

THE INSTRUMENTATION AND
CALIBRATION OF THE MCGILL
HYPERSONIC SHOCK TUNNEL

by

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SUMMARY

This report describes the instrumentation of the recently completed Hypersonic shock tunnel at McGill University. Also included are the results of preliminary testing and calibration carried out on the combustion driver section, the shock tube, and the complete tunnel.

The loading system by which the driver gases are metered into the combustion chamber is described, as well as the electrical system used to ignite the mixture. A description of the ionization gages used to measure incident shock velocity, along with the piezo-electric pressure transducers for measuring pressure behind the incident and reflected shocks in the tube, and the stagnation pressure in the test section is also given.

The high pressure resulting from the combustion of a stoichiometric mixture of oxygen and hydrogen, diluted with 76 or 80% helium, is used to break a steel diaphragm and compress the test gas by a reflected shock process. Combustion tests produced peak pressures approximately 25% below those predicted by constant volume combustion theory. In the shock tube, incident shock Mach numbers up to 6.69 were produced in air at a pressure of one atmosphere, giving rise to pressures behind the reflected shock of up to 6,500 psi. However, due to attenuation in the tube, these values

were about 30% below the results expected from theoretical considerations based on no losses. The test section flow Mach number was found to be 20.5, and the tunnel running time was about one quarter of a millisecond.

A short résumé of the safety precautions and operating procedures used with this facility is included.

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INTRODUCTION

Shock tubes and shock tunnels have become increasingly important research tools in the past decade with the advent of hypersonic rockets and artificial satellites (References 1 and 2). The ability of this type of facility to produce stagnation values of temperature, pressure and enthalpy beyond those obtainable in conventional wind tunnels allows complete simulation of flow at high Mach numbers in the upper atmosphere, though for only a matter of milliseconds. Thus, the knowledge gained from these facilities has been made available only by the development of specialized instrumentation, capable of measuring accurately conditions of very short duration. References 2, 3 and 4 outline the approaches to the problem, and the instrumentation techniques used at three different laboratories.

In order to evaluate shock tunnel data it is necessary to know the Mach number and ambient conditions in the test section. As it is often impossible to measure these directly, without disturbing the flow over the model under study, tunnels are generally calibrated for a set of initial conditions, which are duplicated for other tests, and an indirect measurement is used to check flow conditions. An example of this method, as used by the Cornell Aeronautical Laboratory to calibrate their 11 x 15 inch Mach 10 shock tunnel, is given in references 2 and 5. There the measurement of

the incident shock velocity in the driven tube, and the use of thermodynamic charts (eg. Ref.6) provide the total conditions of pressure, temperature and enthalpy in the nozzle reservoir. Assuming isentropic nozzle expansion, these will also be the total conditions in the test section. To calibrate the tunnel, CAL inserted a pitot probe at various positions in the flow, and by measuring stagnation pressure and knowing the total pressure, they were able to determine the Mach number and hence the flow conditions from Mollier data (eg. Ref.7). The results were checked by direct measurement of pressure behind the reflected shock, and the static pressure on the tunnel side wall. The measured pressure in the stagnation region was within 5% of the calculated values, while the test section Mach number calculated using side wall static pressure was almost the same as that from the pitot pressure. For their heat flow studies, flow conditions were checked by measuring incident shock velocity and tunnel static pressure only.

The Shock Tunnel

Early in 1964 construction was completed of McGill University's high performance shock tunnel ST-2 (Figs. 2 and 3). It is a combustion driven tunnel capable of producing air flow in the test section totally simulating conditions at Mach 10 at an altitude of 120,000 feet. The 3.5 inch ID driver (breech)

is 12 feet long, and capable of withstanding pressures of 180,000 psi. The 60 foot long driven tube consists of five 90 mm anti-aircraft gun barrels bored and honed to 3.625 inch ID, and capable of withstanding 32,000 psi. The high enthalpy air behind the reflected shock is expanded through a primary nozzle, a Prandtl-Meyer 10° deflection, and a final nozzle to the 11x15 inch test section (see Fig.3). A complete description of the design and construction of this facility is contained in reference 8. A computer program has been written by the author in collaboration with Mr. N.F. Amin to calculate the theoretical performance of this tunnel. (Ref.9).

INSTRUMENTATION

The instrumentation problem may be roughly divided into two areas; measurement of the steady conditions in the various sections of the tunnel before firing, and measurement of the transient conditions of the flow itself. In the case of the McGill tunnel, only the more basic instrumentation has so far been used, capable of determining the tunnel capabilities and characteristics.

Loading System

The shock tube driver is loaded from a bank of commercial compressed gas cylinders located near the control bunker. Space for 20 cylinders exists and has been divided up into 6 for hydrogen, 4 for oxygen and 10 for helium (or nitrogen used in earlier tests). Each gas is fed into a separate manifold made of 1/4 in. OD 304 stainless steel tubing and Imperial-Eastman stainless steel fittings, which leads through a shut-off valve and a one-way check valve into the metering panel. By means of the valves on each individual cylinder, gas from any particular one may be selected. Thus by using partially empty cylinders at lower pressures and "topping up" with the full ones, the driver may be loaded up to 2000 psi from cylinders originally at about 2200 psi. When not in use, the pressure is turned off and

the lines are drained. A nitrogen cylinder is installed at the end of the hydrogen manifold so that all hydrogen may be flushed out of this line after use.

Metering Panel

Figure 5 shows the metering panel used to measure the gases into the driver, and to obtain the driver pressure before firing. A schematic piping layout has been painted on the front to aid in the loading procedure. The lower 3 valves admit the 3 different gases, while the upper 3 allow the pressure to be read on the respective pressure gages. The centre row of valves open the panel to either the driver, to a vent to atmosphere (through a 1/4 in. ID nylon tube leading outside the building) or to a feed out line (visible on the front of the panel) on which pressure transducers may be statically calibrated against the bourdon gages. The valves are rated at 30,000 psi, and the needle type cut off allows accurate and positive control of the gas flow.

As each gas percentage in the driver section is determined by its partial pressure, an accurate means of checking this is necessary. It was felt that one gage would not be accurate enough over the whole range of 0-2000 psi, so the 3 gages shown in fig. 5 were installed, and are used over different pressure ranges. The one on the left is a two turn 0-500 psia Wallace and Tiernan bourdon type gage, cali-

brated in one-half pound increments and accurate to $1/4$ of one psi. It was factory calibrated prior to installation on the panel. It is protected by an Eagle Engineering "Gage Guard" adjusted to cut off at 450 psi. The other two gages are Helicoid bourdon type, and accurate to $1/4$ of 1%. The one in the centre has a range of 0-1500 psia in 10 lb. increments, while the one on the right has a range of 0-3000 psia in 20 lb. increments.

The metering panel is situated in the control bunker, and is connected to the driver by means of $1/4$ in. OD, $1/16$ in. ID Aminco high pressure tubing, capable of withstanding pressures up to 100,000 psi. While this is an added safety feature, due to the pressure drop along the line it makes loading the driver rather slow.

Driver

Figure 2 shows the rear of the driver section. The loading line mentioned in the previous section can be seen on the top left centre, leading from the bunker and passing through the shut-off valve, a pressure relief fitting and into the driver. The relief fitting contains a diaphragm set to blow out at 59,000 psi, but after some initial tests it was found that pressures from the driver were so attenuated by having to pass back into the feed line and through the $1/16$ in. diameter loading line that a detonation peak pressure

would not be felt there. The fitting, however, has been left in place.

Also in the figure can be seen the Bridgeman seal assembly. After some tests with the original Bridgeman plug described in Ref. 8, a new plug was designed so that pressure measurements could be made as close to the burning gas as possible. The new plug is shown in figures 6 and 7. The current to ignite the gas mixture is fed through the threaded stainless steel rod shown, which is insulated by means of a Teflon insert. The gases are fed through the plug and are distributed along the length of the driver by means of a stainless steel feed line containing 12 holes, .013 inch in diameter. The gas is injected laterally from the tube, which lies at the bottom of the driver, thus imparting a swirling motion to it. By loading at high feed pressures it is hoped to achieve a high degree of mixing in the driver.

Ignition System

Ignition of the gases in the driver is achieved by discharging four 3 microfarad 15KV capacitors charged to the correct voltage through a tungsten wire stretched along the centre line of the tube. As described in reference 8 the system uses 220 Volts AC, and by means of a high voltage transformer and a tripler circuit transforms this up to the 15,000 volts DC used to charge the capacitors (see circuit diagram, Fig.8), the charging voltage may be varied to any desired value. To fire the system a control circuit is used, so that

turning the ignition key in the control bunker causes a solenoid to remove a dielectric shield from the gap between two metal balls, allowing a spark to discharge the capacitors through the tungsten wire (Fig.9).

Test Section

Prior to testing, the shock tunnel is evacuated to the micron range. Before firing, the vacuum is checked by means of a McLeod gage or a Tempcor thermocouple vacuum gage. For all these tests the driven tube was at a pressure of one atmosphere, which is measured on a barometer. The gases in all sections are assumed to be at room temperature prior to the tests.

Ionization Gages

The measurement of the incident shock velocity is one of the most important in the tunnel, since the total conditions in the nozzle reservoir are determined from it. In order to do this, ionization probes are utilized to detect the passage of the shock. Two of these are used, separated by a distance of one foot, and the time interval between the shock passage over them can be measured on a Berkely electronic counter or an oscilloscope to give a direct measure of shock velocity.

This type of gage has been used successfully at both

the University of Toronto (Ref.3) and the General Electric Laboratory (Ref.4) for this purpose. A voltage is maintained across a gap inside the tube, which is shorted out by the ionized air behind a shock wave. This type of gage is quite simple, and has a rise time of about 1 microsecond, but can only be used with shock strengths of 4.5 or greater (Ref.3).

The gages for ST-2 are shown in figs. 10 and 12. They were designed to take pressures of up to 20,000 psi with a factor of safety, and without pressure or voltage leaks. The gap between the 1/16 in. diameter center electrode and the case is .015 inches and is maintained at a potential of 300 volts DC. As described in reference 8, reinforcing rings were shrink fitted onto the final barrel, and holes 12 inches apart were drilled into them to take the pressure and ionization fittings. Thus a measure of the shock velocity is taken over a relatively short distance, and very close to the end of the driven section. The electrical circuit for the ionization gages is shown in Fig.13, while the Kepco power supply and the Berkely counter are shown in Fig.14.

Pressure Transducers

In order to measure the pressures in the tunnel, three piezo-electric type pressure transducers are used (Fig 15). These operate on the piezo-electric effect, ie. stresses on certain faces of some crystals produce an electric

charge on other faces which is proportional to the stress (Ref.10). This charge may then be amplified and read out on an oscilloscope. The advantage of this type of instrument is that it has a fast response time (less than 5 micro-seconds) and can be made quite small.

The two similar transducers shown are Kistler 617 A's which may be used to measure pressures from 0 to 70,000 psi. With them Kistler charge amplifiers are used which convert the charge output from the transducers to a proportional voltage which may be readily fed into an oscilloscope. The amplifier incorporates a high resistance as well, which may be switched into the input circuit to give it a very long time constant. This allows the transducer to hold a charge for several minutes, allowing it to be calibrated statically, either on a dead weight tester or against an accurate pressure gage. One of these transducers is used inside the Bridgeman plug at the back of the driver section to measure the pressure in the driver after combustion. The other is mounted in a fitting (Figs.10 and 11) in the 5th barrel of the driven section approximately one foot from the end. In this position it detects the pressure behind the incident and reflected shock as well as any fluctuations due to further waves.

The other gage is a Susquehanna transducer which has a pressure range of 0-2000 psi, with a higher output per psi. It is used with a cathode follower which has no provision for

static calibration. Therefore the gage was calibrated by a step pressure rise in a small shock tube. This transducer is mounted inside a hemisphere model (Fig.16) to measure stagnation pressure in the test section.

Recording Instrumentation

All pressures from the transducers were recorded on the oscilloscopes shown in Fig.14. The one on the left is a Tektronix 555 dual beam scope, while the one on the right is a Tektronix 532 single beam. Tektronix type CA splitter plug-ins are also available so that any beam can be split to record two different inputs. Dumont oscilloscope cameras were used on both instruments so that permanent records of tests could be made, which were readily available after each test was completed.

Optical System

The Schlieren system existing in the McGill Hyper-sonic Laboratory is presently being modified to study the conditions in the test section. An exploding wire light source will replace the present steady source in order to stop the flow. In the meantime this system has been used to photograph the luminosity surrounding the model during the flow. The system can be seen in position across the test section in figure 4.

RESULTS

Preliminary Combustion Tests

Before proceeding to shock tube tests it was decided to check the combustion driver section and the ignition system to see if smooth burning was obtainable. The solid plate shown in figure 17 was made to fit in the diaphragm position at the end of the driver, but strong enough to contain the explosions and thus give constant volume combustion. A transducer was fitted into the center of the plate to allow recording of the combustion pressure. Another transducer was fitted in the back of the original Bridgeman plug (mentioned in Ref. 8) at the end of a 1/4 inch diameter, 10 inch long recess leading into the driver. In order to maintain driver strength it had been decided that no holes would be bored in the driver walls. This second transducer was an attempt to evaluate the possibility of using this type of fitting to measure the pressure in the driver when regular breaking diaphragms were used.

The gases were loaded from the commercial cylinders through the metering panel and directly into the driver. This method has been used successfully by Nagamatsu (Ref.11) and Duffy and Rogers (Ref.12), though others (Ref.13 and 14) have used pre-mixed mixtures. The procedure used was to evacuate the driver to a few millimeters of mercury. Then, approximately

1/4 of the helium was added, followed by all the oxygen, another 1/4 of the helium, then all the hydrogen, and finally the remainder of the helium. By this means the hydrogen and oxygen were never in contact in the lines. Though a very rich mixture was in the driver after the hydrogen was loaded, it was felt that little danger of premature ignition existed as no charge was on the ignition capacitors at this time, the driver section was well grounded, and no shocks were possible in the loading line due to its small diameter and long distance from the metering panel. The final amount of helium was loaded at as high a pressure as possible in order to promote turbulence and good mixing at the inlet jets. Between 5 and 10 minutes was allowed from the time loading was completed until the mixture was ignited.

Initially the ignition system described in Ref. 8 was used, which was patterned after the one used at the U.S. Naval Ordnance Laboratory in Maryland. It consisted of the capacitors and charging system already described, and utilized a 1/2 inch wide strip of aluminum foil stretched the length of the tube, which was perforated at 3 inch intervals to provide high resistance points where the current burned through and ignited the gas mixture.

The results of one of the preliminary tests is shown in figure 18a. The top trace was inverted and measures the pressure in the plate at the diaphragm end of the tube. The lower trace was from the transducer at the back of the

Bridgeman plug. (The second trace on both was due to a second sweep as the pressure dropped). Though it was not felt that detonation had occurred, the burning was quite rough with pressure fluctuations of almost $1/3$ peak pressure. The transducer located at the end of the 10 inch recess exhibited many more fluctuations and it was felt that this was due to shock and rarefaction waves travelling along the length of this small tube.

References 13 and 14 have also reported rough burning with this type of ignition. The explanation advanced was that the electrical energy to initiate combustion was being added too violently. In order to get a smoother ignition in our driver the use of tungsten wire, as mentioned in reference 13, was tried. First the appropriate energy needed for the .010 inch diameter wire was found by some open air tests. At lower voltages the wire glowed, but unevenly along its length. At the higher voltages it glowed very brightly, and broke apart. Examination of the wire showed it had started to vaporize on the outer surface. A median discharge voltage of 11,000 volts was chosen to ignite the mixture, as this caused the wire to glow evenly along its 12 foot length, but not to disintegrate.

A different method of calibrating the pressure transducers was also used. They were checked against the bourdon gages as a system (transducer, cable, amplifier, cable, oscilloscope) to get a calibration factor, instead of being

adjusted to give a certain pressure reading per centimeter of trace deflection. This method is easier, and less prone to come out of adjustment. The calibration was checked after every four or five shots, and was found to vary very little. Pressures were read to ± 1 millimeter on the oscilloscope scale, so that the accuracy of the pressure reading is $\pm 5\%$. Design was also started on the new Bridgeman plug (Fig.7) which incorporates a fitting for holding a pressure transducer within $1/4$ inch of the burning gases. By this means it was hoped to eliminate the extra pressure fluctuations in the long recess leading to the transducer.

Tests were continued however, to check the tungsten wire ignition system. Figure 18b shows the results of one of these tests. The burning was quite smooth and pressure fluctuations, though still present, were of much lower amplitude. The lower trace was quite similar to those shown in references 11, 12 and 13 for a similar mixture. Wilkins and Carros (Ref. 13) attributed these small fluctuations to pressure waves in the burnt mixture.

Figure 18c shows the final type of trace obtained with the new plug installed. The smoother burning and longer ignition time reported in references 12 and 13 for 80% mixtures is evident. Very small pressure fluctuations after peak pressure can be seen, but the advantage of having pressure pickups as close to the burning gas as possible is quite evident.

