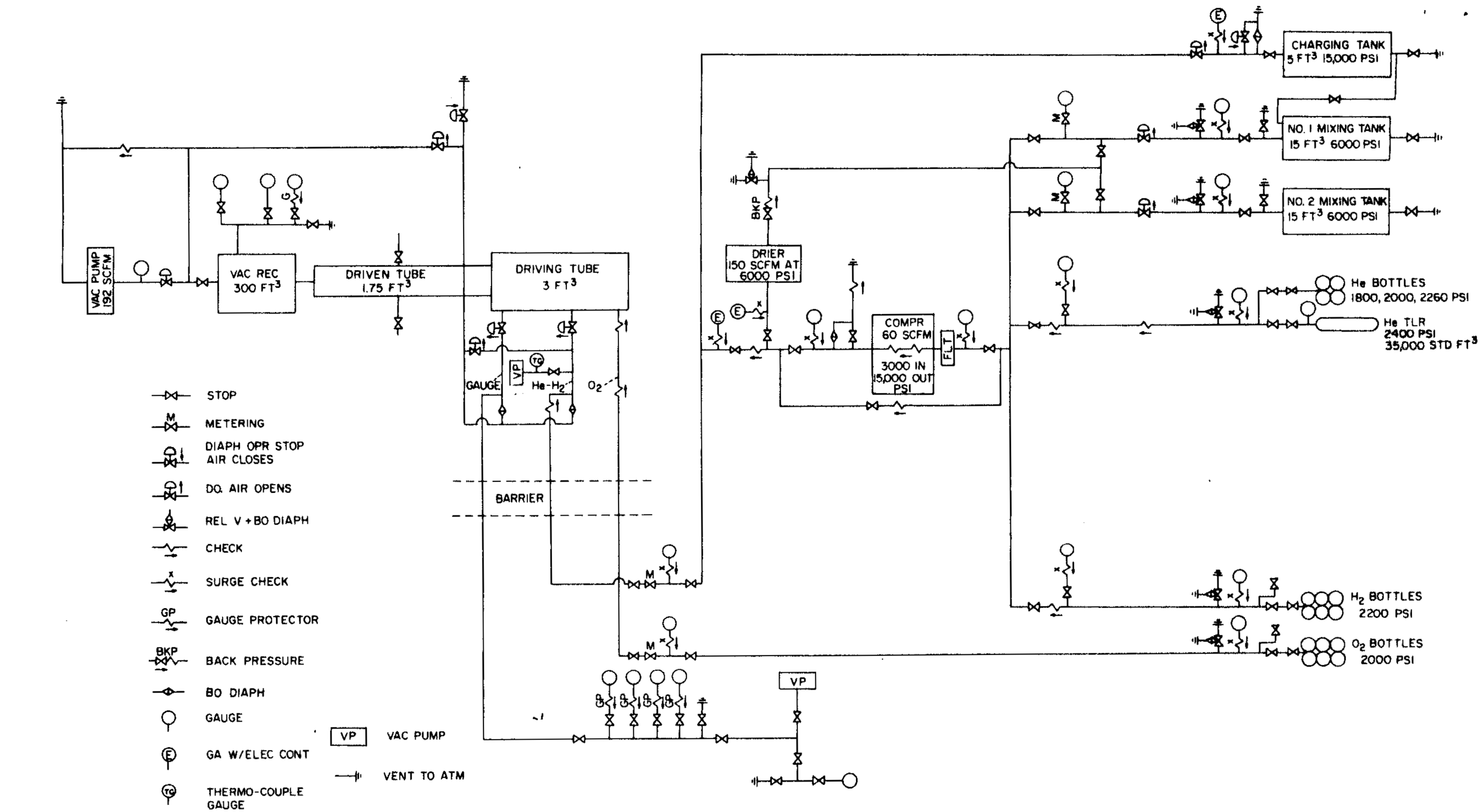

Fig. 10.- Schematic drawing of combustible gas piping.

