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DESIGN FEATURES OF THE GENERAL ELECTRIC  
RESEARCH LABORATORY HYPERSONIC SHOCK TUNNEL

by

H.T. Nagamatsu, R.E. Sheer, Jr., L.A. Osburg, and F.H. Cary

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## ABSTRACT

Design features of the General Electric Research Laboratory hypersonic shock tunnel are described. Particular emphasis is placed on many of its unique features. The loading and ignition system for consistent driver combustion without detonation is discussed. The anchoring of the driver and the slip joint clamping section that holds the main scored diaphragm is described in some detail. By boring and honing the stainless steel tubes, the attenuation of the shock wave in the long driven section was minimized. The use of a second diaphragm and a slip joint at the entrance to a conical nozzle is explained. The development of instrumentation necessary for shock tunnel operation is shown to have progressed to a point where the hypersonic shock tunnel is an extremely useful and versatile tool for hypersonic research. It is possible to simulate the Mach numbers and temperatures encountered by ICBM's, satellites, and space vehicles at the high altitude conditions.

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# DESIGN FEATURES OF THE GENERAL ELECTRIC RESEARCH LABORATORY HYPERSONIC SHOCK TUNNEL\*

H. T. Nagamatsu, R. E. Sheer, Jr., L. A. Osburg, and K. H. Cary

## I. INTRODUCTION

In recent years, advances in rocket and missile technology have made possible hypersonic vehicles such as intercontinental ballistic missiles, satellites, and space probes. The high speeds necessary for these vehicles give rise to numerous environmental problems, particularly in the areas of fluid dynamics and physics of high-temperature gases. For example, at a Mach number of 20, which is necessary for a 5000-mile ballistic vehicle, the air temperature can be as high as 6500°K during the re-entry trajectory. Air at these high temperatures can no longer be considered as a simple mixture of inert nitrogen and oxygen molecules; instead it will dissociate, ionize, and experience chemical reactions between some of the constituents. These phenomena at high temperatures are referred to as real gas effects for air.

Many of the conventional experimental tools for obtaining aerodynamic information, such as supersonic and hypersonic wind tunnels, become inadequate for investigating these real gas effects. Thus, there has existed a need for experimental facilities capable of simulating the Mach number and the high stagnation temperature encountered by these hypersonic vehicles.

The primary tools for hypersonic research are helium tunnels, hypersonic wind tunnels, shock tubes, shock tunnels, and recently developed hotshot tunnels. Each one of these tools is best suited for the study and research necessary for specific hypersonic problems, but no single one is best for all problems.

The helium tunnel<sup>(1-4)</sup> is best suited for study in the high Mach number range (20 to 35) of purely aerodynamic problems, and only in the ideal gas case where no temperature or real gas effects are encountered.

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For long test periods, several hours, the hypersonic wind tunnel<sup>(5-8)</sup> may be utilized. Many types of investigations can be conducted in wind tunnels, but research at high Mach numbers and the study of real gas effects is limited by the allowable temperatures for the tunnel components.

The shock tube<sup>(9-15)</sup> is a satisfactory tool for studying high-energy quasi-steady flows about bodies for short time periods. However, in the desirable testing region of the shock tube the flow Mach number will only be about three.

The hotshot tunnel<sup>(16, 17)</sup> is producing reasonably high-temperature, high Mach number flows under some real gas conditions. These are obtained by discharging a high-energy arc in a gas-filled reservoir chamber and then expanding this gas through a conical nozzle. At present, there is one problem that is gradually being overcome, where the arc is tending to vaporize material from the electrodes and the nozzle throat. This is introducing impurities into the flow which makes the data interpretation very difficult.

The shock tunnel<sup>(18-22)</sup> combines the high thermodynamic gas properties available from a shock tube with the test section Mach number variation available in a hypersonic wind tunnel. With this type of facility, both the flight Mach numbers and stagnation temperatures associated with hypersonic vehicles can be simulated simultaneously.