Tests were carried out at increasing loading pressures

at helium concentrations of 70, 75 and 80%. The results are shown in figure 19. It can be seen that the results are below the theoretical values as used in reference 9, which were obtained from the Canadian Armament and Research Development Establishment. However the theoretical values do not take into account the effects of heat loss to the walls, which would have a lowering effect. As the fineness ratio of this combustion chamber is relatively large ($\frac{L}{D} = 40$), it is possible that this would account for the discrepancy of about 25%. Both Nagamatsu (Ref.11) and Cohen (Ref.15) found values below theoretical. Their discrepancies were smaller however, 15% and 22 % respectively.

Rough burning was noted at 70% helium and 1000 psi loading pressure, and at 1500 psi with 75% helium very rough burning or detonation occurred. Reference 11 mentions pressures of up to 150 times loading pressure from detonations in a long tube. As this would overstress the driver section, combustion testing in the constant volume combustion chamber was discontinued in favour of testing with breaking diaphragms. The rupturing diaphragm provides pressure relief, which is especially important near detonation conditions.

Shock Tube Tests

During the construction of the tunnel a capping nut and end plate assembly were made which could be attached to the end of any of the driven tube barrels to close off the tube. This fitting was attached to the end of the final barrel to effectively turn the facility into a 60 foot reflected shock tube. The ionization gages and pressure transducer fitting described previously were installed in order to measure shock wave velocity, and the pressure behind both the incident shock wave (P_2) and the reflected shock wave (P_5) at the end of the tube.*

For the first few shots the ionization gages did not trigger properly. The circuit shown in figure 13 (which was taken from reference 3) was then set up. This proved more satisfactory, though the large resistance of the gap gives lower voltages and slower rise times than expected. However, pictures of the combustion pressure history in the driver with breaking diaphragms were taken, as shown in figure 20a.

* The standard shock tube notation as used in any of the references is followed in this section. The original pressure in the shock tube ahead of the shock wave is known as P_1 , the static pressure behind the incident shock wave as P_2 , and the stagnation pressure behind the reflected shock wave is known as P_5 .

This is quite similar to those made by Hendershot at Convair (Ref.14). Then, after six shots at 1000 pounds loading pressure with 75% helium in which combustion had occurred and the diaphragms had opened up perfectly, a severe detonation occurred which shattered the diaphragm and broke the pressure transducer. The pressure history of this test is shown in figure 20b. The pressure starts building up smoothly as in normal combustion, but then suddenly rises vertically off the scale. This is similar to detonations reported by Nagamatsu (Ref.11), as opposed to those reported by Hendershot (Ref.14) which rose rapidly from the very onset of burning.

As the initial conditions were exactly the same as for the previous tests which had produced good burning, it is not known what caused the detonation, though a delay in checking the instrumentation held up firing till about 20 minutes after loading was complete. This delay may have allowed some stratification of the loaded gases to have occurred. It is felt more likely that a kink in the ignition wire caused a hot spot, or perhaps the wire had been broken while the gases were being loaded. This would cause ignition to occur over a short distance instead of the whole length of the tube. In spite of the fact that the diaphragm petals were torn completely off, the pressure rise was still sufficient to rupture the sensing diaphragm of the pressure transducer which was made for use up to 70,000 psi. As no replacement transducer was immediately available, and no reason could be determined for

the detonation, it was decided to proceed with testing without making combustion pressure measurements, at least until reproducible combustion could be obtained. A few subsequent detonations, all at loading values similar to those that produced good combustion on other occasions, have shown the prudence of this move.

Some of the results of the shock tube tests are shown in figures 21, 22 and 23. At first the outputs from the ionization gages were fed into the two inputs of a chopped trace, with one inverted, as shown in figure 21a. By this means a voltage rise from the start gage triggered both sweeps, and a voltage rise from the stop gage deflected the lower trace downward, thus indicating when the incident shock wave had reached this position. The extra sweeps on the figure are caused by the ionized air behind the reflected shock re-triggering the scope. The upper trace in figure 21a is a pressure record from the transducer in the reinforcing ring located 10 1/2 inches from the end of the shock tube. This record is expanded in figure 21b which is also triggered from the start ionization gage. This picture clearly shows the zero position as a small white dot, followed by a short trace at atmospheric pressure while the shock moves from the triggering gage to the pressure transducer. The incident shock raises the pressure quickly to P_2 , which remains constant till the reflected wave coming back from the end of the tube raises the pressure to P_5 . After .5 millisecond the

reflected rarefaction wave coming from the back end of the driver begins to lower the pressure to the final value. Though it was expected that the reflected shock would raise the pressure almost vertically to P_5 , in all cases so far it has risen sharply to only approximately one-half the maximum value, and then gradually increased to the final reading. The reason for this is not fully understood. Reference 16 shows pictures of P_5 in a cold hydrogen driven shock tube at lower Mach numbers, which exhibit similar behavior though not to such a degree. This reference also shows records of the pressure behind a reflected shock measured at the end wall, which rapidly rose to a certain value, and then over a period of 5 milliseconds slowly rose to a slightly higher value. This may indicate that the reflected shock does not bring the test gas completely to rest as theory dictates, but due to the viscous effects at the wall a small velocity toward the closed end of the tube remains, slowly building the pressure up to its final value. This would account for the slower build up to P_5 in our case, where the measurement is made farther away from the closed end. However the fluctuations on this part of the trace show that the rise might instead be due to extra compression waves coming from the end wall of the tube, or from the viscous interaction between the shock and the boundary layer near the end.

The values worked out from figure 21 agree quite closely with the theoretical values calculated in reference 9.

The horizontal distance to the voltage drop from the second ionization gage was measured as 3.1 cms or 155 microseconds. This works out to an incident shock velocity of 6,450 fps corresponding to an incident shock Mach number of 5.66. The pressure behind the incident shock was measured as 600 psi, or 40.8 atmospheres. For a Mach number of 5.66 reference 9 gives a theoretical P_2 of 39.5 atmospheres. The peak pressure of P_5 was measured as 4,320 psi or 294.5 atmospheres, while the corresponding value from Ref.9 is 285 atmospheres. It can be seen that P_5 remains relatively constant for only .5 millisecond before the reflected rarefaction wave from the far end of the driver starts to decrease the pressure. This was not expected to occur so quickly, and will most certainly be the limiting factor on shock tunnel running times. Modifying the tunnel by either lengthening the driven tube, or inserting a restriction plate at the primary diaphragm could produce an increase in the running time.

For later tests the time sweep was speeded up to increase the accuracy in measuring shock velocity, and the sensitivity was decreased to cut down the extra sweeps. The results are shown in Fig.22. For this test the velocity was calculated as 6,625 fps, or Mach 5.83. P_2 was measured as 550 psi or 37.5 atmosphere, while P_5 was measured as 4,460 psi or 302 atmospheres. The theoretical values from Ref.9 give 40.8 and 305.0 atmospheres respectively. For this test also the length of time P_5 remained steady was only .5 millisecond.

It is interesting to note on figure 22b that the incident shock striking the end of the tube causes the pressure transducer to ring, as seen on the trace midway along P_2 . Also for both these tests the Berkely electronic counter read .17 milliseconds, corresponding to a shock velocity of 5,882 fps. The fact that it does not have microsecond discrimination means that in the range we are interested in the difference between adjacent readings is about 7%, well below the accuracy of the oscilloscope. Therefore it was decided to use the counter as a check only, and to rely on the scope for accurate measurements. By reading the scope to ± 1 millimeter on this larger scale, the accuracy of shock wave velocity measurements is about $\pm 1.5\%$.

Figure 23 represents a further improvement, where the ionization gages are connected to the scope so that their outputs are added algebraically. By inverting one input a more accurate measure of the time the shock takes to reach the second ionization gage (as evidenced by the abrupt downward turn of the trace) can be made. As well the use of the single sweep function (not used in the lower trace of figure 23) eliminates all extra sweeps. The results for figure 23 are: shock velocity, 6,755 fps; shock Mach number, 5.96; P_2 , 645 psi or 43.8 atmospheres; P_5 , 4,500 psi or 306 atmospheres. Corresponding theoretical values for $M = 5.96$ are 43.5 and 325 atmospheres. In this case the reflected rarefaction wave

arrives very quickly, and in fact may have started lowering the pressure before it even reached its peak value.

The results of the shock tube tests are shown graphically in figures 24, 25 and 26, along with some results for the complete tunnel. Figure 24 shows the Mach numbers measured at the end of the tube for tests at different loading pressures with helium percent as a parameter. Also shown are the theoretical values of Mach number as calculated in reference 9. Since no combustion pressure readings were made after the destructive detonation mentioned, similar Mach number values for combustion pressure 25% below the theoretical value were also included, which are more in line with the results from combustion tests. It is found that the actual Mach number values measured were still 30% below even these values. This is almost definitely due to incident shock wave attenuation in the driven tube. Hendershot (Ref.14) gives two reasons for shock attenuation, namely, losses due to the finite opening time of a real diaphragm, and viscous effects along the walls in the high velocity flow behind the incident shock. He also reports a 30% drop in shock Mach number along a shock tube which was shorter, but of smaller diameter.

A large variation is evident in the tests at 1500 psi loading pressure while those at 1000 psi are fairly close. This was due to diaphragm experimentation at the 1500 psi level, while at 1000 psi only one type of diaphragm was used; 1/8 inch thick steel plate cross-scribed and annealed

after machining. These gave good breaks, as shown in figure 27, with very few particles travelling down the tube. Mach numbers were reproducible within 7%, as seen in figure 24.

At 1500 psi loading pressure tests were made with diaphragms made of 3/16 inch steel plate, 1/4 inch steel plate, and 10 and 12 gage stainless steel plate, some annealed and some not, some resulting in good breaks, and some which broke up completely. The diaphragms of 1/4 inch steel plate proved especially disappointing; of the five tried none broke successfully. On examination it appeared that this plate was too thick to bend easily on opening, especially around the relatively sharp (1/4 inch radius) corner of the first barrel. The petals appeared to have been torn off in tension, probably even before they had opened completely. The diaphragms most successful at 1500 psi were those of 10 gage annealed stainless steel plate, also shown in figure 27. It is felt that by using this one type of diaphragm exclusively much more repeatable results could be obtained at this loading pressure. The few tests carried out at 2000 psi were inconclusive, and more work will have to be done on diaphragm design, ignition and combustion at this elevated pressure.

Figure 25 gives measured pressure behind the incident shock. Results generally lie within 10% of the theoretical value as calculated in reference 9. However results for P_2 are quite difficult to measure with any accuracy since the rise is usually less than 1 centimeter on the scale of the

oscilloscope, and the scope trace is about 1 millimeter wide, and sometimes even wider due to ringing of the transducer.

Figure 26 gives the measured pressure behind the reflected shock. Here considerable scatter is evident, especially in the tests done on the complete tunnel, though the trend of the points is definitely along the theoretical line. The results for the shock tube tests are tabulated in figure 31.

Shock Tunnel Tests

The purpose of the shock tube is to create a mass of high enthalpy, high pressure air for subsequent expansion to a high Mach number. This is accomplished by the triple expansion nozzle contained in the test section shown in figure 3. The primary nozzle is two dimensional, with an area ratio of 48:1, giving a Mach number of approximately 4. In order to prevent damage to the models in the test section the air is then expanded around a 10° Prandtl-Meyer deflection plate, thus

the pressure rise was calculated and the pressure record from the oscilloscope calibrated. By doing several tests at low pressure, the transducer calibration factor was determined as 58 ± 5 millivolts per psi. This is slightly above the manufacturer's specifications of 50 mv/psi.

In order to cut down nozzle starting times a .004 inch thick Mylar diaphragm is fitted in front of the primary nozzle and the whole test section is evacuated to about 500 microns of mercury.

The results for two of the complete tunnel tests are shown in figures 28 and 29. The driver initial loading conditions for figure 28 were 1000 psi and 76% helium diluent. From the upper picture it was determined that the incident shock Mach number was 5.42 and that the stagnation pressure behind the reflected shock was 3,220 psi. Figure 28b is a trace of the pitot pressure in the test section. It was triggered from the trace for P_5 which re-triggered as the pressure decreased, accounting for the extra fluctuating trace on the lower figure. It can be seen that P_5 reaches its peak value .2 milliseconds after triggering and remains constant for about .6 milliseconds. The pressure in the test section remains steady for .6 milliseconds, and after rising for .2 milliseconds is relatively steady for only .25 milliseconds before dropping off rapidly. This indicates that the tunnel starting time is about 0.6 milliseconds, and steady flow is established for only 250 microseconds.

The peak pitot pressure was measured as .156 psi. By referring to charts in reference 7, this was found to correspond to Mach 20.8.

Figure 29 gives the results from another test, this one at an initial loading pressure of 1500 psi and 76%. From the upper picture the shock Mach number was calculated as 5.34, and the peak pressure behind the reflected shock as 4,520 psi. This appears to be well above the theoretical value, and paradoxically above the value for the previous case which was at a slightly higher Mach number. However it is noted that before rising to its final value the P_5 trace levels off at about 3,350 psi which is much closer to the theoretical value. This secondary rise was noted on other traces for loading pressures of 1500 psi at 76% and is probably due to a shock wave emanating from the interaction of the reflected shock wave and the contact surface.

Figure 29b shows the pitot pressure measured in the tunnel. This trace, along with the others, was triggered by the start ionization gage, allowing a better record of the changes in pressure. It can be seen that .5 milliseconds before the pitot pressure starts rising, there are relatively large fluctuations in the trace. Whether these are actual pressure fluctuations or only due to vibrations in the tunnel is not known, though the latter is more likely. In this case the pressure rise to the peak value is slower, and the steady pressure is very short or non-existent before dropping down

and beginning to fluctuate. It is felt that the nozzle starting time was large, and with the short (.5 millisecond) steady pressure in P_5 , the nozzle reservoir pressure dropped just as steady flow was being established. The peak pitot pressure was measured as .271 psi which corresponds to a test section Mach number of 20.1.

Test section Mach numbers could be calculated for 7 of 10 full tunnel tests. The results are shown in figure 31. It can be seen that 5 of the values are very close to Mach 20.5, while the other two differ by 5 and 10%.

Figure 30 shows a picture taken of the luminescence surrounding the model during flow. This is similar to the phenomenon reported by Nagamatsu et al in reference 17. In this case the thickness of the luminous region is about 0.3 inches. The incident shock Mach number was 6.40, giving a stagnation temperature in the nozzle reservoir of 7,300°R.

CONCLUSIONS and RECOMMENDATIONS

1. The McGill Hypersonic Shock tunnel has been instrumented sufficiently to measure the performance of the shock tube and expansion nozzle.
2. The combustion pressure ratios (pressure before combustion to pressure after) determined experimentally are considerably lower than the theoretical values, due to heat loss to the chamber walls.
3. The best type of diaphragms for loading pressures of 1000 and 1500 psi have been determined and give repeatable results.
4. Shock Mach numbers are also much lower than the theoretically predicted values, due to shock wave attenuation in the driven tube.
5. Incident shock Mach numbers of 5.5 can be obtained repeatably at a loading pressure of 1000 psi with 76% helium diluent, and with atmospheric air in the driven tube.
6. Shock Mach number results for 1500 psi are still rather scattered, but by concentrating on the one type of annealed stainless steel diaphragm repeatability should be possible.

7. The test section Mach number is 20.5. The inlet lips of the final nozzle should be adjusted to give a smaller area ratio, and hence a lower Mach number. For the stagnation values of pressure and temperature obtained in the tests at 2000 psi loading pressure, a test Mach number of 10.5 would totally simulate conditions at an altitude of 120,000 feet.
8. The tunnel running time is only about 250 micro-seconds, and is limited by the early arrival of the reflected rarefaction wave at the nozzle inlet.
9. A Schlieren system is being set up to photograph the flow.
10. The test section vacuum capability should be improved to at least 10 microns of mercury in order to lower nozzle starting times even further.
11. More tests must be carried out to determine the best type of diaphragm for use at a loading pressure of 2000 psi.
12. Tests should also be carried out on the ignition and loading system to try to eliminate the occasional unexplained detonations.

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APPENDIX

Safety Precautions and Operating Procedures

The shock tunnel is located in a section of the basement laboratory of the MacDonald Engineering building at McGill University. A layout of the facility is shown in figure 1.

The driver is bolted firmly to the floor of the building as outlined in Ref.8. As shown in figure 1 it is in one corner with a thick basement wall on one side and behind it. On the other side a blast shield has been set up to protect the rest of the laboratory in case of an explosion. Above the driver is a heavy floored mezzanine used to store steel stock and fittings, and which would greatly reduce any explosive force reaching the floors above. The actual loading and firing of the tunnel is done from a bunker with 6 inch sand filled walls and railroad tie roof located 50 feet from the combustion section.

The gas lines were leak tested on installation at the maximum pressure they are expected to hold (2000 psi). However, when not in use all the supply cylinders are turned off and the lines are drained to atmosphere through the vent line. A nitrogen cylinder on the end of the hydrogen manifold is used to flush these lines completely. A large capacity exhaust fan capable of changing the air in the complete laboratory every 40 seconds is installed in one of the walls

in case any gas leakage is detected.

Having this facility in a large room easily accessible to undergraduate students as well as visitors to the university necessitated a warning system around the shock tunnel area. A system of flashing red lights and prominent warning signs was installed. These lights were placed at all entrances to the laboratory, and were put in operation during the last 10 minutes before firing. As well, several blasts of a loud warning buzzer are sounded with 2 minutes to go, and one final 15 second blast just before the actual firing.