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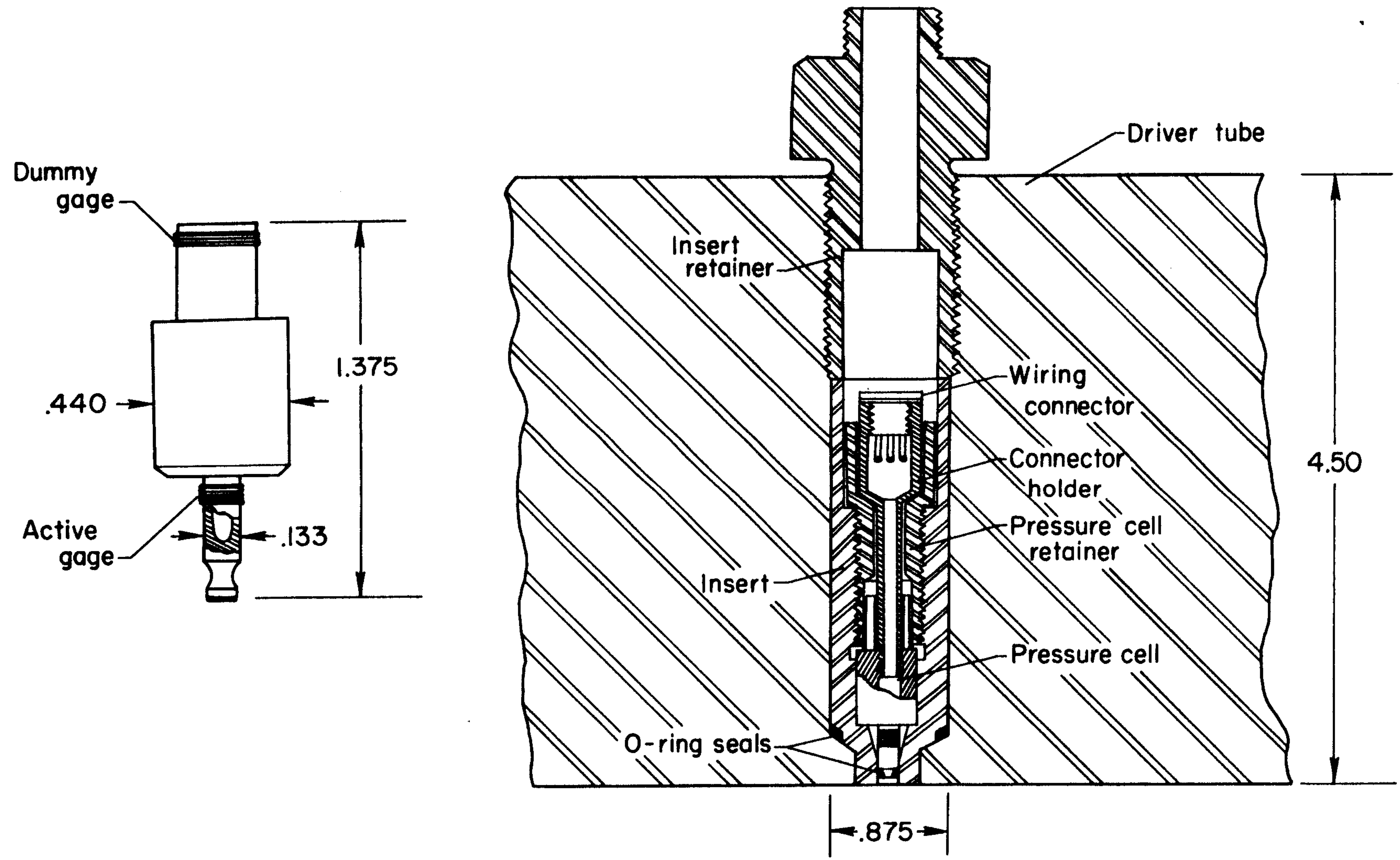
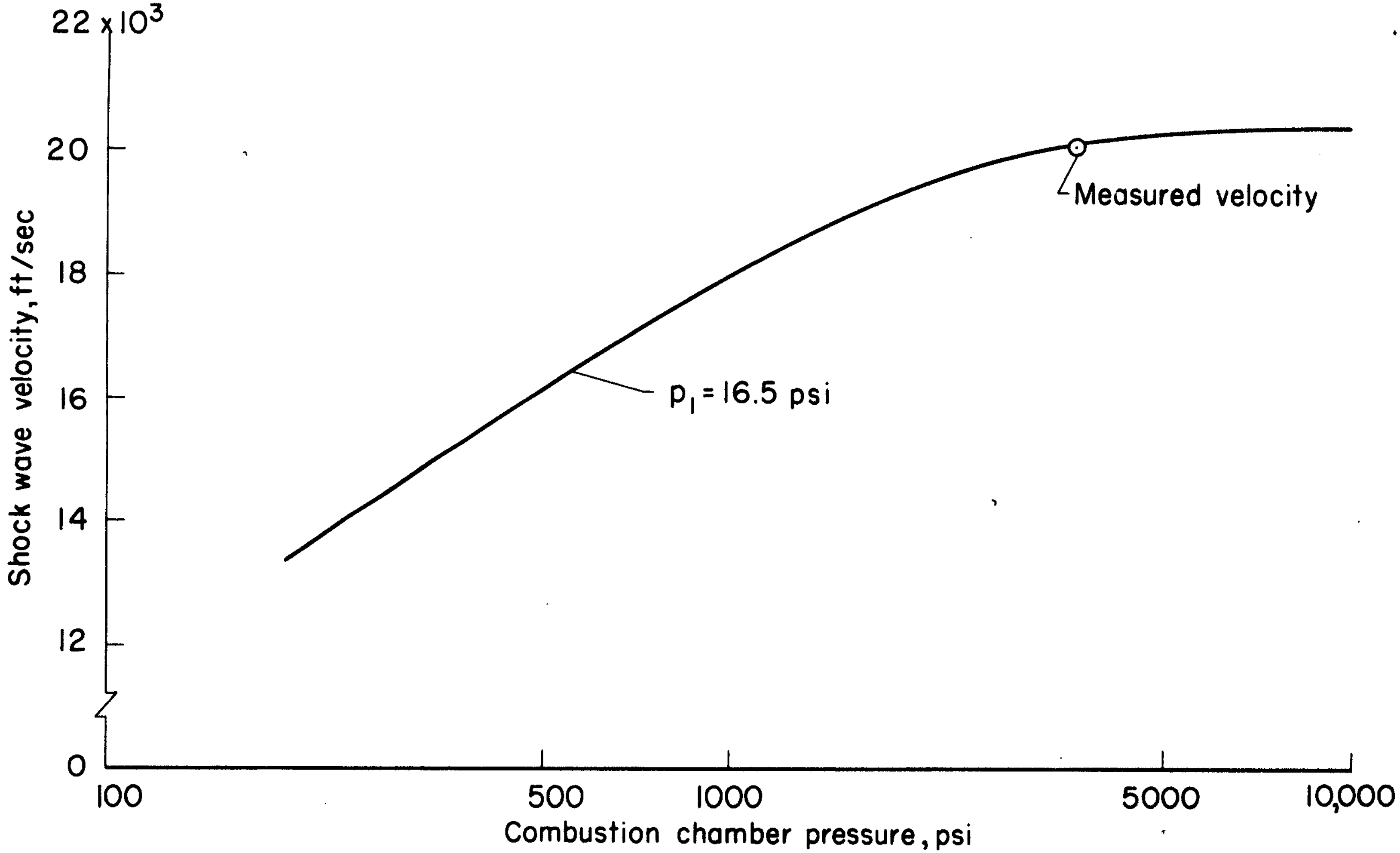