A shock tunnel<sup>(18-22)</sup> consists of a high pressure or driver section and a low pressure or driven section separated by a diaphragm. When the diaphragm breaks, a shock wave propagates down the driven section while an expansion wave propagates into the driver section, accelerating the driver gas into the driven section. Between the incident shock wave and the contact surface, there exists a uniform flow of compressed and heated gas which is available for test purposes. When a nozzle is placed at the end of the driven section, the compressed and heated gas behind the incident shock wave is expanded to high velocities to produce hypersonic flow in the test section. If the flow behind the incident shock wave is passed directly into a diverging section, this is known as a straight-through nozzle. If the end of the driven section is closed except for a small entrance to a converging-diverging nozzle, the incident shock wave reflects from the end of the tube, which compresses and heats the gas further and brings the flow to rest. This heated and compressed gas then expands in the nozzle to produce hypersonic flow in the test section. This arrangement is called a reflected nozzle, and a schematic drawing of shock tunnel processes with such a nozzle is presented in Fig. 1.

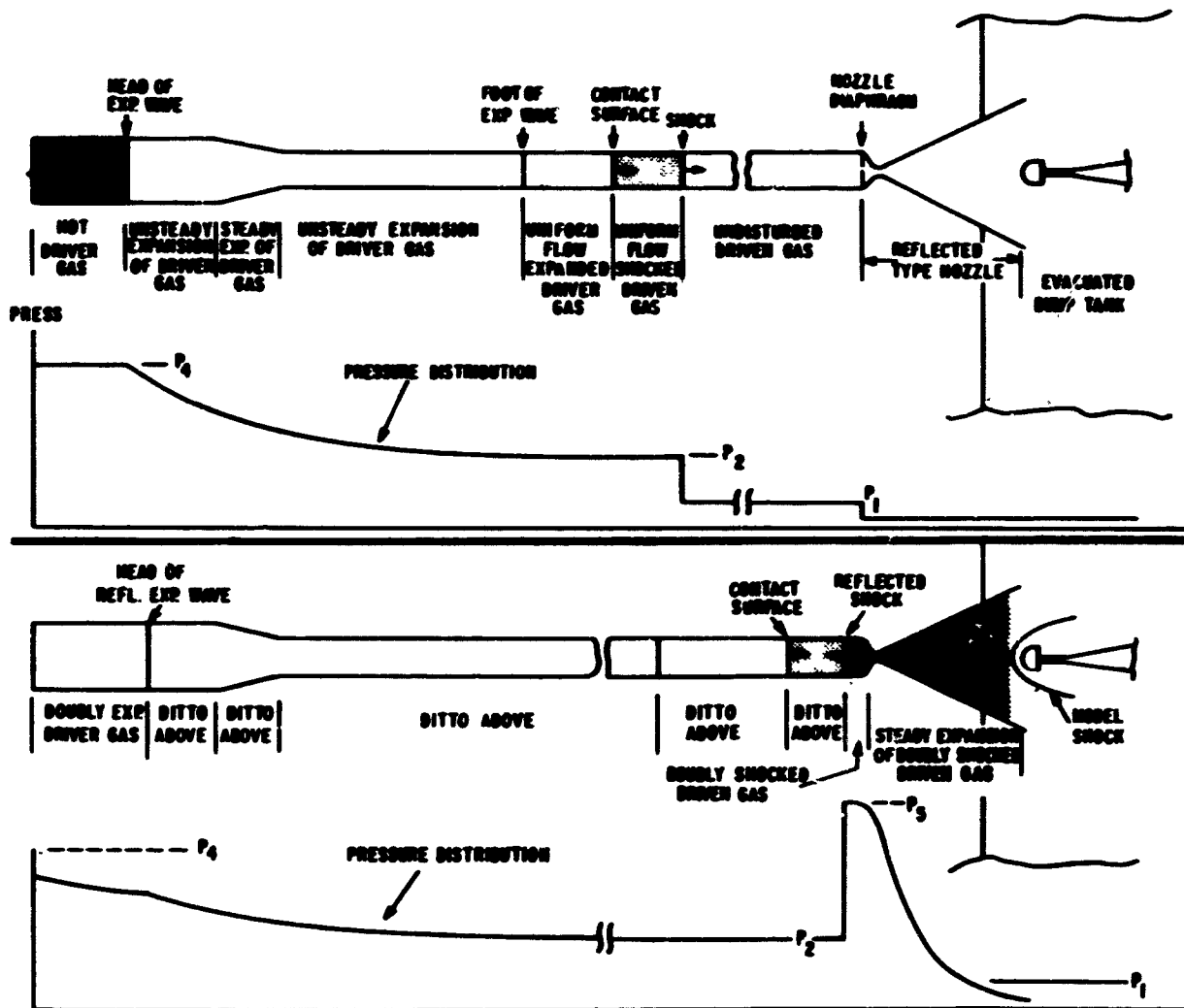


Fig. 1 Idealized picture of shock tunnel phenomena.

The following sections will describe the GE Research Laboratory shock tunnel which has been in operation since early 1957.

## II. DRIVER

### A. Driver and Diaphragm Section

The hypersonic shock tunnel consists of a driver, a diaphragm section, a shock tube or constant area section, and a nozzle partly installed in a dump tank, as shown in Figs. 2 and 3. The 20-foot-long driver section, constructed of chrome-molybdenum steel, was bored and honed to an inside diameter of 6 inches with a wall thickness of 4 inches. The design driver operating pressure after combustion is 10,000 psi with an adequate margin of safety. To prevent corrosion