The high voltage ignition system is completely closed in, and is not turned on until everyone is out of the area. Orange lights on the front warn if the power has been turned on, and red lights warn if the high voltage power is on. Though the discharge takes place through a spark gap, a ground line is always attached to the high voltage lead after each shot before disconnecting it from the combustion tube. It is left in place until the final check before the following shot to prevent any accidental discharges.

Over the testing period many procedures have evolved to ensure the most effective use of this facility. Strict use of, and adherence to check lists has proven a must.

When not in use the tunnel is usually cleaned and left with the 3 sections (driver, driven tube, and test section) open to atmosphere. As well, most of the instrumentation is removed and stored. Before a shot, compressed air from the

laboratory 100 psi line is blown through the tube to remove any dust, and to fill the tube with fresh atmospheric air. The appropriate diaphragm is then put in position with the scribe marks on the downstream side. A fresh piece of tungsten ignition wire is attached to the loading line and high voltage lead on the Bridgeman plug, and the whole assembly is put into position. It has been found that all "O" ring seals on the driver must be greased each time, and replaced regularly to ensure a complete seal. Before the driven tube is screwed into the driver, a lamp is inserted and a final visual check is made on the tungsten wire to see that it is positioned correctly in the centre of the driver, and has not been broken in the tightening process. After the driven tube has been attached the first 100 psi of helium are fed into the driver to check that it is gas tight.

The primary nozzle containing the secondary diaphragm is fitted in place, and the driven tube is positioned over it. Then the ionization gages are installed after they have been cleaned to ensure that the electrodes are not fouled. The pressure transducer to measure P_5 is also positioned after a touch of silicone grease has been put on the tip to reduce the effects of thermal shock in the stagnation region.

While the gases are being loaded final checks are carried out on the ionization gage circuit, pressure transducers, oscilloscopes and cameras. After the driver is completely loaded a final check is carried out to see that all valves

and doors are closed and all connections and switches are in the correct position. Personnel are cleared out of the area and the capacitors are charged to the correct voltage. Then the vacuum pumps are turned off, the cameras are opened, and after a final blast on the warning buzzer the tunnel is fired. The time interval between completion of loading the gases, and ignition is kept between 5 and 10 minutes.

After firing, all instrumentation readings are checked and the tube is opened up immediately. The water formed during combustion is distributed over the interior walls of the driven tube and test section, and as they are not plated, a thin film of rust forms very quickly. Therefore compressed air from the Laboratory air supply is blown through the tube as soon as possible to dry it out. After the diaphragm has been removed and examined and the Bridgeman seal removed, and as soon as the tube and driver are completely dry, they are cleaned by means of a rotating wire brush mounted on the end of an air turbine which is pushed the entire length of the tube. This removes the rust and deposits which have formed, and blows them down the tube ahead of it. The shock tunnel is then ready for the next test.

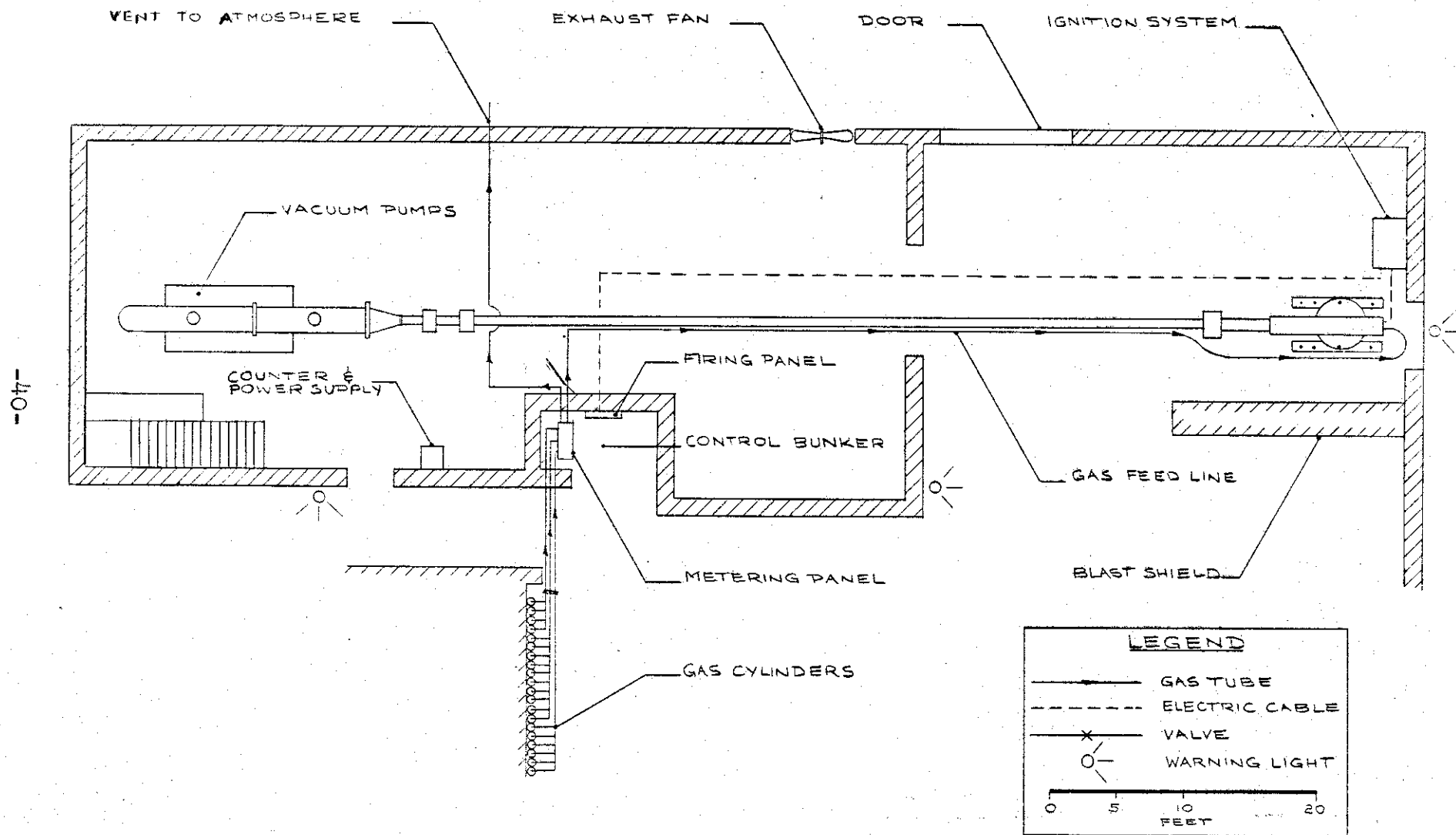


FIGURE 1. FLOOR PLAN OF THE MCGILL HYPERSONIC LABORATORY

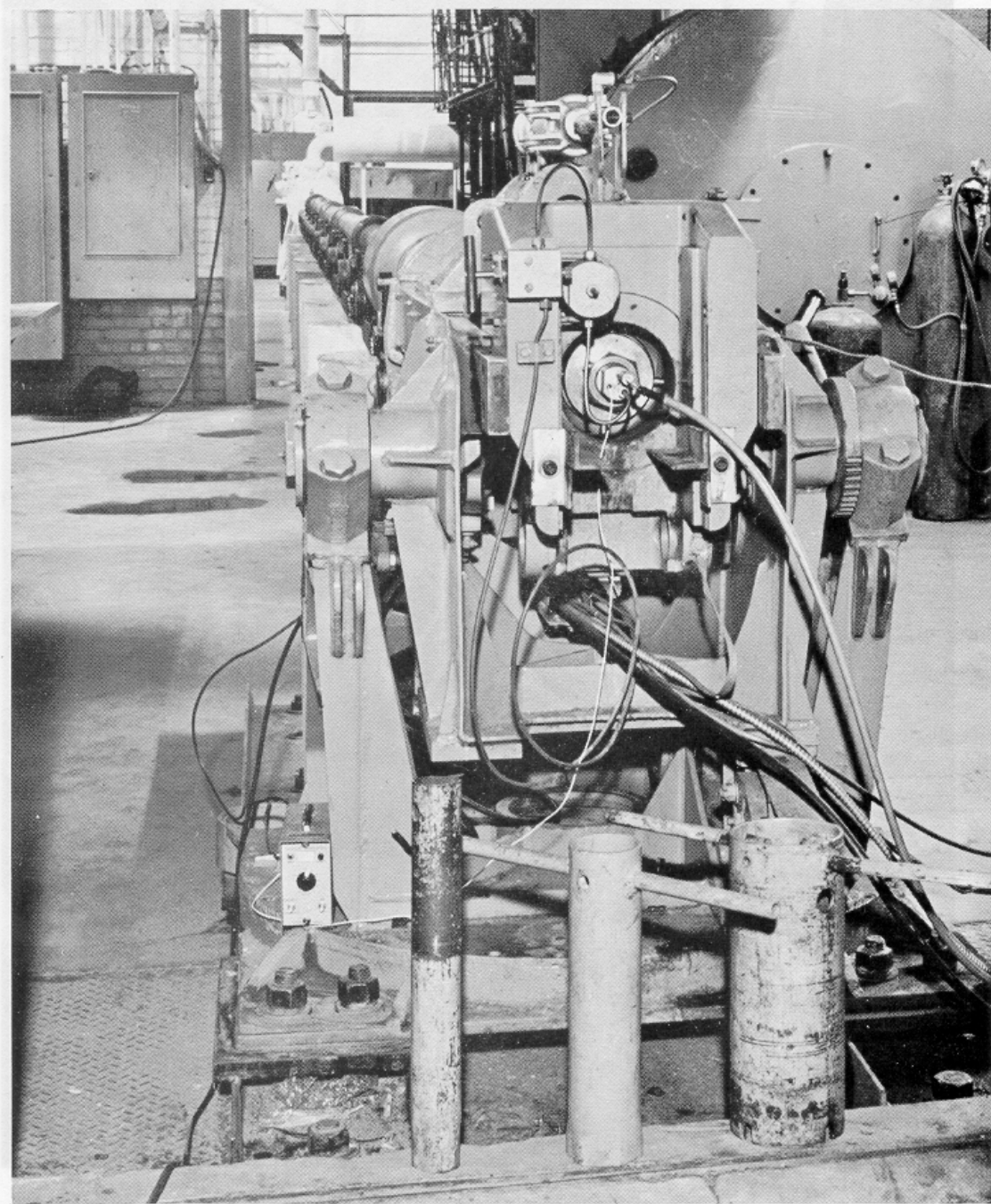


FIGURE 2. SHOCK TUNNEL - DRIVER SECTION

In the centre is the loading end of the combustion driver section. The Bridgeman seal is in position, with the gas loading line and high voltage connection leading into it. Coming from it can be seen a pressure transducer cable.

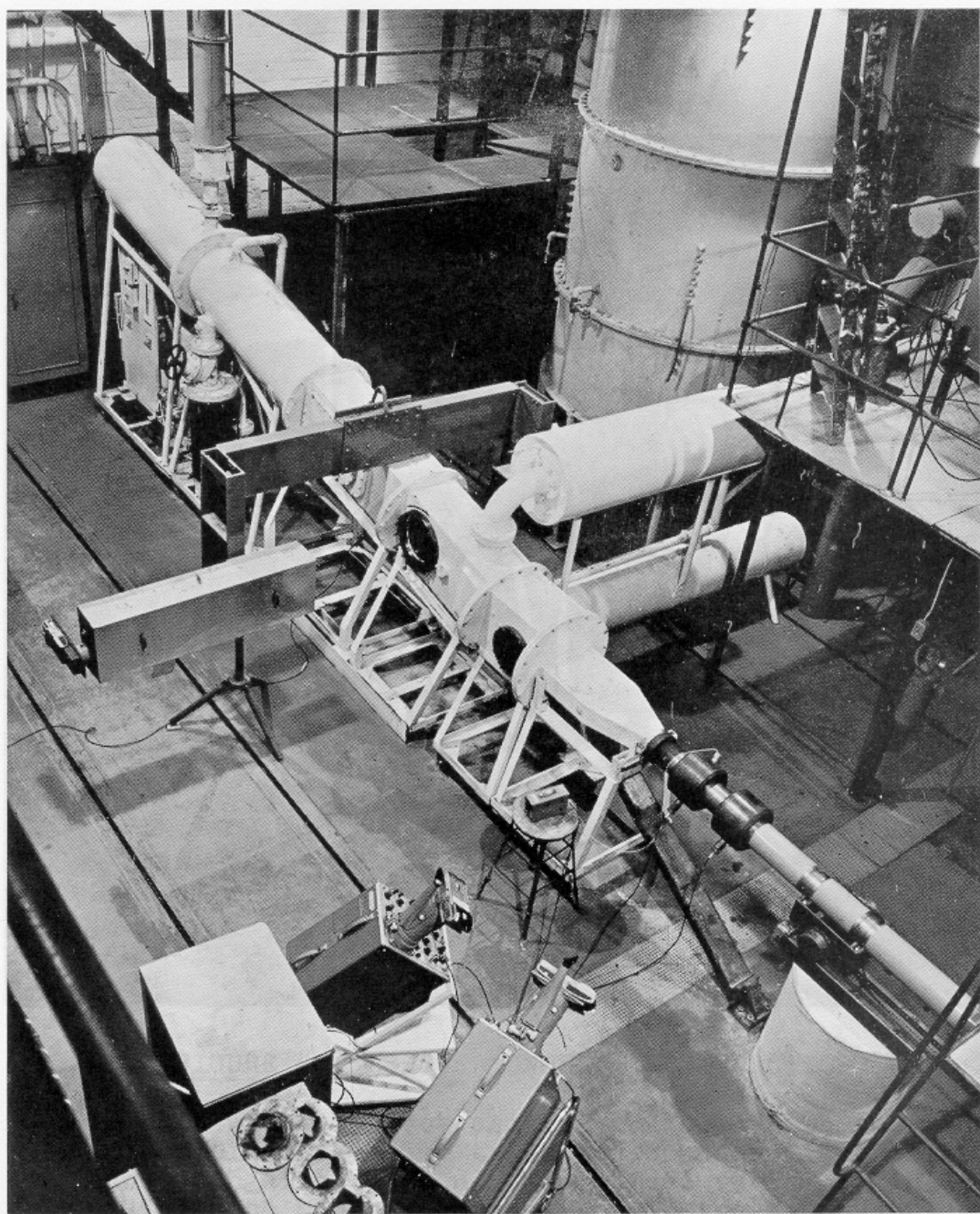


FIGURE 3. SHOCK TUNNEL - TEST SECTION

Coming from the lower right can be seen the driven tube, with the reinforcing rings containing pressure and ionization gages. The primary nozzle, test section, and evacuated dump tanks are also shown.

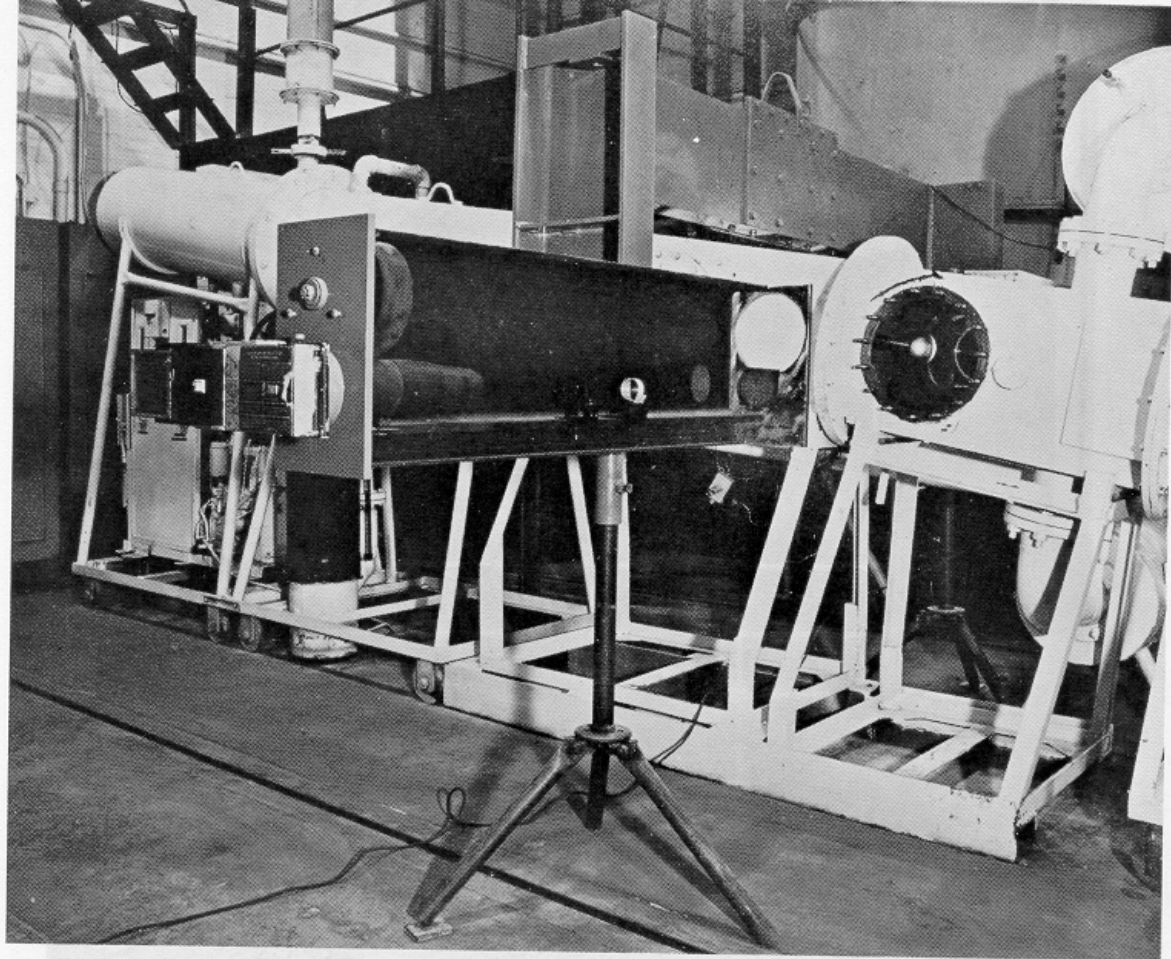


FIGURE 4. SHOCK TUNNEL - TEST SECTION

In this view the test section is shown with the model in position. The dump tanks and boundary layer bleed tanks can also be seen. The optical system is in position to photograph the flow in the test section.