Fig. 11.- Driving tube pressure cell and installation detail.



(a) Combustion drive, driven gas - nitrogen.

Fig. 12.- Shock wave velocity versus combustion chamber pressure.

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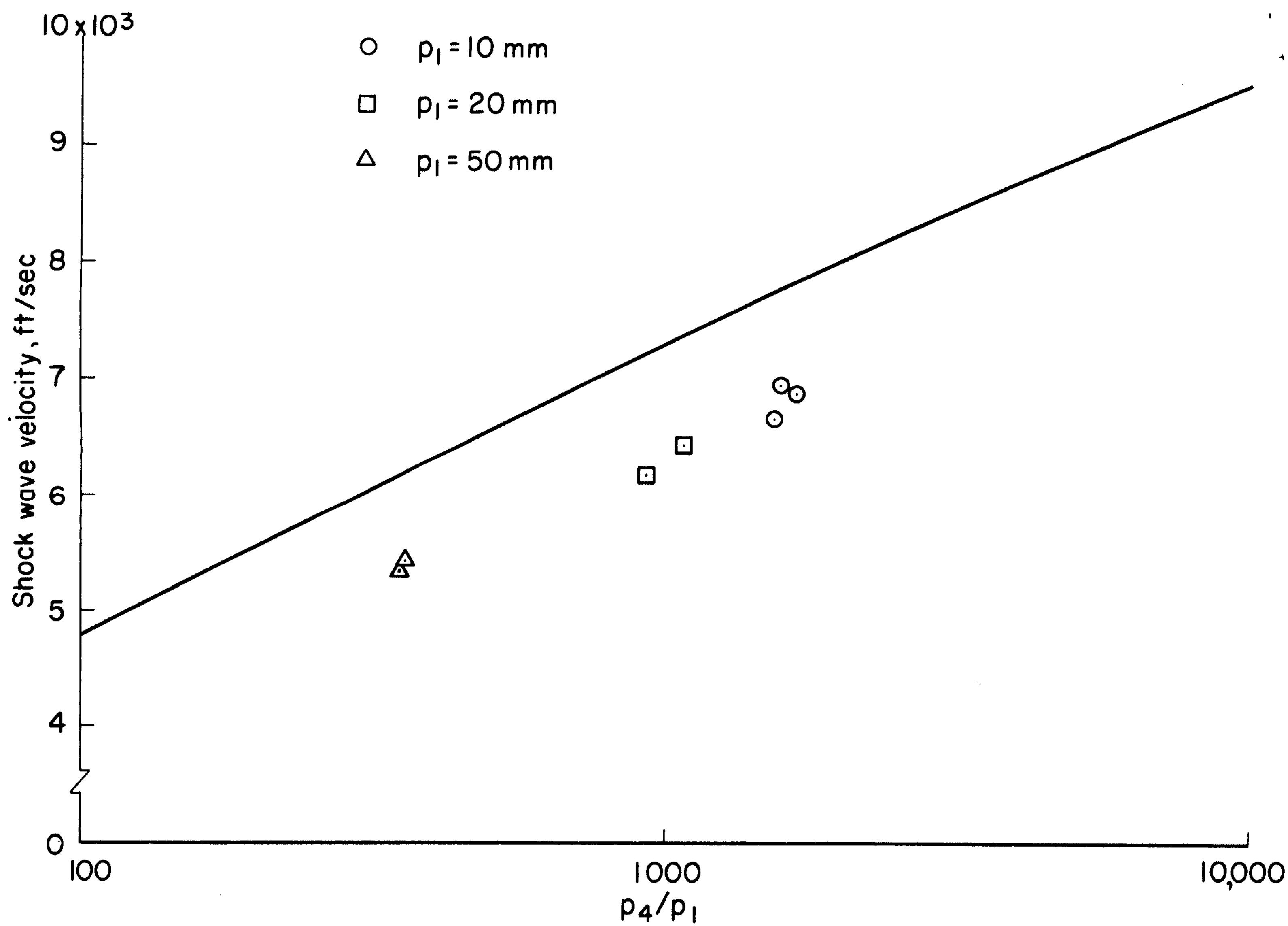

(b) Cold helium drive, driven gas - argon.

Fig. 12.- Concluded.

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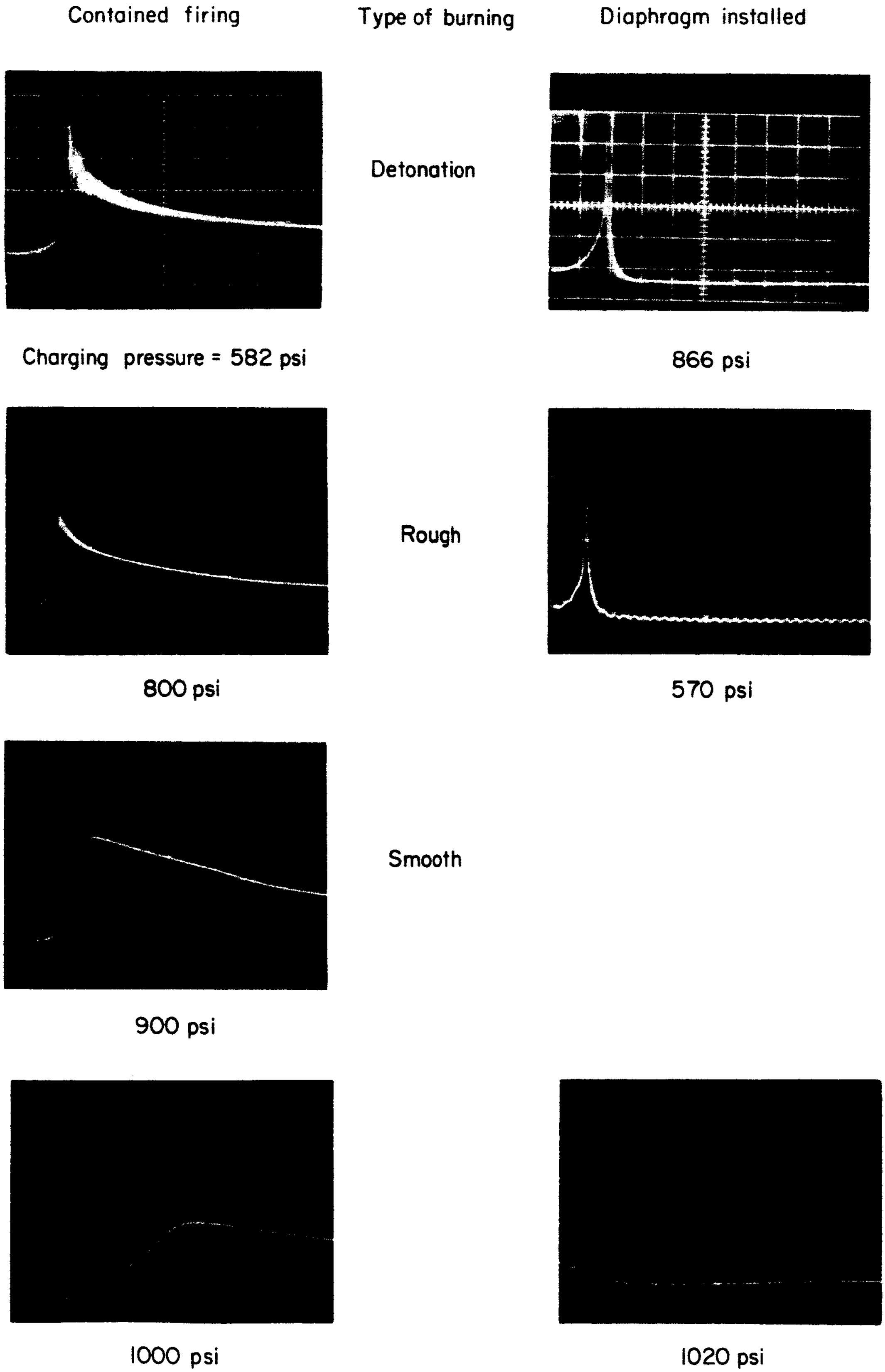