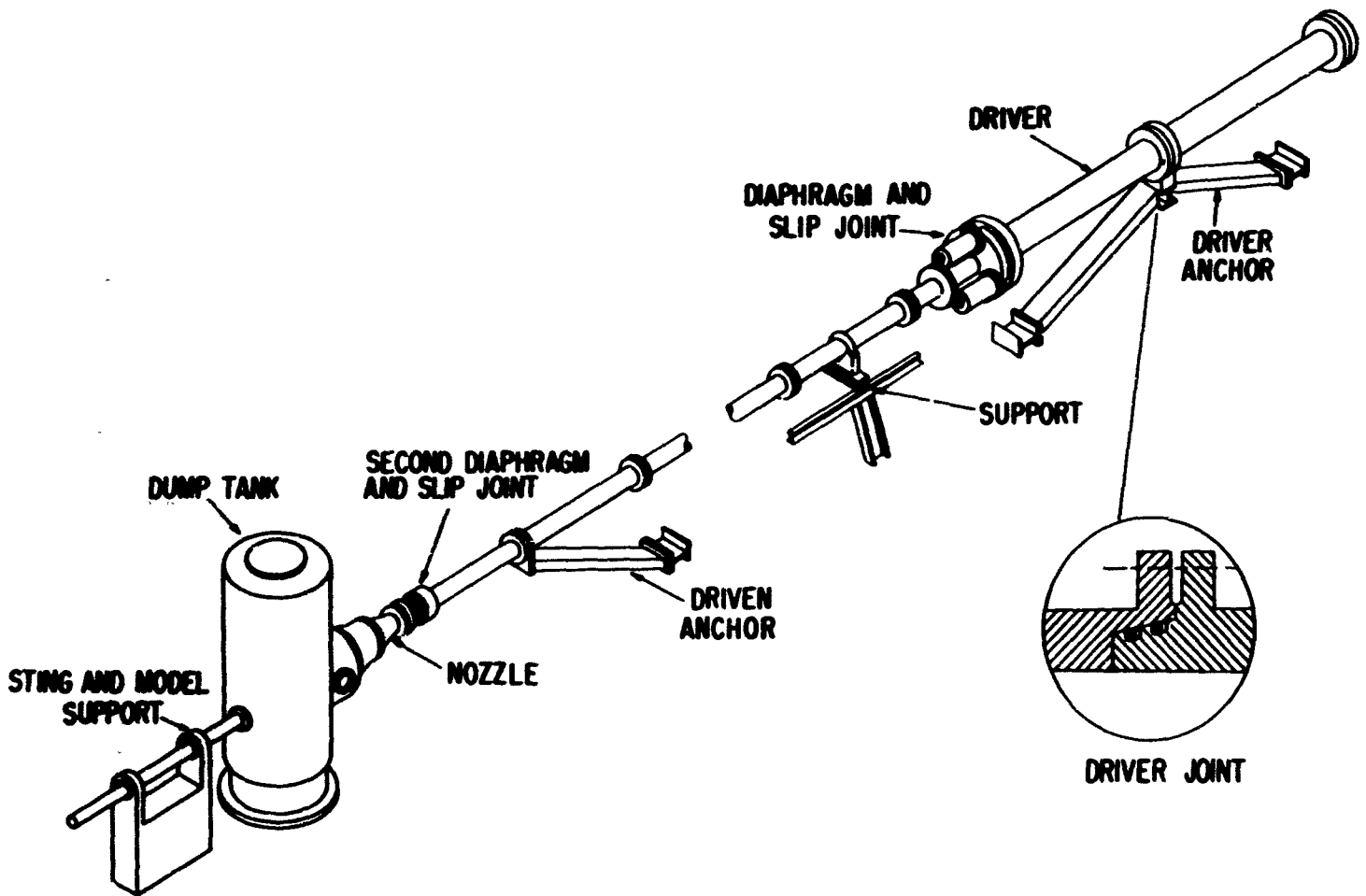


Fig. 2 Over-all shock tunnel schematic.

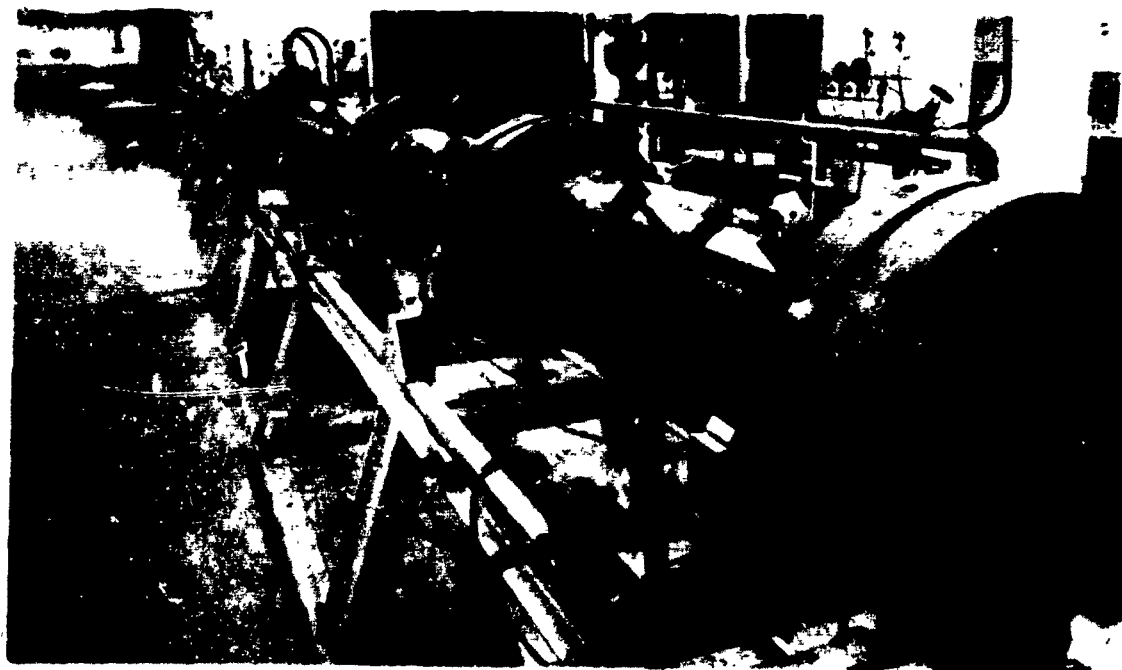


Fig. 3 Shock tunnel looking from driver end.

the inside surface of the driver is plated with a 0.005-inch layer of hard chromium. The length of 20 feet for the driver was selected so that the reflected driver expansion would not be the limiting factor in nozzle testing time.