By means of the valves and pressure gages on this control panel, the hydrogen, oxygen, and helium can be measured into the driver section in the correct proportions.

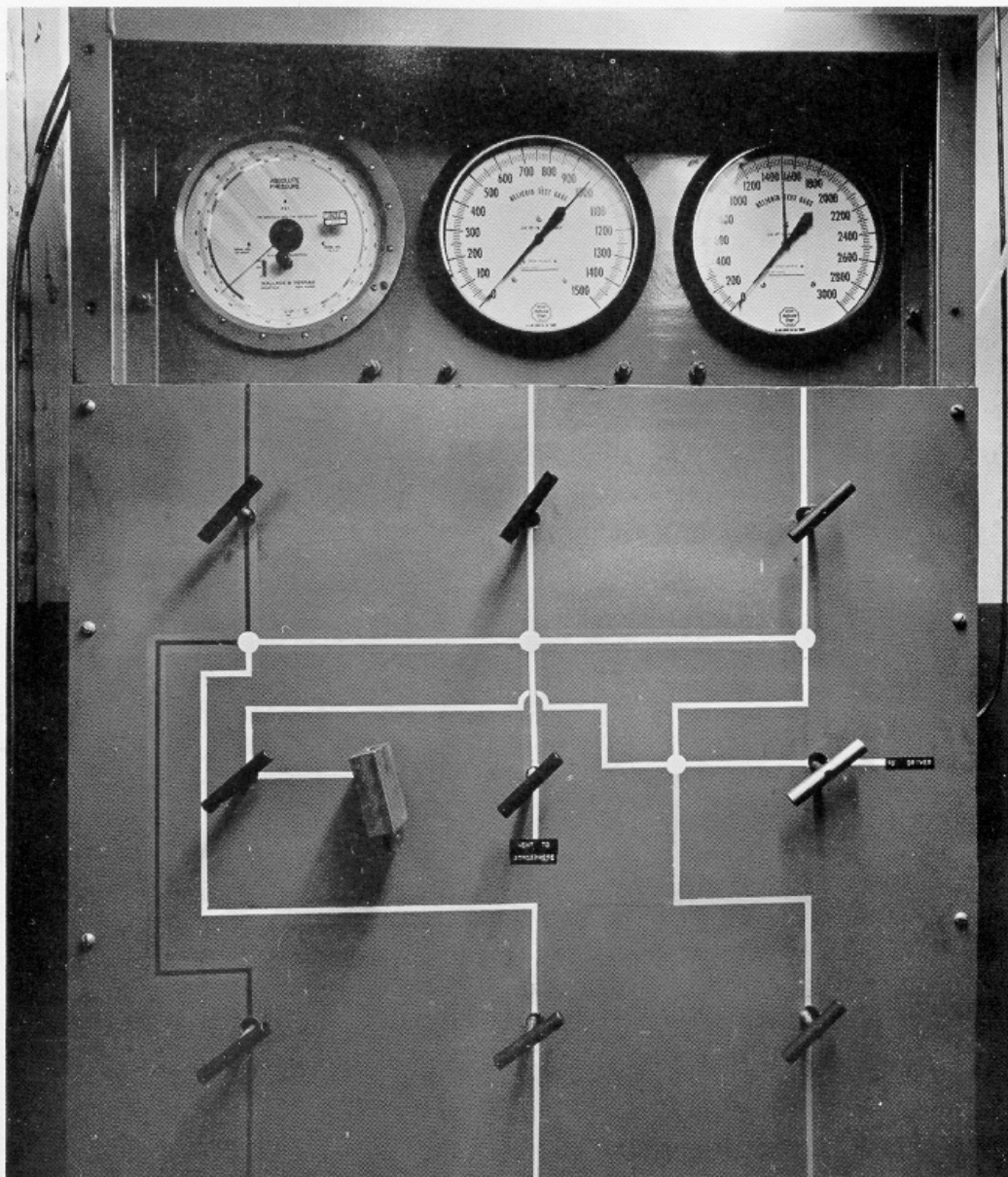


FIGURE 5. GAS METERING PANEL

By means of the valves and pressure gages on this control panel, the hydrogen, oxygen, and helium can be measured into the driver section in the correct proportions.

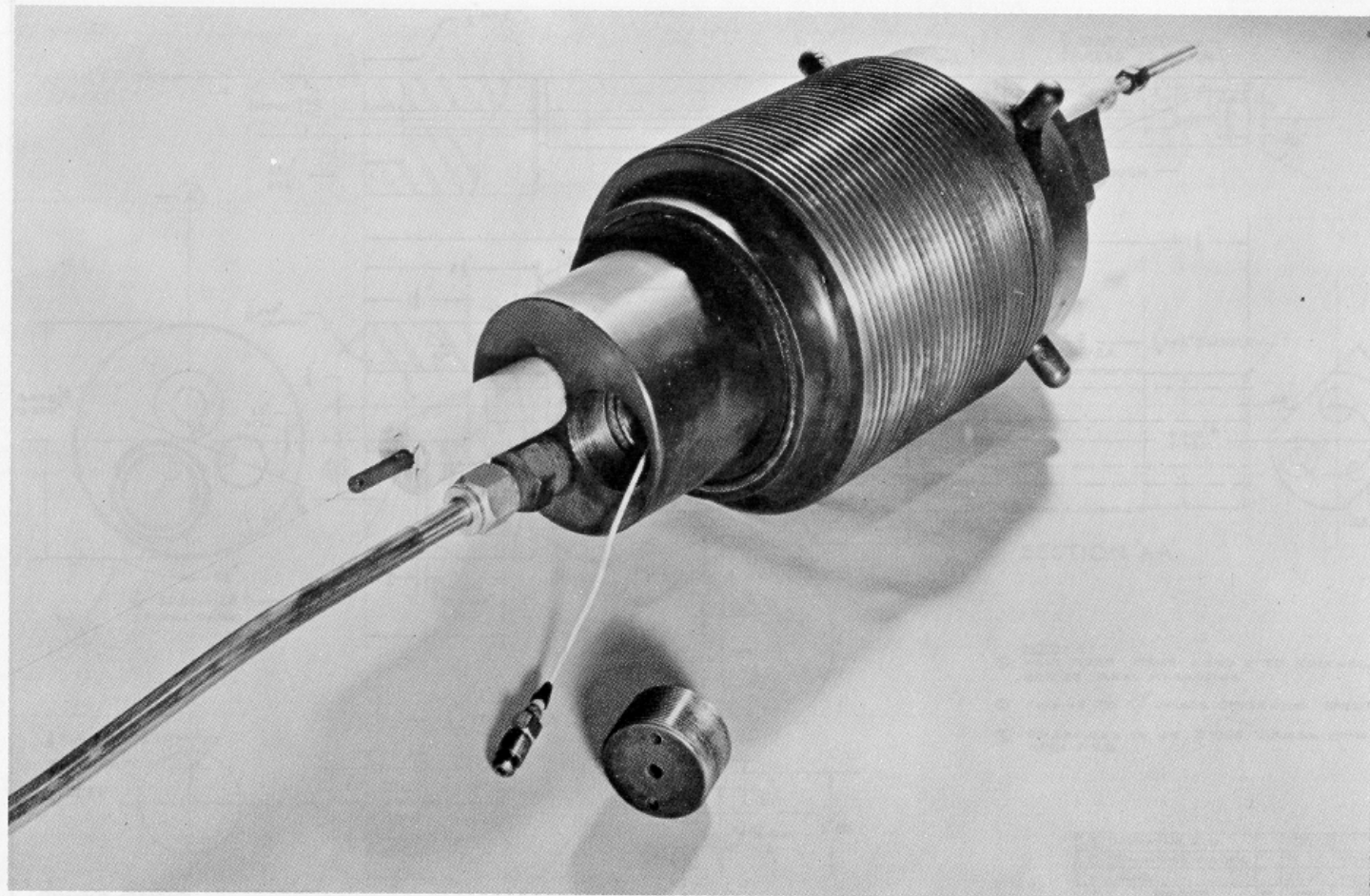


FIGURE 6. BRIDGEMAN SEAL ASSEMBLY

The tungsten wire used to ignite the gas mixture is seen attached to the high voltage lead which is insulated from the Bridgeman plug by the white Teflon insert. Gases from the back end are distributed into the driver by the feed line visible at lower left. The transducer for measuring combustion pressure and its' fitting are also shown.