Fig. 13.- Typical records of combustion chamber pressure after ignition.

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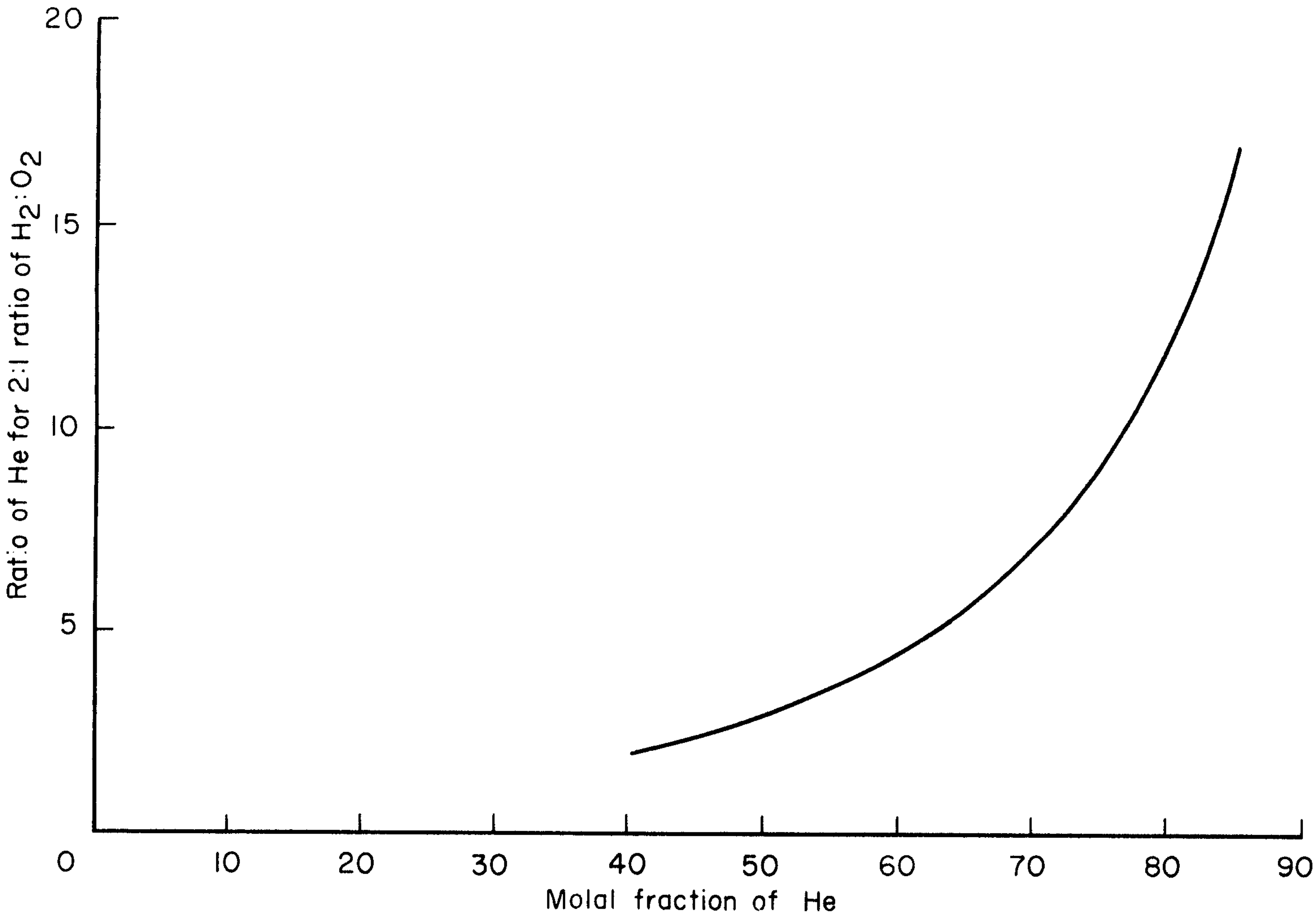
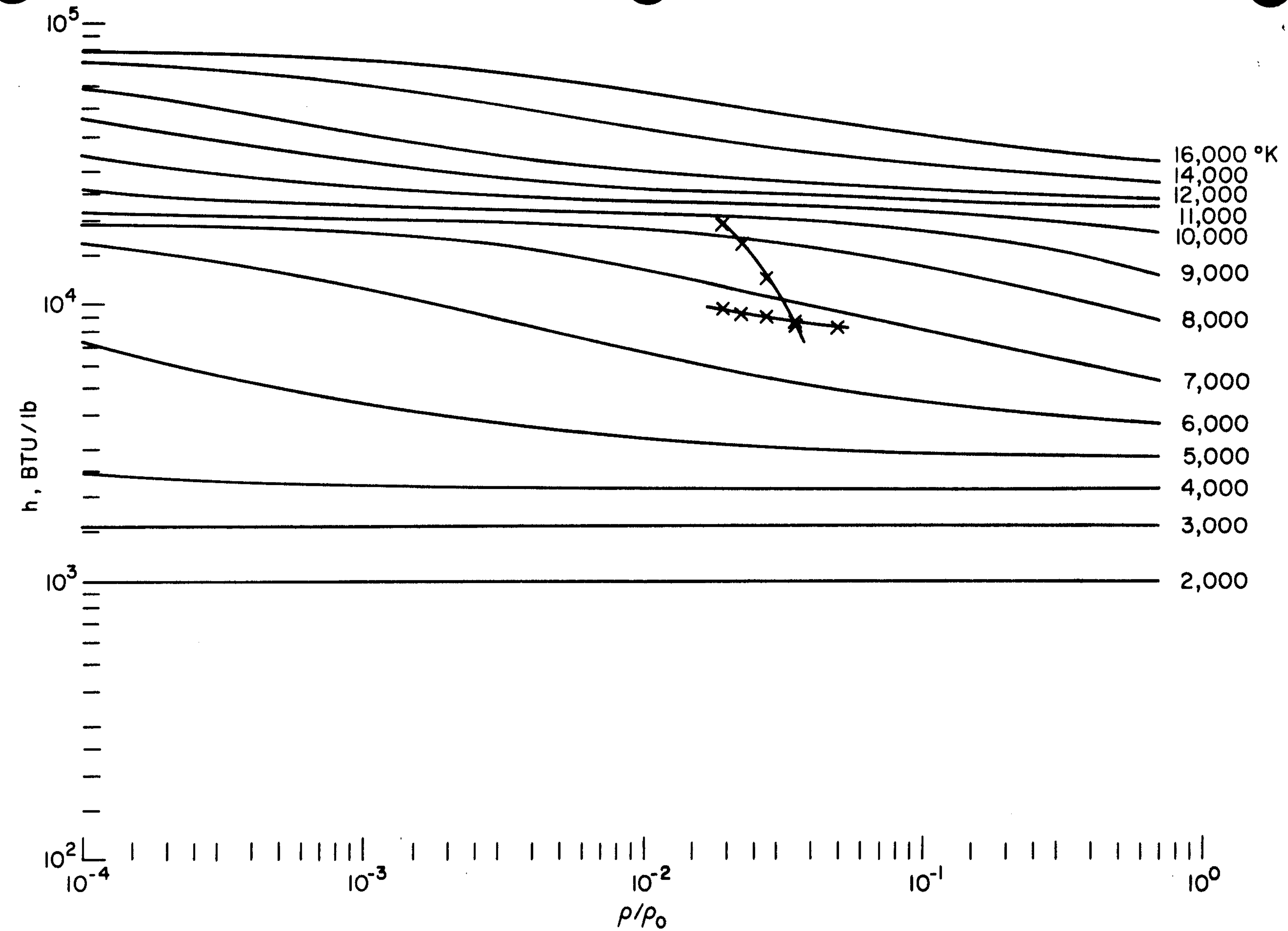