The driver is made in two 5-foot sections and one 10-foot section to allow for any future modifications and for ease of handling in the assembly. The joints between sections and between the end cap and the end section are male and female 4-degree taper joints with "O" ring and leather backup ring seals on the tapered surface (Fig. 2). This type of joint and seal has been hydrostatically tested to 30,000 psi. The tapered joint eliminates alignment problems and the binding of mating parts. All of the holes in the driver walls are made identical so that all of the plugs for loading, ignition, etc., may be interchanged.

The 6-inch inside diameter driver section is connected to the 4-inch inside diameter driven tube by a conical transition piece which is 4 feet long. At the entrance of the transition section, there is a section which holds the diaphragm as shown in Fig. 4. Three hydraulic pistons operating at 3000 psi pressure are used to move the clamping unit of the diaphragm section. Check valves and mechanical locks prevent the opening of the clamping section during the combustion process.

The movable clamping unit is designed to slip over the transition piece and is sealed with "O" rings similar to a piston seal. This allows the clamping section to be opened for the changing of the diaphragms and will also keep the recoil movement of the driver and the impact of the diaphragm slapping the clamping section from being transmitted to the driven section.

Stainless steel, copper, monel, and aluminum have been used for the diaphragm material. For most operations stainless steel has been utilized since it has reasonably high yield strength. The stainless steel diaphragms open uniformly and do not shatter as they are slapped against the inside wall of the clamping section. It was originally thought that in order to have a diaphragm open fully in a circular tube, and not lose any leaves, it would have to open with at least six segments or that a spacer with a square opening would have to be inserted to allow a four-segmented diaphragm to open properly. Actually, for the present installation the diaphragms with four segments open more consistently than the ones with six segments. The diaphragms form to the circular cross section very well as they open making the square insert unnecessary. To permit the diaphragm to open into petals, two



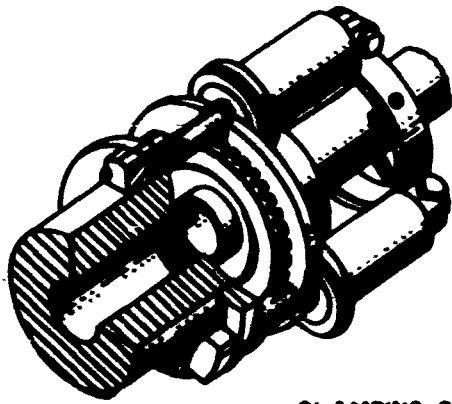
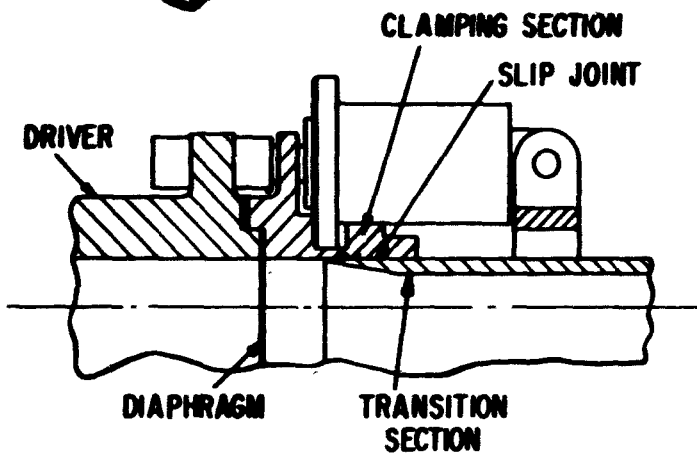


Fig. 4 Clamping section and slip joint.



grooves are cut at right angles to each other to a depth of one-third to one-half the material thickness (Fig. 5). A cutter radius of 0.020 inch is maintained in order to keep the stress concentration consistent. The pressure at which the diaphragm bursts is controlled by varying the material thickness and the depth of the cuts. Consistent bursting pressures have been achieved by this method of fabricating the diaphragm.