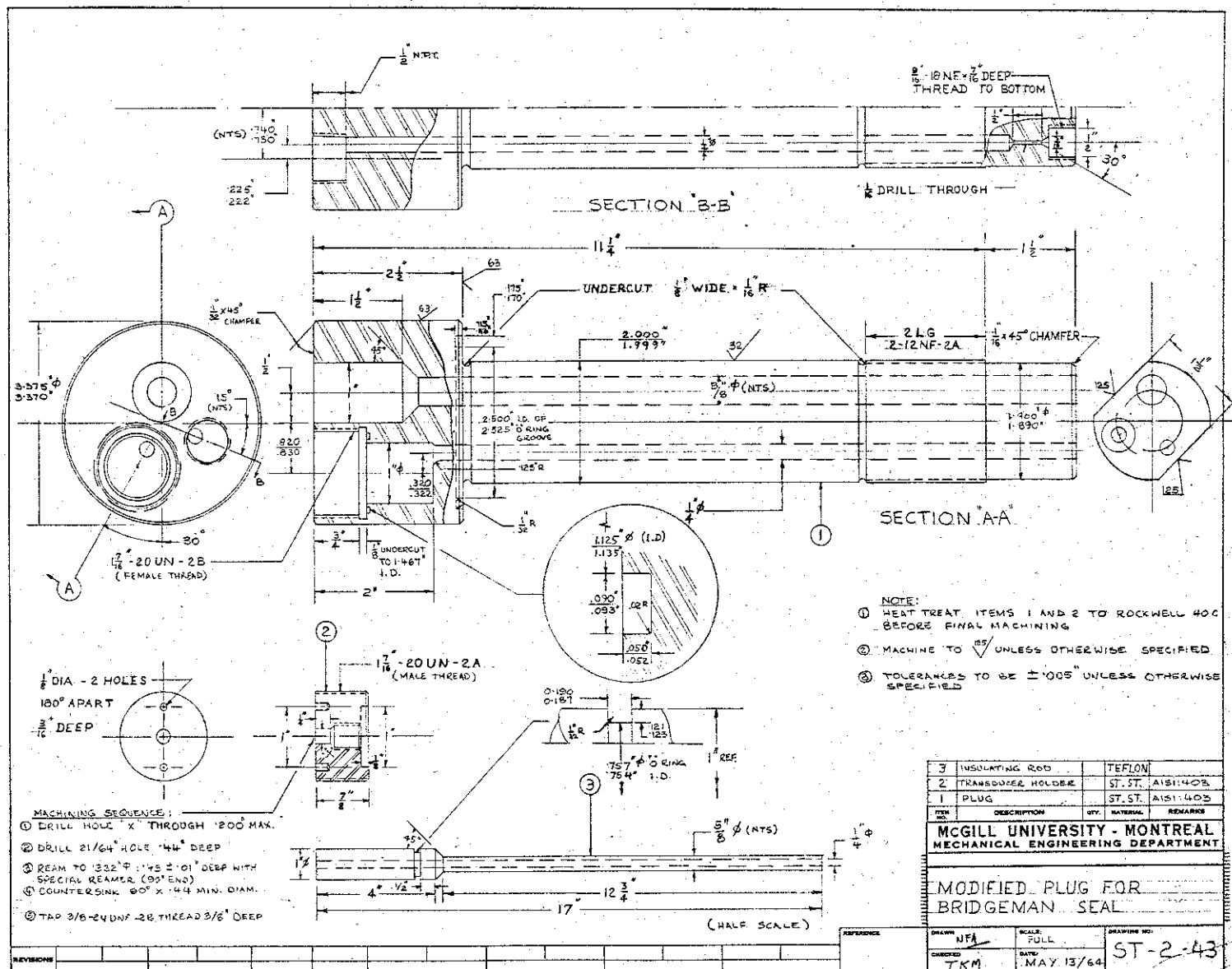


FIGURE 7. ENGINEERING DRAWING OF MODIFIED BRIDGEMAN PLUG

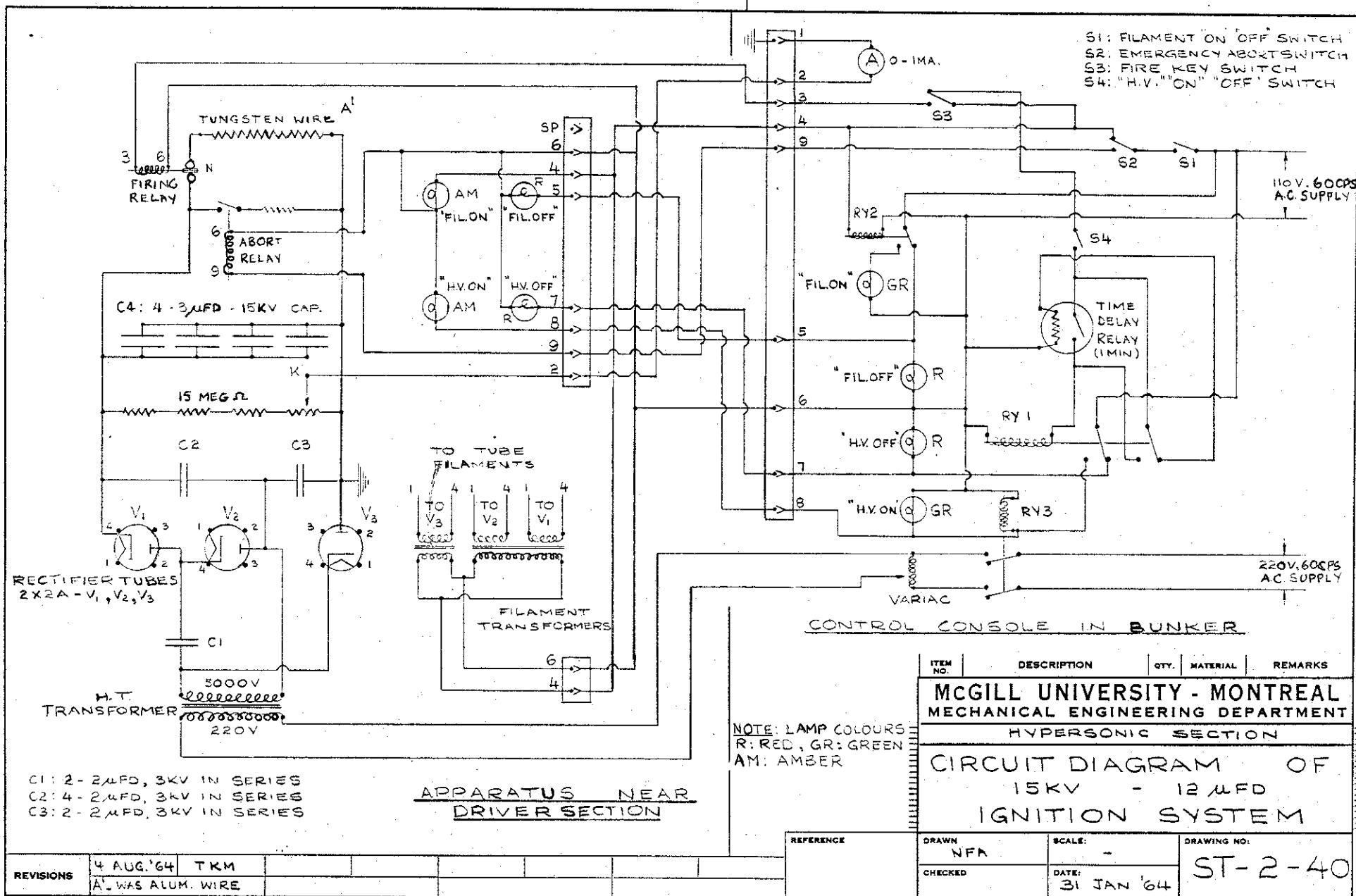


FIGURE 8. IGNITION SYSTEM CIRCUIT DIAGRAM

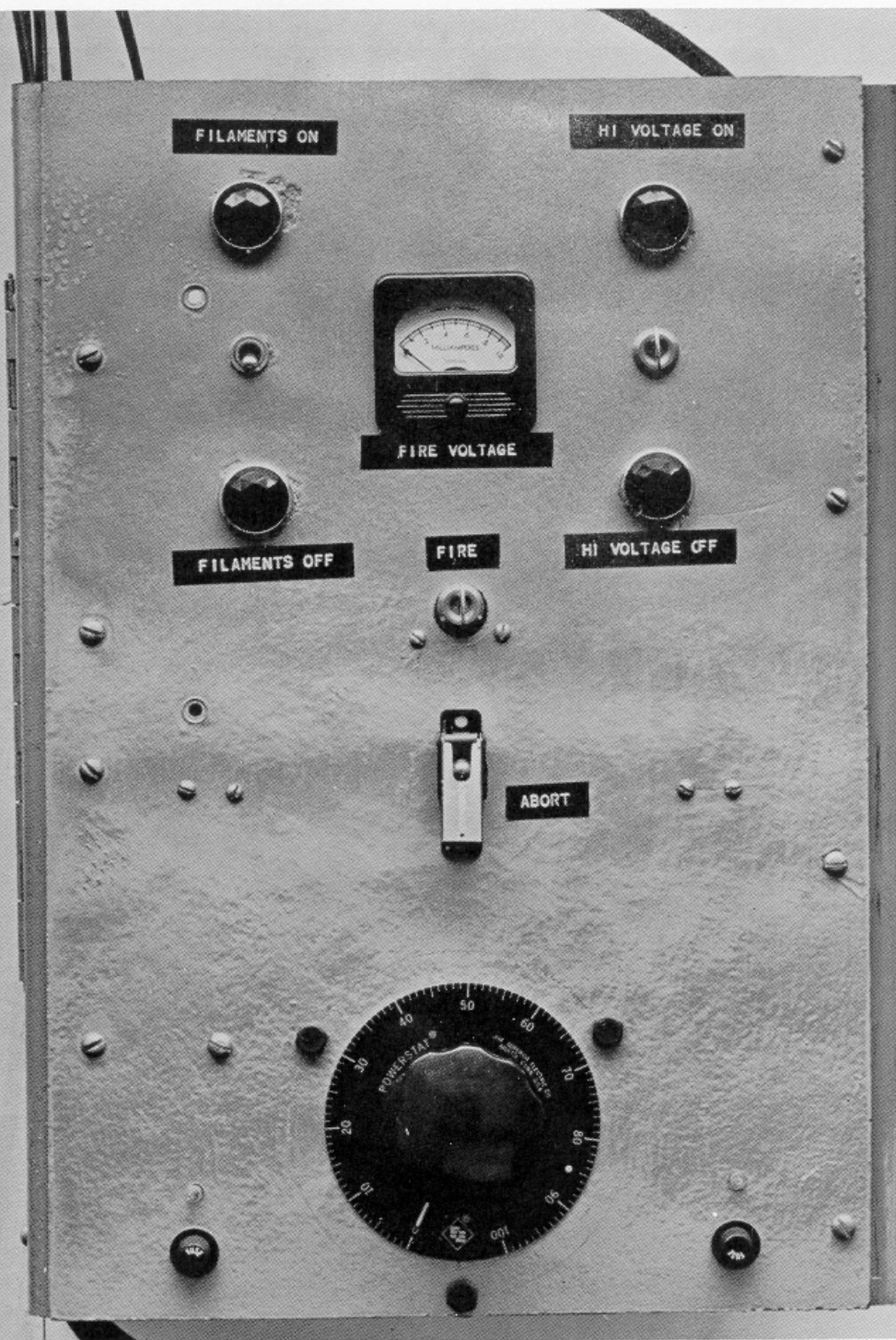


FIGURE 9. IGNITION CONTROL PANEL

This panel contains all the switches necessary to charge and fire the ignition system. The Variac which controls the voltage put on the capacitors is seen at the bottom.

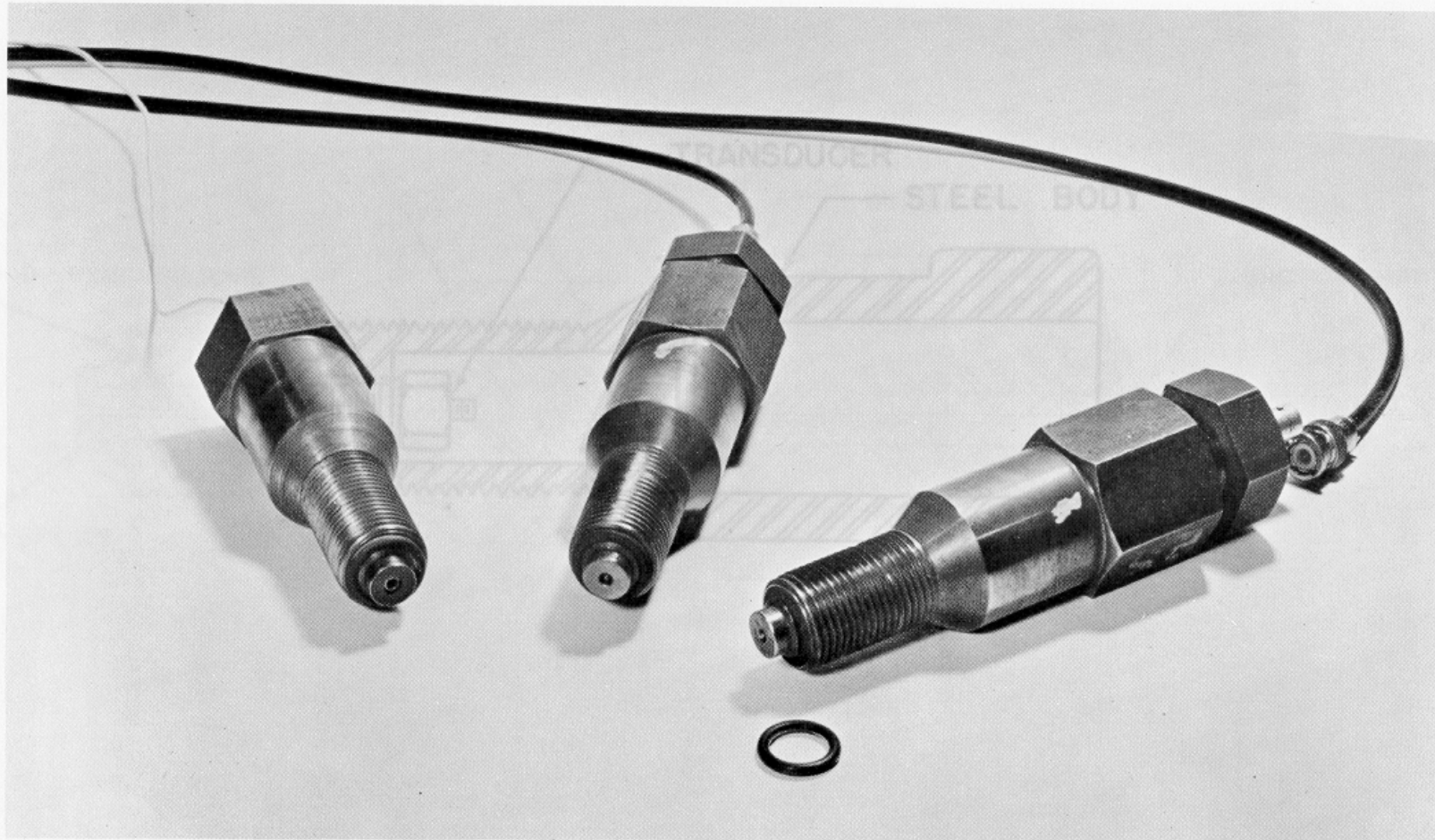


FIGURE 10. PRESSURE AND IONIZATION FITTINGS

These fittings are mounted in the reinforcing rings shrunk onto the final barrel of the driven tube. The one on the left contains a pressure transducer used to measure the pressure behind the incident and reflected shocks. The two on the right are ionization probes used to determine the incident shock wave velocity.