Fig. 14.- Variation of helium ratio with molal fraction of helium in stoichiometric mixture of hydrogen and oxygen.



(a) Specific enthalpy versus density.

Fig. 15.- Thermodynamic properties of nitrogen in equilibrium.

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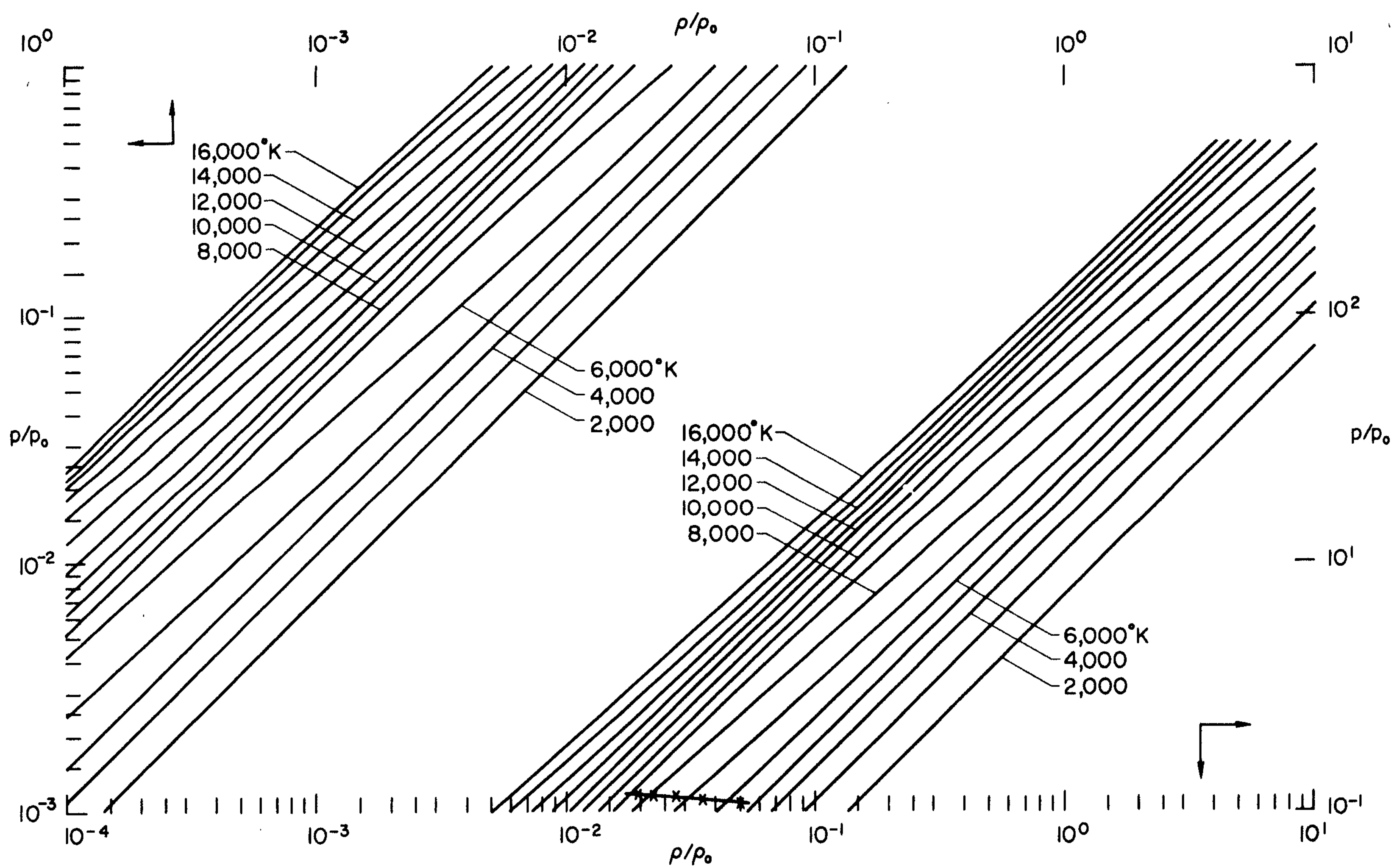

(b) Pressure versus density.