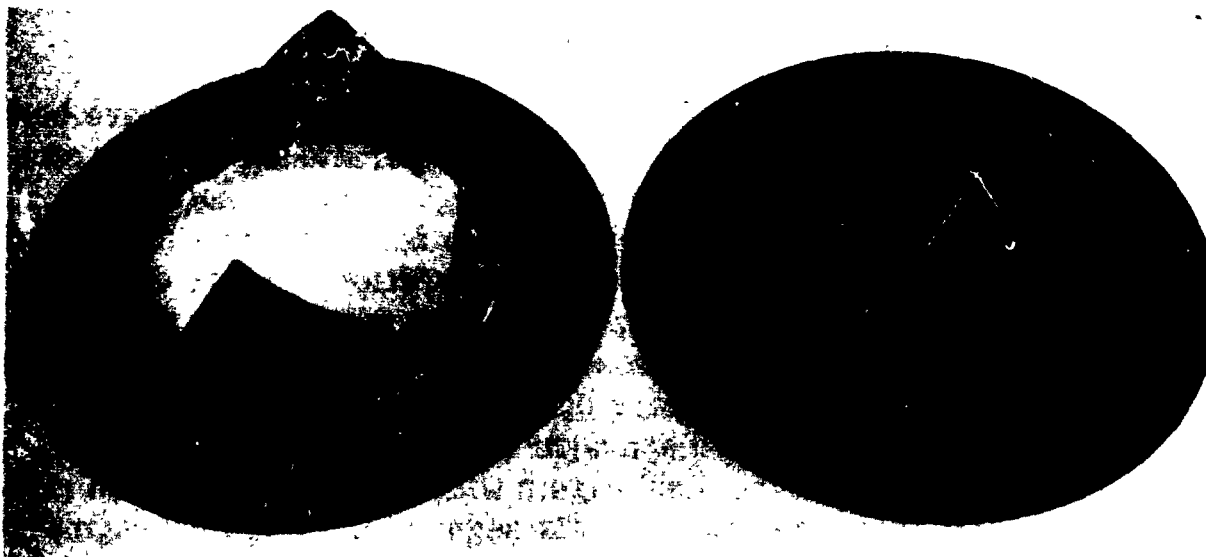


Fig. 5 Diaphragm before and after opening.

## B. Anchor and Supports

To permit longitudinal recoil of the driver section when strong shocks are produced, the driver is anchored to the floor, as shown in Figs. 2 and 3, by two 12-inch steel channels which are bolted through 1-inch-thick rubber inserts to the steel beam embedded in the floor. The driver is mounted on adjustable V-blocks which are supported on a welded framework of crane rail and I beams, which in turn are welded to I-beams embedded in the floor.

## C. Spark Plugs and Ignition System

The spark plugs that were originally used were an automotive-type plug, reinforced with glass tape and epoxy resin for added strength. These plugs would average 200 shots before replacement, and would ignite the driver gas at loading pressures lower than 500 psia.<sup>(23)</sup> For ignition above 500 psia, a special heavy-duty spark plug was designed and constructed (Fig. 6). This plug will fire repeatedly at 1000 psia and will average 600 shots before replacement of a small section of epoxy resin.

To produce uniform combustion and to minimize the possibility of detonation in the driver, eighteen spark plugs are mounted flush with the inside wall on 12-inch centers in a spiral arrangement around the