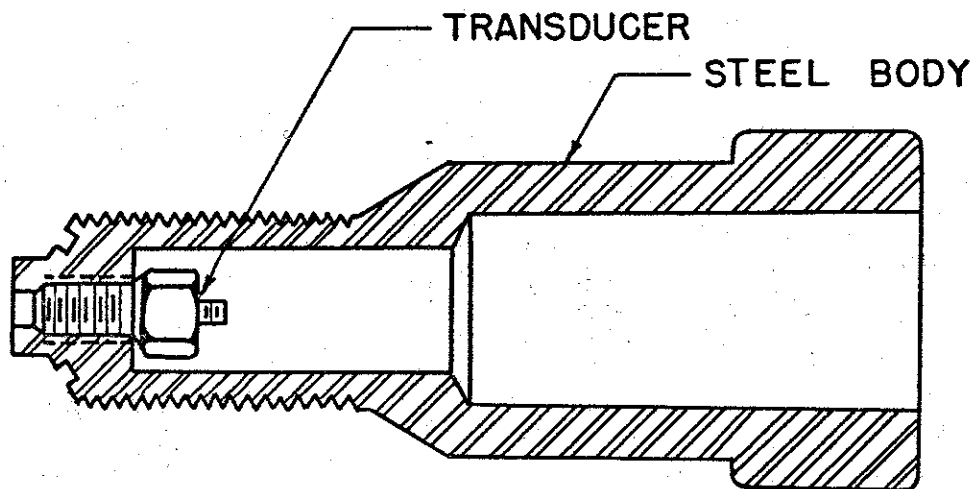


FIGURE 11. PRESSURE MEASUREMENT FITTING

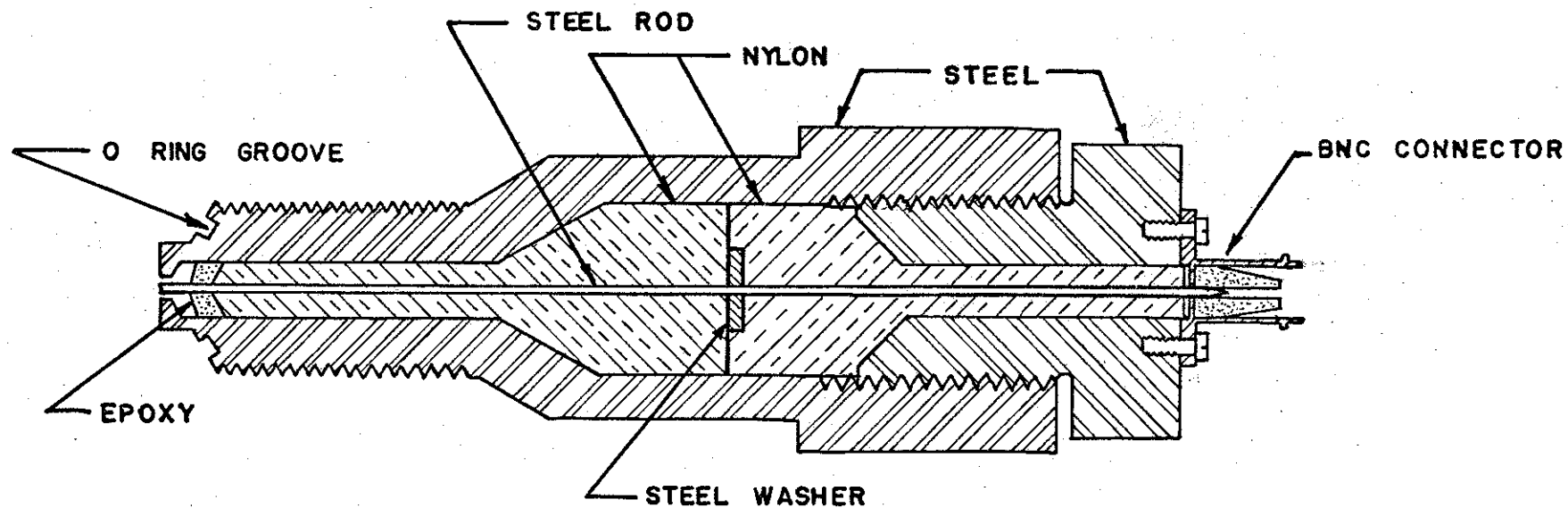


FIGURE 12. IONIZATION PROBE FITTING

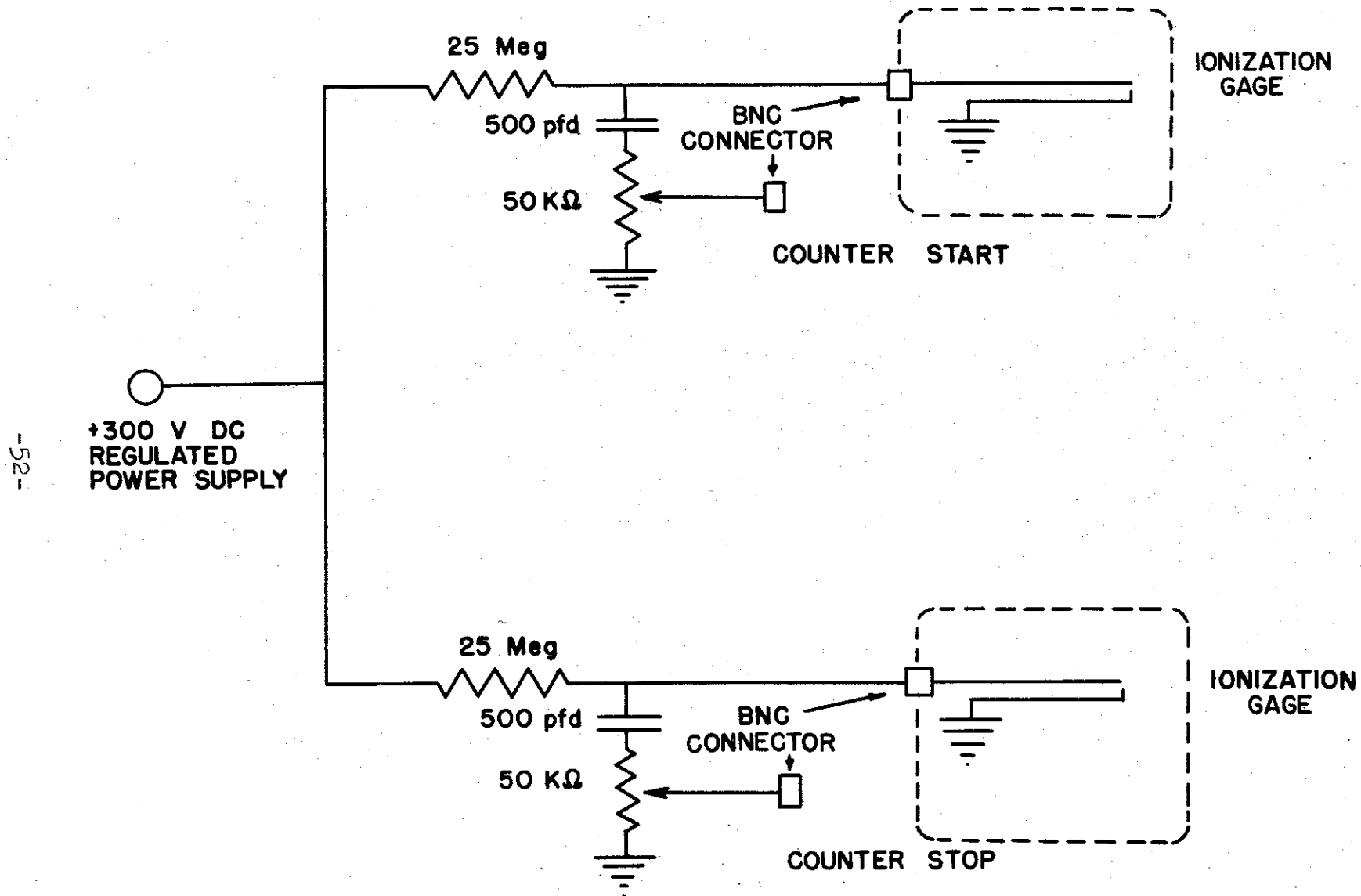


FIGURE 13. IONIZATION GAGE CIRCUIT

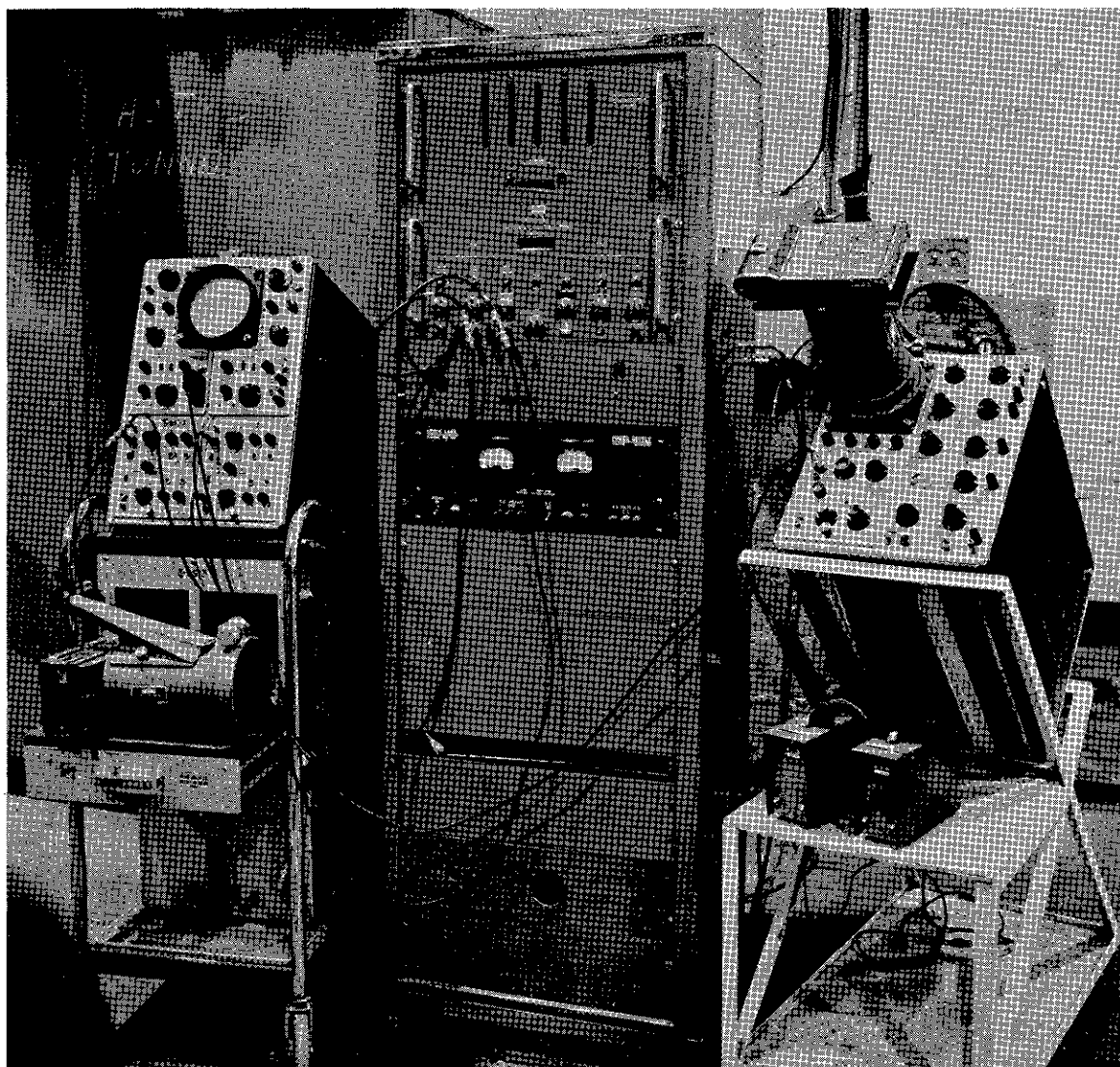


FIGURE 14. RECORDING INSTRUMENTATION

On the left is a Tektronix 555 dual-beam oscilloscope with a Dumont Polaroid camera in front. In the rack in the centre are a Berkely electronic counter and a Kepco regulated power supply used to maintain the voltage across the ionization gages. On the right is a Tektronix 532 oscilloscope with another Dumont camera mounted. Below it are two Kistler charge amplifiers.

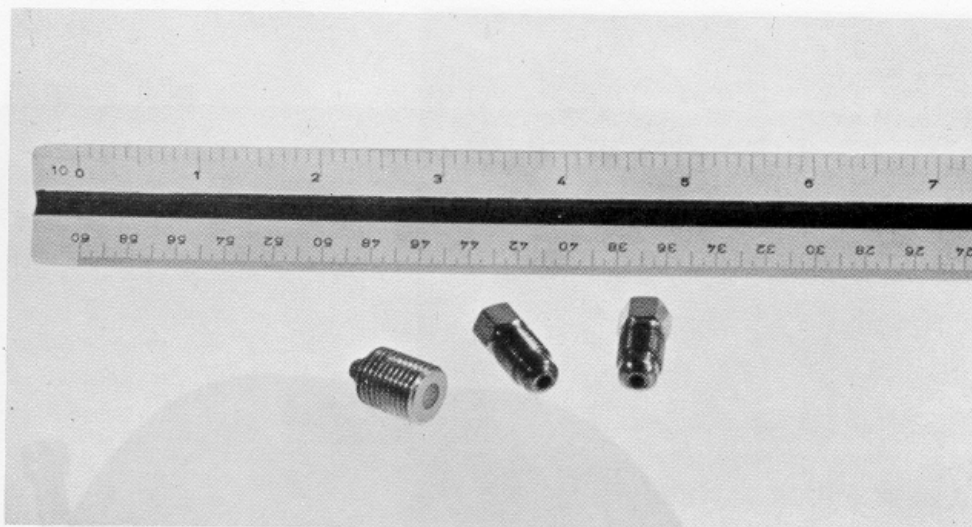


FIGURE 15. PRESSURE TRANSDUCERS

The miniature piezo-electric transducers used to measure pressure are shown here. The one on the left is made by Susquehanna and has a range of 0-2000 psi. The other two are Kistler 617A's with a range of 0-70,000 psi.

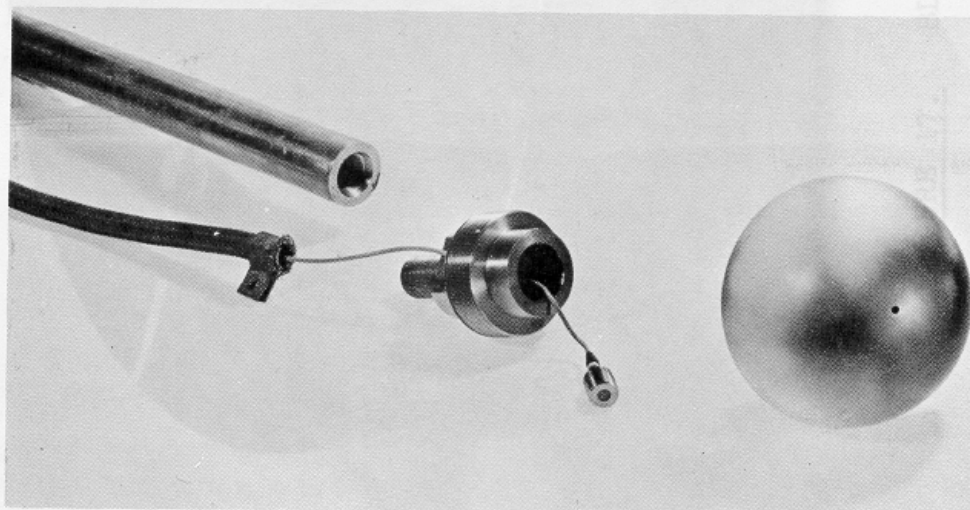


FIGURE 16. MODEL ASSEMBLY

A disassembled view of the four inch diameter hemisphere model, showing the mounting sting, insert, and the transducer used to measure the stagnation pressure in the flow.

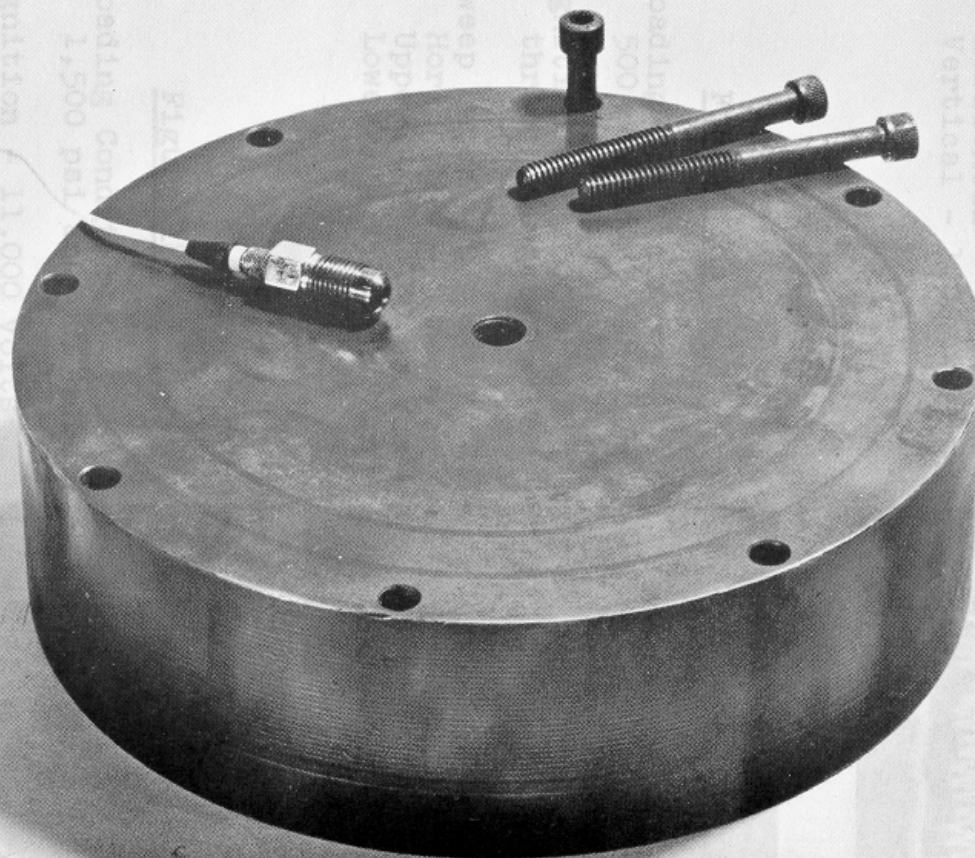


FIGURE 17. BLANKING PLATE

This two inch thick plate is used to seal off the diaphragm end of the driver section during combustion testing. The transducer shown is mounted in the fitting in the center to measure combustion pressures inside the driver.

Figure 18a

Loading Conditions -
500 psi and 75% helium

Ignition - 15,000 volts
through aluminum strip

Sweep rates -
Horizontal - 5 msec/cm
Vertical - 1000 psi/cm

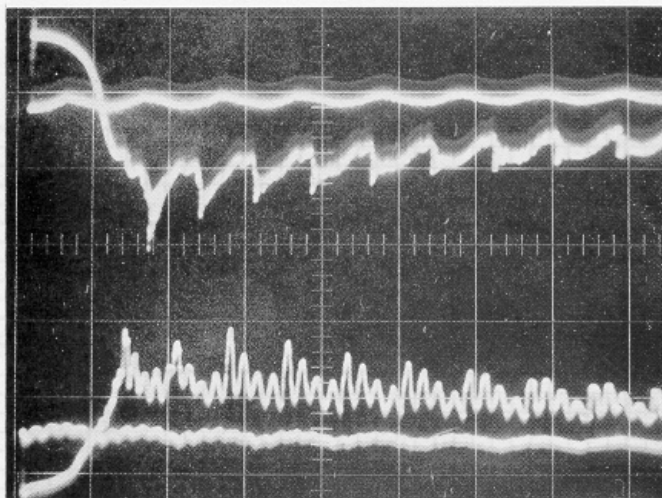


Figure 18b

Loading Conditions -
500 psi and 70% helium

Ignition - 11,000 volts
through tungsten wire

Sweep Rates -
Horizontal - 5 msec/cm
Upper - 930 psi/cm
Lower - 1,380 psi/cm

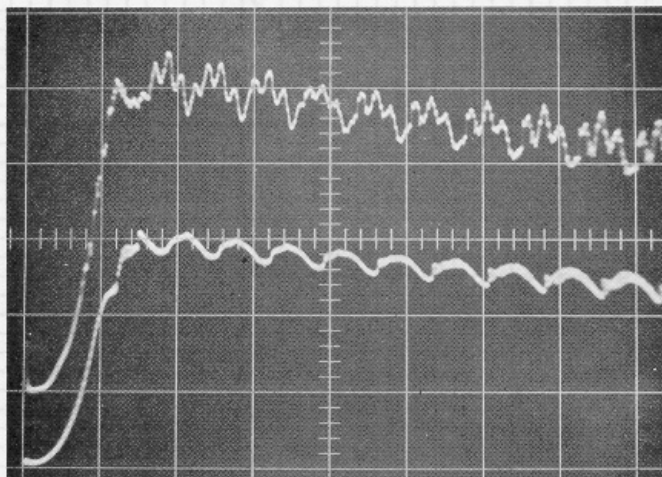


Figure 18c

Loading Conditions -
1,500 psi and 80% helium

Ignition - 11,000 volts
through tungsten wire

Sweep Rates -
Horizontal - 5 msec/cm
Upper - 2,250 psi/cm
Lower - 2,500 psi/cm

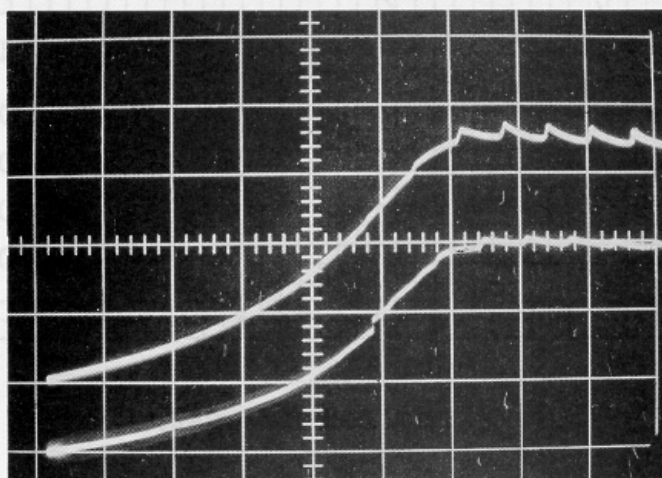


FIGURE 18. CONSTANT VOLUME COMBUSTION TESTS

tests at different pressures, and different concentrations of the helium diluent.

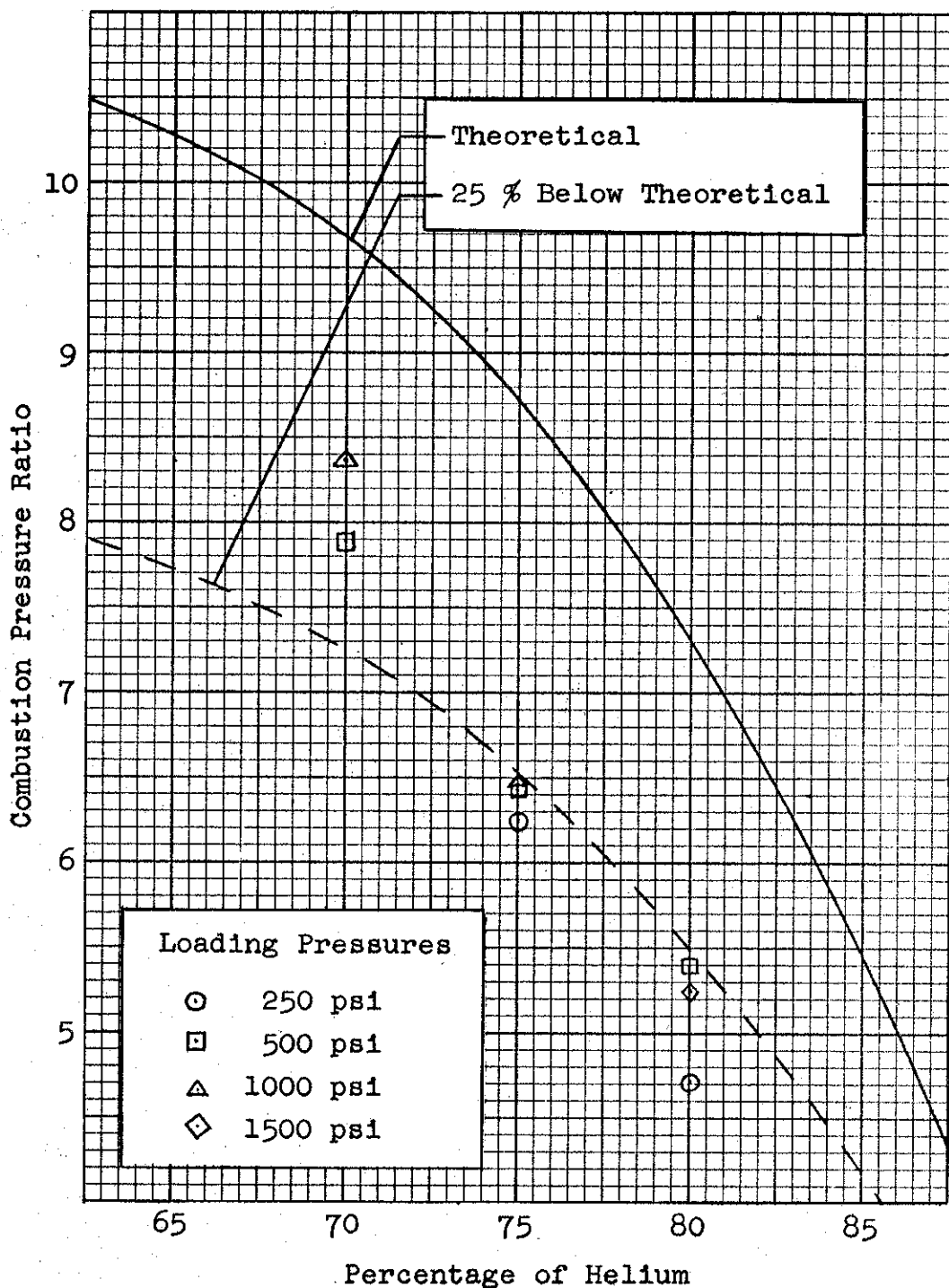


FIGURE 19. CONSTANT VOLUME COMBUSTION

Results of constant volume combustion tests at different pressures, and different concentrations of the helium diluent.