Fig. 15.- Concluded.

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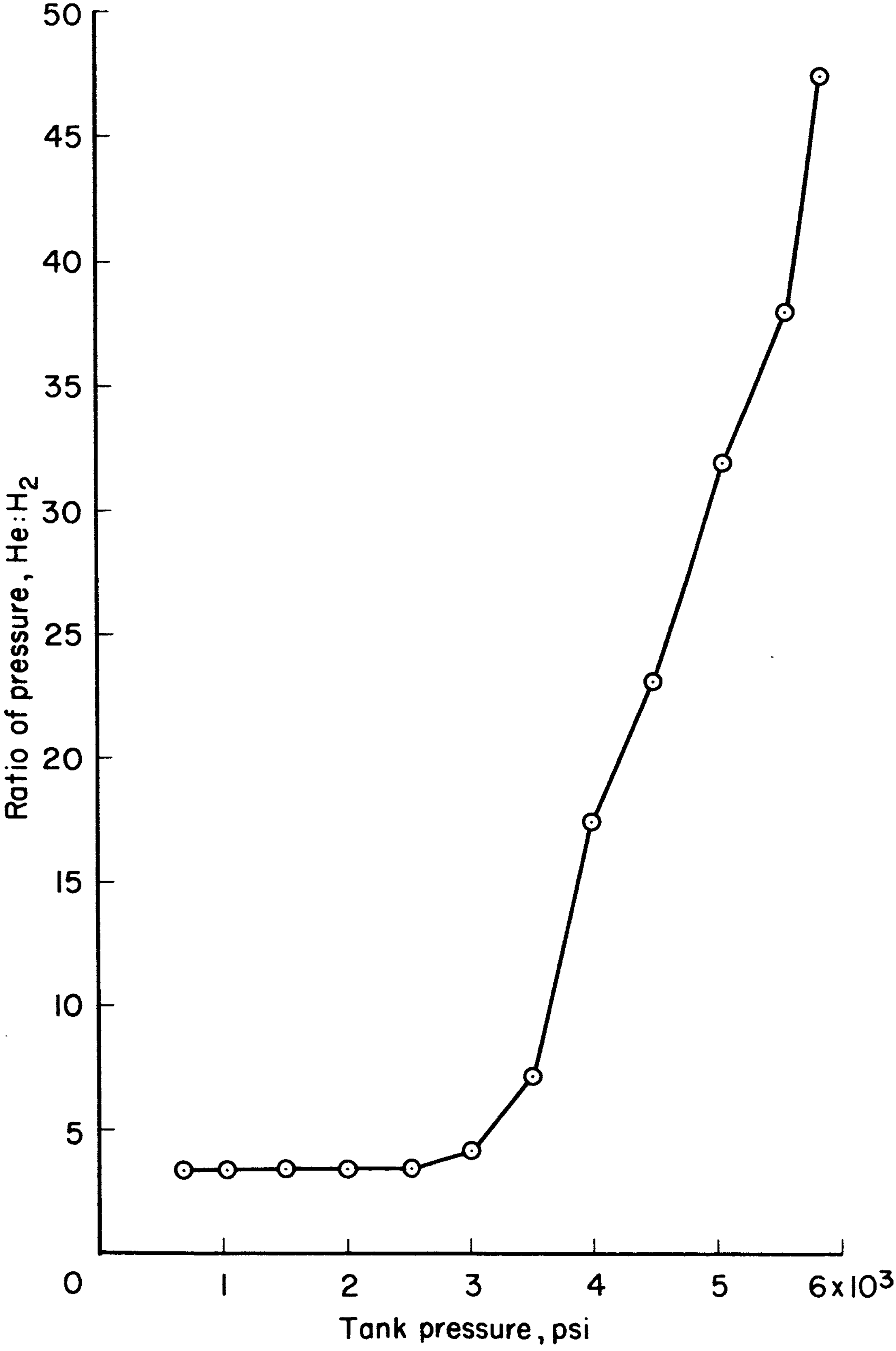

Fig. 16.- Variation of the He:H_2 ratio measured in the mixture issuing from the storage vessel during blow-down.