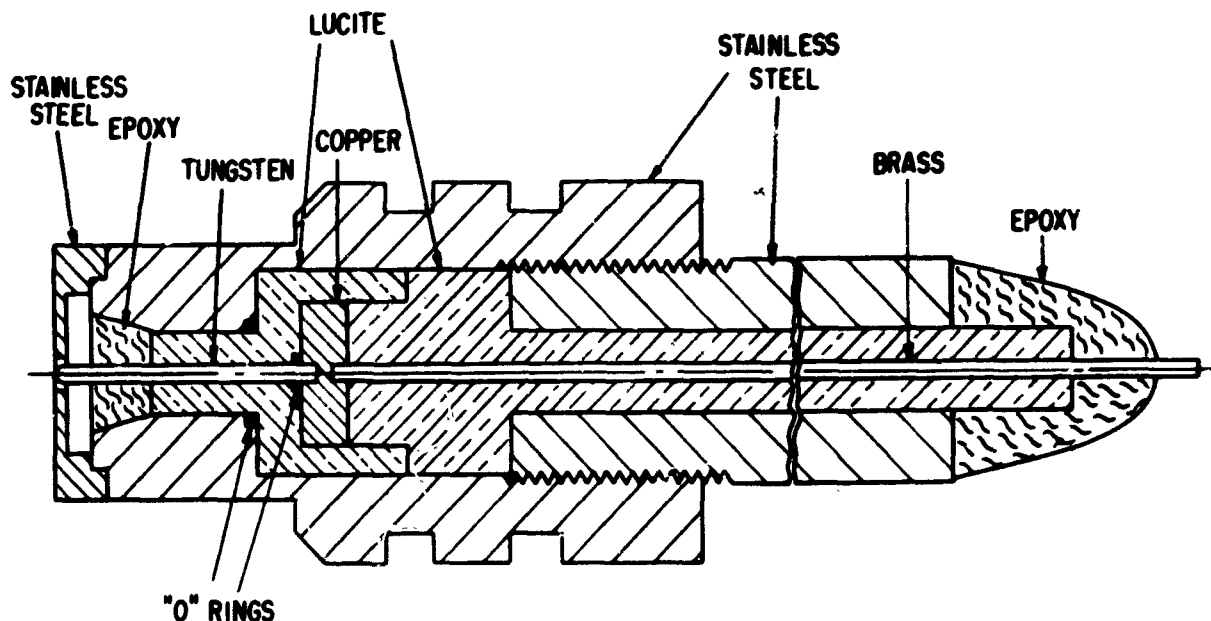


Fig. 6 Spark plug.

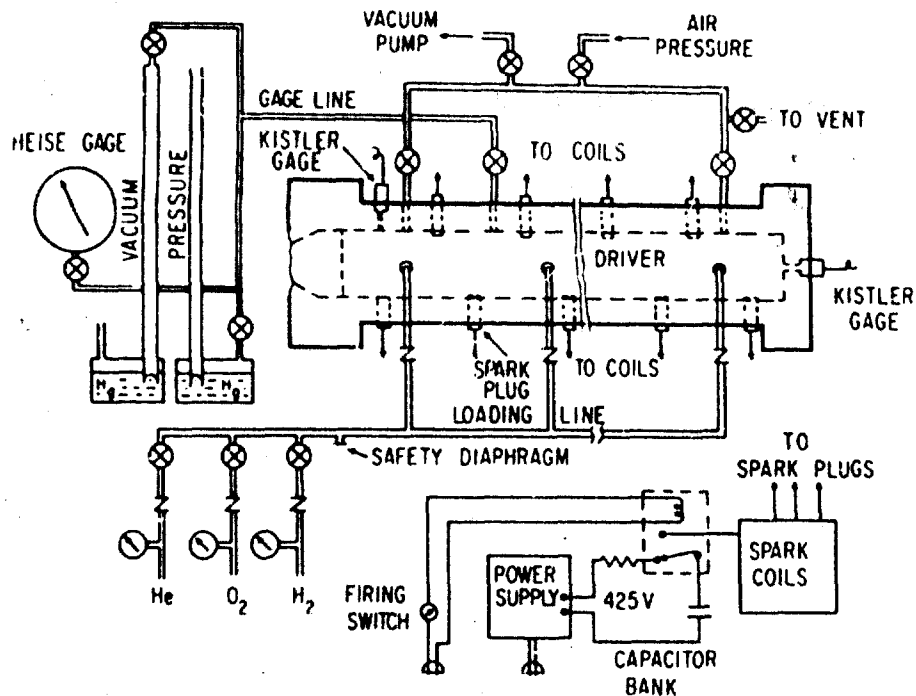


Fig. 7 Driver schematic of loading and ignition.

driver.<sup>(21, 23)</sup> A bank of capacitors, charged to 450 volts, is discharged through an automotive-type coil to each plug (Fig. 7). All the capacitors are discharged by a single solenoid switch to simultaneously ignite the mixture at all 18 locations.