Figure 21a

Upper Trace - Pressure at
end of the Shock Tube

Figure 20a

Smooth Combustion

Sweep Rates -

Horizontal - 5 msec/cm

Vertical - 1300 psi/cm

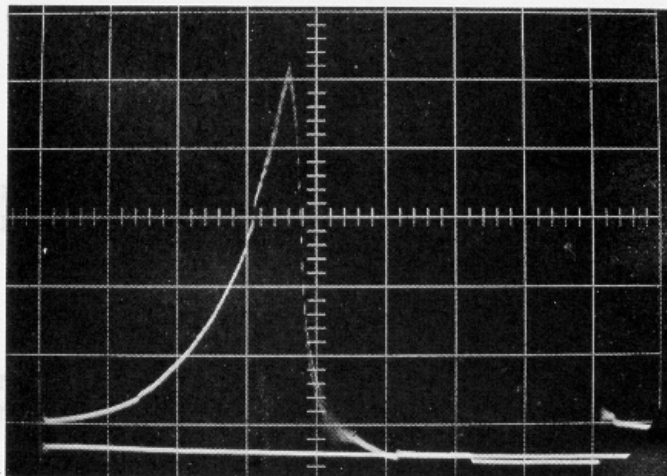


Figure 21b

Pressure near the
end of the Shock Tube

Figure 20b

Detonation

Sweep Rates -

Horizontal - 5 msec/cm

Vertical - 1300 psi/cm

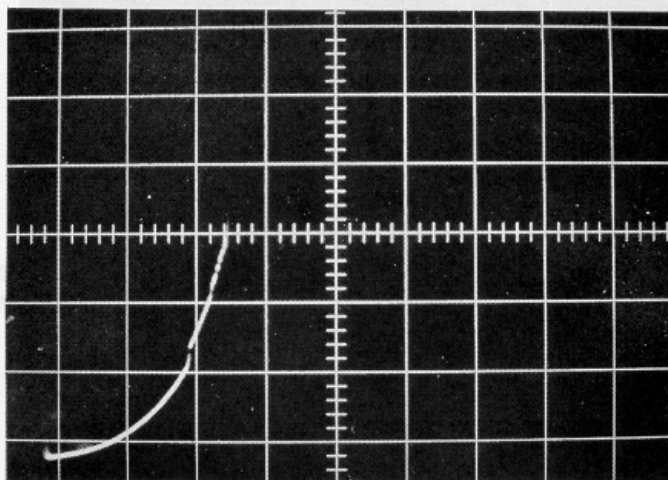


FIGURE 20. COMBUSTION PRESSURE HISTORIES

For both of these cases the initial conditions were 1,000 psi loading pressure with 75% helium diluent. Ignition was by discharging the capacitors from 11,000 volts through a tungsten wire. The initial conditions were 1,500 psi loading pressure with 80% helium diluent. The incident shock Mach number was calculated as 5.66, and the stagnation pressure behind the reflected shock wave as 4,320 psi.

Figure 21a

Upper Trace - Pressure at
end of the Shock Tube
Sweep Rates -
Horizontal - 1 msec/cm
Vertical - 1,320 psi/cm
Lower Trace - Ionization
Gages
Sweep Rates -
Horizontal - 50 μ sec/cm
Vertical - 10 volts/cm

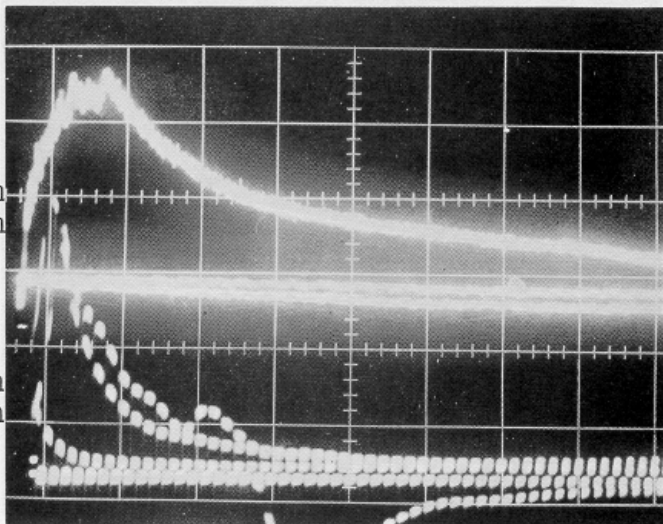


Figure 21b

Pressure measured near the
end of the Shock Tube
Sweep Rates -
Horizontal - 0.5 msec/cm
Vertical - 921 psi/cm
Horizontal - 0.5 msec/cm
Vertical - 921 psi/cm

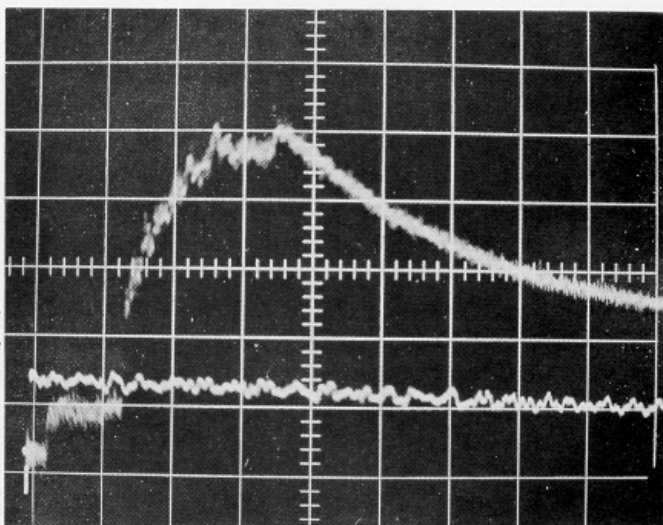


FIGURE 21. SHOCK TUBE TEST RESULTS

The initial conditions for this test were 1,500 psi loading pressure with 80% helium diluent. The incident shock Mach number was calculated as 5.66, and the stagnation pressure behind the reflected shock wave as 4,320 psi.

Figure 22a

Upper Trace - Pressure at
end of the Shock Tube
Sweep Rates -
Horizontal - 21 msec/cm
Vertical - 1,320 psi/cm

Lower Trace - Ionization
Gages (normal Gages)
Sweep Rates -
Horizontal - 20 μ sec/cm
Vertical - 10 volts/cm

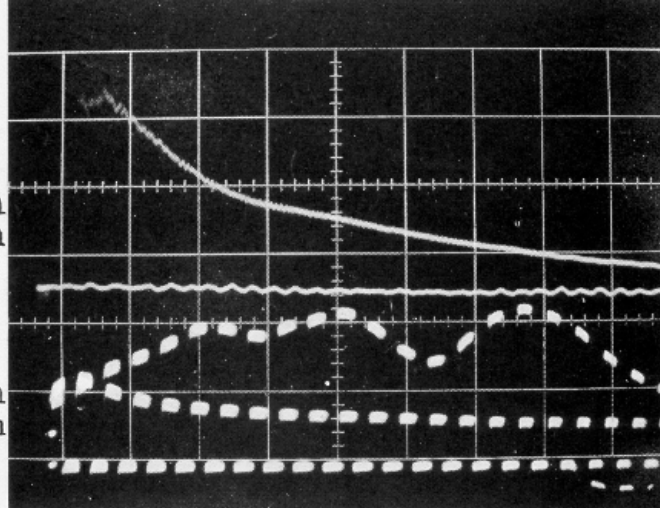


Figure 22b

Pressure measured near the
end of the Shock Tube

Sweep Rates -
Horizontal - 0.5 msec/cm
Vertical - 921 psi/cm

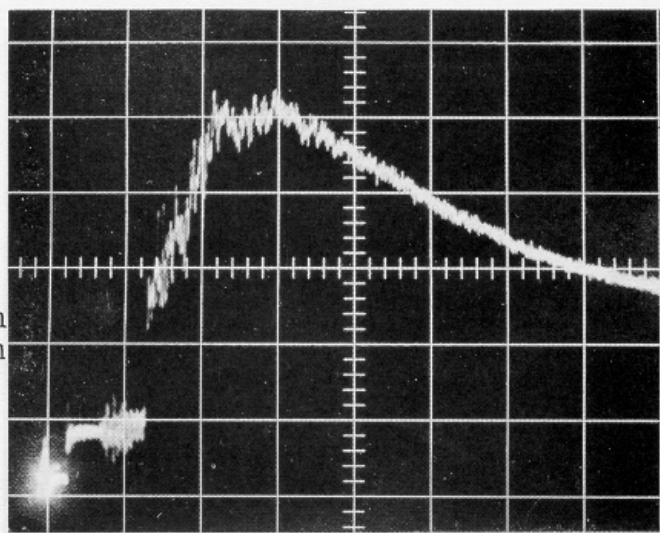


FIGURE 22. SHOCK TUBE TEST RESULTS

The initial conditions for this test were 1,500 psi loading pressure with 80% helium diluent. The incident shock Mach number was calculated as 5.83, and the stagnation pressure behind the reflected shock wave as 4,460 psi.

Figure 23a

Upper Trace - Ionization
Gages (single sweep)
Sweep Rates -
Horizontal - 20 μ sec/cm
Vertical - 5 volts/cm

Lower Trace - Ionization
Gages (normal sweep)
Sweep Rates -
Horizontal - 50 μ sec/cm
Vertical - 2 volts/cm

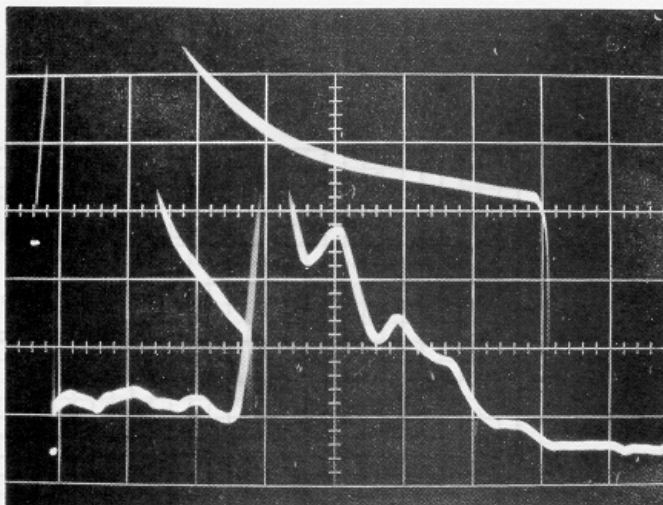


Figure 23b

Pressure measured near the
end of the shock tube

Sweep Rates -
Horizontal - 0.5 msec/cm
Vertical - 921 psi/cm

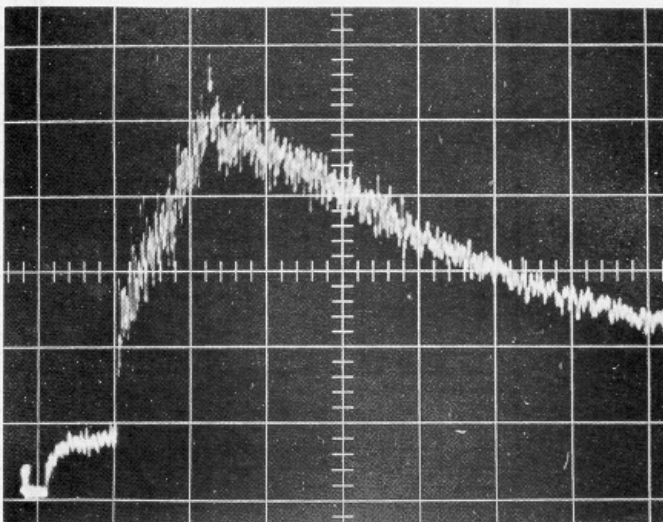


FIGURE 23. SHOCK TUBE TEST RESULTS

The initial conditions for this test were 1,500 psi loading pressure with 80% helium diluent. The incident shock Mach number was calculated as 5.96, and the stagnation pressure behind the reflected shock wave as 4,500 psi.

FIGURE 24. TEST INCIDENT SHOCK MACH NUMBERS

Incident Shock Wave Mach Number

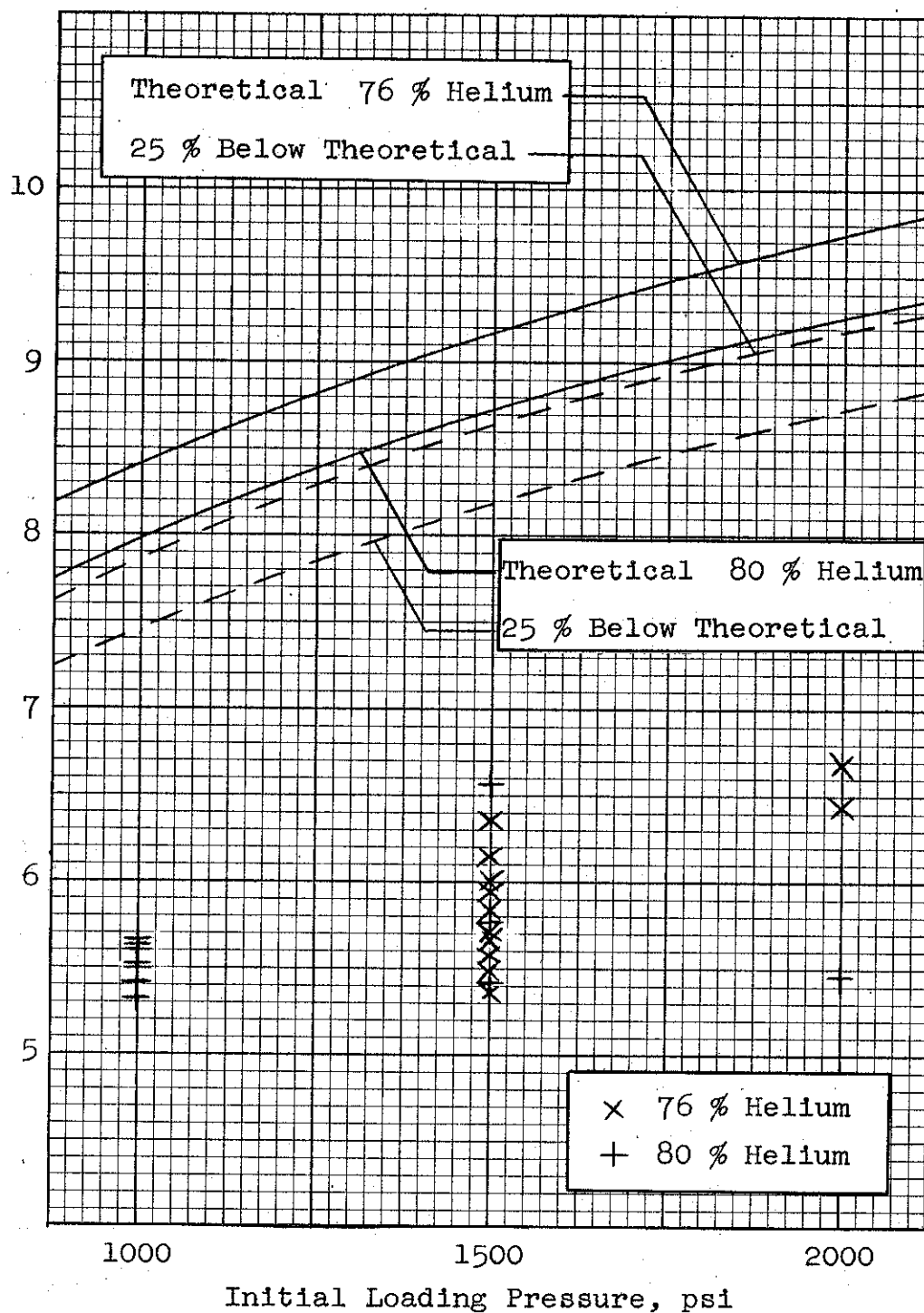


FIGURE 24. TEST INCIDENT SHOCK MACH NUMBERS

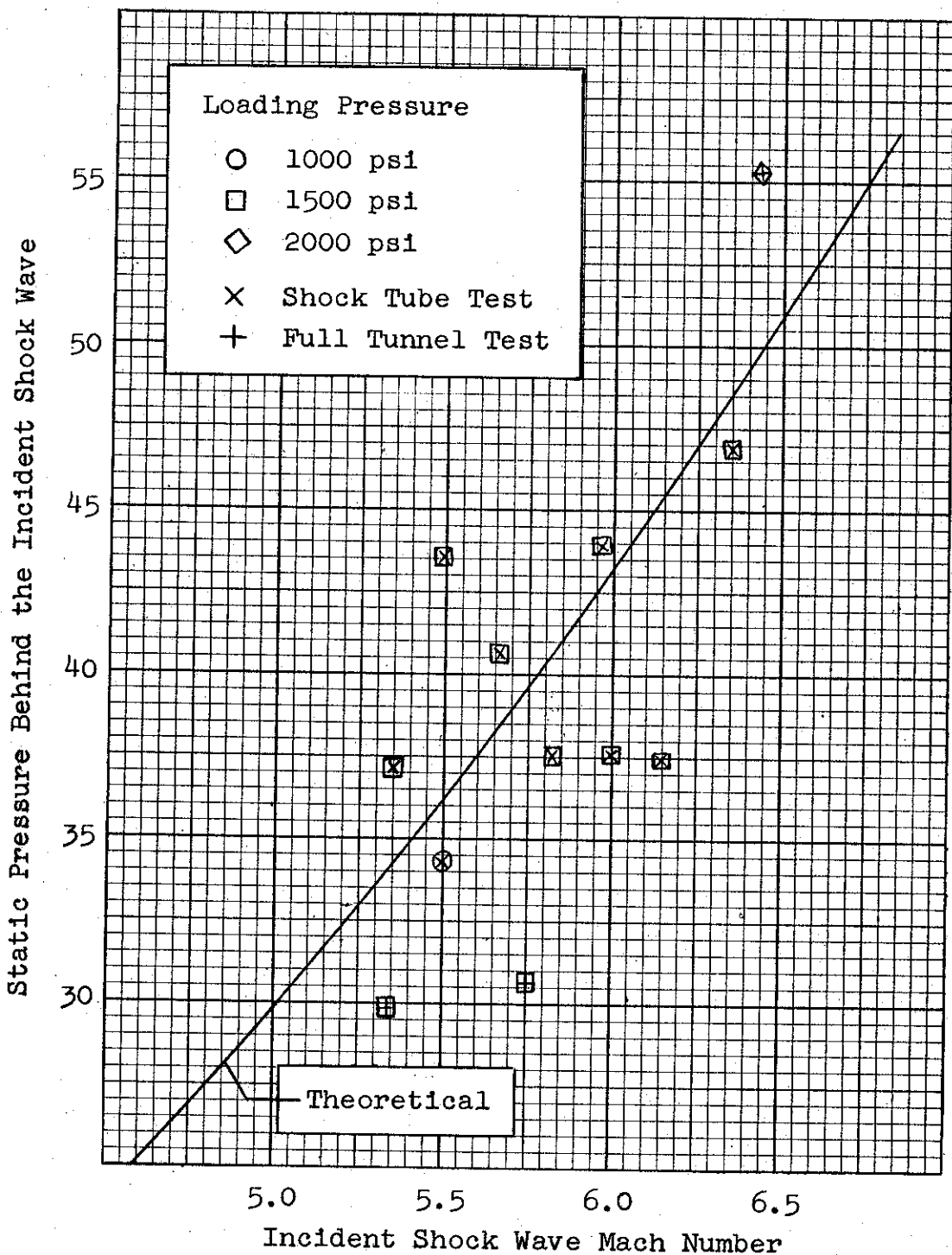


FIGURE 25. STATIC PRESSURE BEHIND INCIDENT SHOCK

The static pressure measured behind the incident shock wave is plotted against the measured incident shock Mach number for various tests.

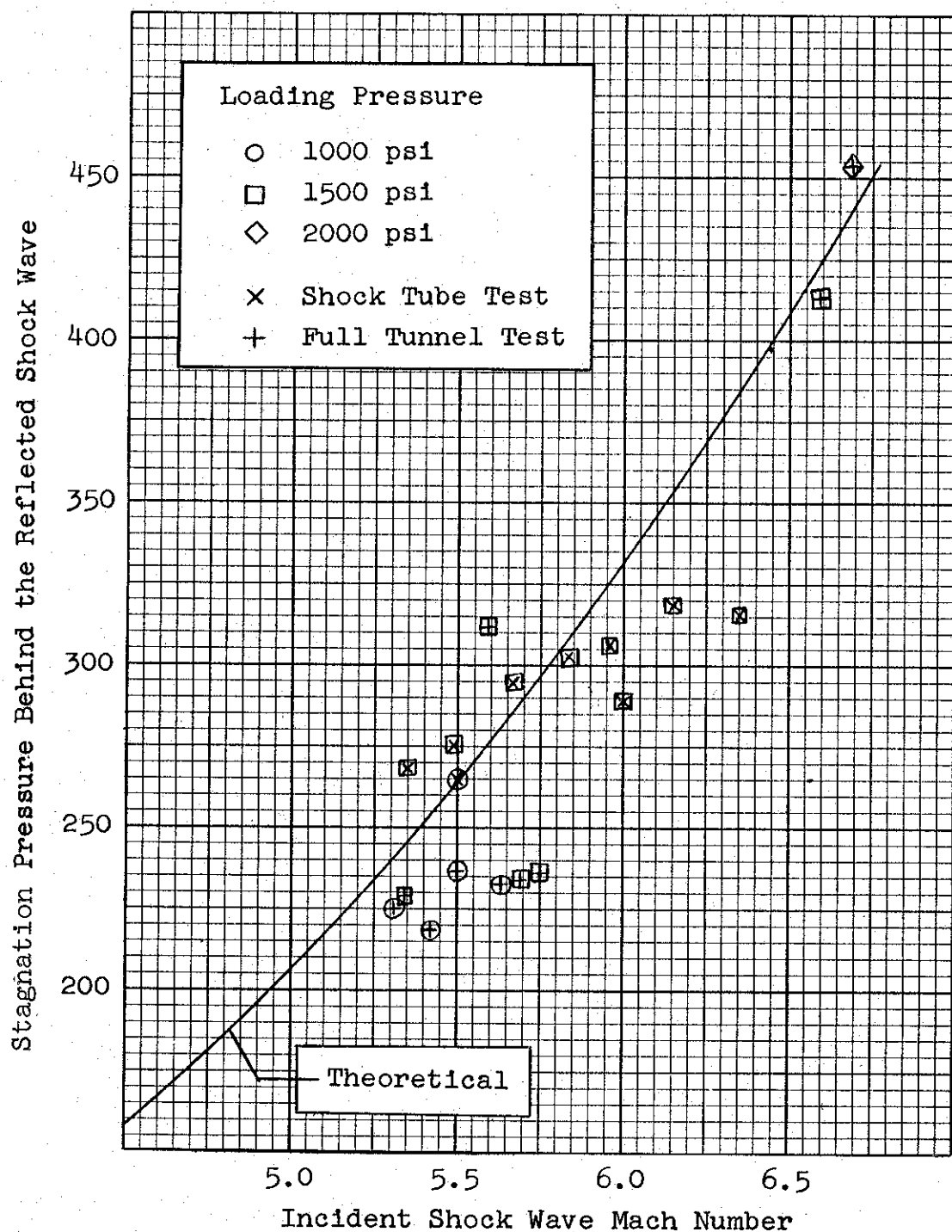


FIGURE 26. REFLECTED SHOCK STAGNATION PRESSURE

The pressure measured behind the reflected shock wave is plotted against the measured incident shock Mach number for various tests.

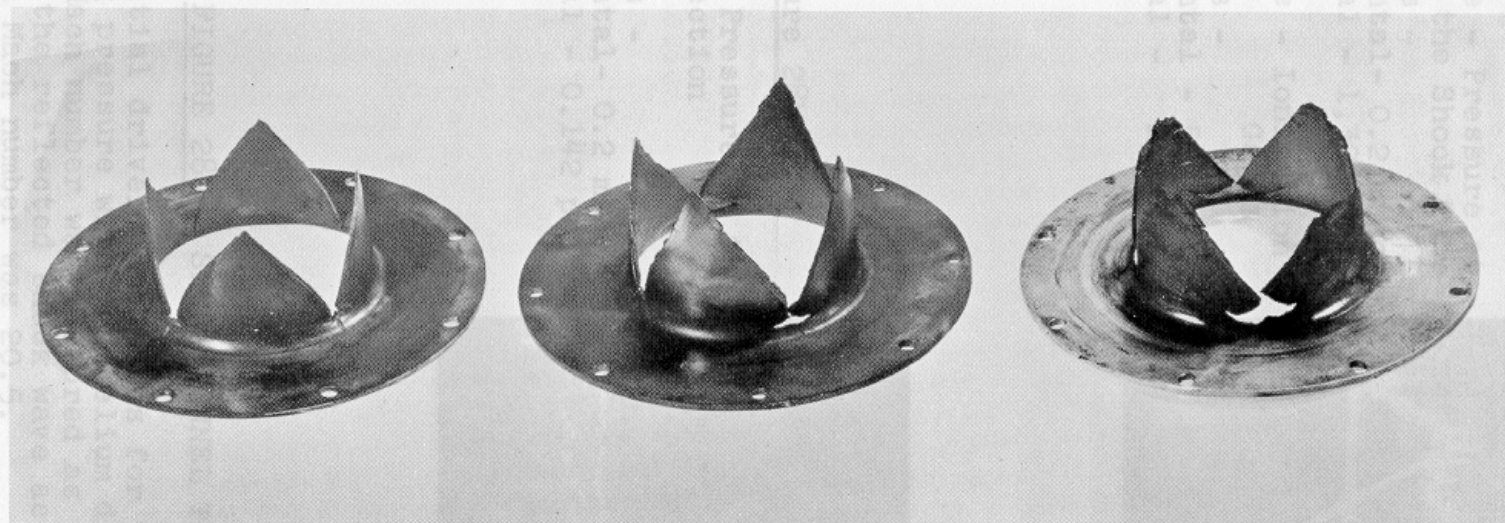


FIGURE 27. PRIMARY DIAPHRAGMS AFTER RUPTURE

This figure shows three of the different diaphragms used. The one on the left is made of 10 gage annealed mild steel, and shows an almost perfect break. The center one is similar, but $\frac{3}{16}$ inch thick. The one on the right is made of 10 gage annealed stainless steel, and opened fairly well though the tips of the petals were broken off.

Figure 28a

Upper Trace - Pressure at
end of the Shock Tube
Sweep Rates -
Horizontal - 0.2 msec/cm
Vertical - 1,320 psi/cm
Lower Trace - Ionization
Gages
Sweep Rates -
Horizontal - 50 sec/cm
Vertical - 2 volts/cm

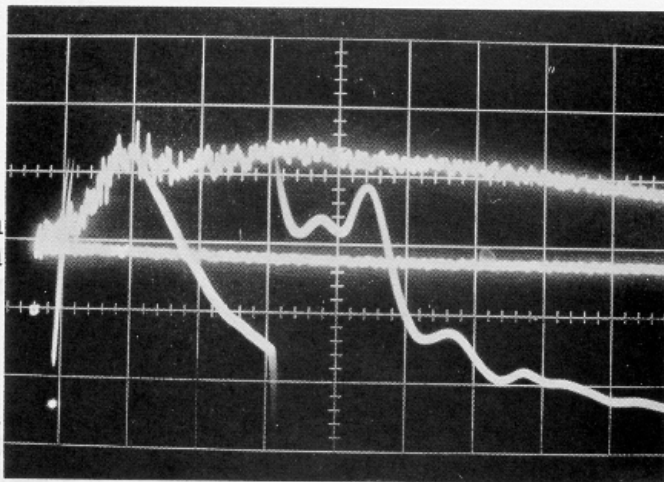


Figure 28b

Stagnation Pressure in the
Test Section
Sweep Rates -
Horizontal - 0.2 msec/cm
Vertical - 0.142 psi/cm

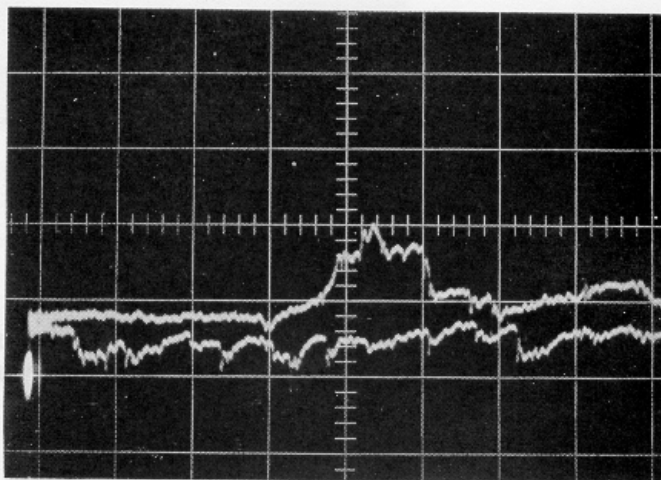


FIGURE 28. SHOCK TUNNEL TEST RESULTS

The initial driver conditions for this test were 1000 psi loading pressure with 76% helium diluent. The incident shock Mach number was measured as 5.42, and the pressure behind the reflected shock wave as 3,220 psi. The test section Mach number was 20.5.

Figure 29a

Upper Trace - Pressure at
end of the Shock Tube
Sweep Rates -
Horizontal - 0.5 msec/cm
Vertical - 1,320 psi/cm

Lower Trace - Ionization
Gages
Sweep Rates -
Horizontal - 20 μ sec/cm
Vertical - 2 volts/cm

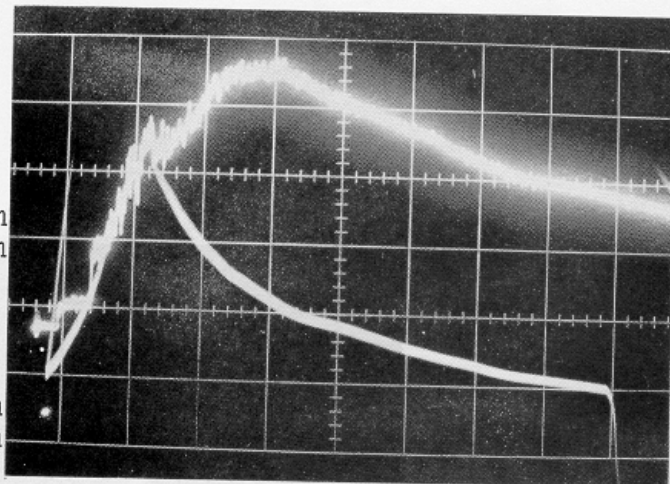
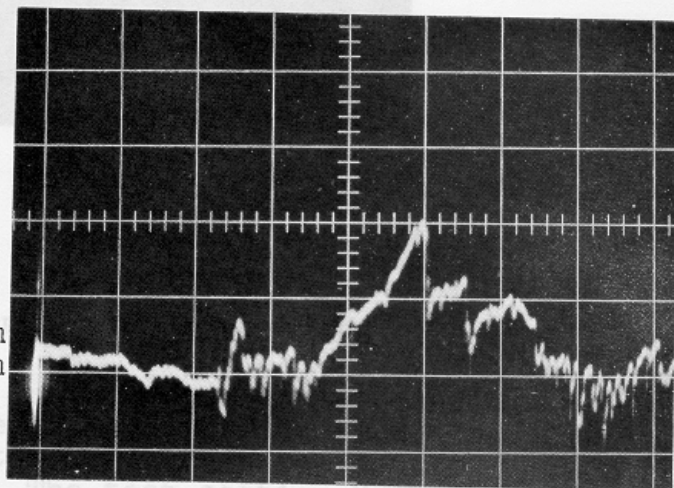


Figure 29b

Stagnation Pressure in the
Test Section

Sweep Rates -
Horizontal - 0.5 msec/cm
Vertical - 0.142 psi/cm



This figure shows the
the four inch hemispherical
reflected stagnation pressure
reservoir was 7,300°R. The test section Mach number
was 20.5. The bright area above the model is due
to extra light reaching the film.

FIGURE 29. SHOCK TUNNEL TEST RESULTS

The initial driver conditions for this test were 1500 psi loading pressure with 76% helium diluent. The incident shock Mach number was measured as 5.34, and the pressure behind the reflected shock wave as 4,520 psi. The test section Mach number was 20.2



FIGURE 30. LUMINOSITY PHOTOGRAPH

This figure shows the luminous region surrounding the four inch hemispheric model during flow. The reflected stagnation temperature in the nozzle reservoir was $7,300^{\circ}\text{R}$. The test section Mach number was 20.5. The bright area above the model is due to extra light reaching the film.

	Initial Loading Pressure (psi)	Per Cent Helium Diluent	Incident Shock Mach No.	Pressure behind Incident Shock (psi)	Pressure behind Reflected Shock (psi)	Tunnel Pitot Pressure (psi)	Tunnel Flow Mach Number	Fig. No.	Remarks
Shock Tube Tests	1000	76			3,130				Ion gage failed Low results
	1000	76	5.66	500	3,000				
	1000	76	5.50	510	3,730				
	1500	80	6.00	550	4,240				
	1500	80	5.66	600	4,320			21	
	1500	80	5.35	550	3,940				
	1500	80	5.83	550	4,460			22	
	1500	80	6.15	550	4,700				
	1500	80	5.49	645	4,050				
	1500	80	5.96	645	4,500			23	
	1500	80	6.35	690	4,650				
	2000	80	5.47	610	5,800				
Shock Tunnel Tests	1000	76	5.31		3,310				Mach No. too low
	1200	76	5.63		3,215				
	1000	76	5.50		3,500	0.272	18.8		
	1000	76	5.42		3,220	0.156	20.8	28	
	1500	80	5.59		4,570	0.217	20.7		
	1500	80	5.68		3,440				
	1500	76	6.58		6,080	0.204	20.7		No pitot pres.
	1500	76	5.34	450	4,520	0.272	20.1	29	
	1500	76	5.75	455	5,350	0.204	21.6		
	2000	76	6.43	800					
	2000	76	6.69		6,700	0.244	20.2		
									P5 off scale

FIGURE 30. TABLE OF TEST RESULTS