#### D. Loading

Besides having ignition take place at a number of locations simultaneously to minimize the possibility of detonation, the gases must be injected into the driver so that good mixing is achieved before combustion. Thus, the gases are injected at six locations, each inlet having an orifice with four 0.018-inch-diameter holes drilled at an angle of 45 degrees to produce spiral motion. The driver is evacuated to a low pressure before the oxygen is injected. Then about 50 per cent of the total helium charge is injected. Next, the hydrogen is added in stoichiometric proportions with oxygen. Finally, the remainder of helium is injected at high pressures and high velocity through the orifice plates to produce a swirling motion of the mixture in the driver and to clear the charging lines of combustible gases. This swirling motion enhances the mixing of the driver gases and

eliminates the long waiting time for the gases to mix through normal diffusion. With this loading procedure, the oxygen and hydrogen mixture is always diluted by a considerable amount of helium during the loading process. This is important since normal detonation pressures as high as 50 to 150 times the initial pressure have been observed.<sup>(15)</sup> Mercury manometers are used to measure accurately the low pressure in the driver during the loading process. For pressures above 60 inches Hg, a Heise Bourdon-type gage is used. After the gases have been injected into the driver, there is a waiting period of about 5 minutes before the mixture is ignited by the multiple sparks. With this method of loading and igniting the gases, extremely reliable and reproducible driver combustion results have been attained.<sup>(24)</sup>

The burning rate of the driver charges can be controlled by varying the percentage of helium in the mixture.<sup>(23)</sup> Good results have been obtained using a mixture consisting of 75 per cent helium with the balance hydrogen and oxygen in stoichiometric proportions. The 75 per cent mixture produces close to the maximum driver gas acoustic velocity as well as a reasonably rapid rise time to peak pressure of 15 to 20 milliseconds. Furthermore, there has been no indication of detonation formation with 75 per cent mixtures. Early combustion tests<sup>(23)</sup> with a 65 per cent helium mixture in a 10-foot driver section produced definite detonation for initial loading pressures greater than about 100 psia with the particular ignition system.

#### E. Safety Features

No relief blowoff diaphragm is installed at the end of the driver section, but the driver is instead sealed off with a 4-inch-thick blind flange. Since the diaphragm is stainless steel and the maximum thickness will be 3/8 inch, the diaphragm will always be much weaker than the end blind flange of the driver. Therefore, the diaphragm will act like a safety valve to prevent excess pressure from developing in the driver section.

In the event it is necessary to release the unburned gases in the driver, a stainless steel tube is connected to the driver and vented to the outside of the building. After normal combustion it is necessary to remove the water formed in the driver by the hydrogen-oxygen reaction. This is accomplished by passing clean dry air through the facility.

The use of hydrogen and the possibility of detonation with its extremely high peak pressures requires precautions to protect the

operating personnel and the equipment. During the charging of the driver, the area housing the driver is ventilated by four exhaust fans on the blowoff roof of the building. This eliminates the possibility of hydrogen accumulating in the driver room. All lines bringing the gases to the driver are designed for an operating pressure of 30,000 psi. A blast mat is installed between the driver and the driven tube, as shown in Fig. 3, to contain any fragments in the driver area. The back wall of the driver room is constructed of material that will blow off under a small pressure differential.

The gases are stored in standard high-pressure bottles which stand along the outside wall of the driver room. All lines coming from these bottles to the loading panel are designed for an operating pressure of 6000 psi. The loading panel is located on the opposite side of the blast mat from the driver room. The entire hypersonic shock tunnel facility is located in a reinforced-concrete building with steel doors. The control room, to which all personnel are evacuated for high-pressure tests, is adjacent to the shock tunnel room and is separated from it by a 12-inch-thick reinforced concrete wall with two high-strength, shatterproof observation windows.

### III. DRIVEN SECTION

#### A. Driven Tube

The constant area or driven section of the shock tube consists of stainless steel tubing with a wall thickness of 1 inch and an inside diameter of 4 inches. In order to minimize the wall viscous effects, the inside surface was bored and honed to obtain an extremely smooth finish. This section was designed for a maximum operating pressure of 10,000 psi. Adjacent sections of the tubes are joined together with a tapered fit and sealed by "O" rings similar to the driver sections. This technique eliminates both inner surface discontinuities at the joints and misalignments that might otherwise result from the impact loadings experienced when the shock tunnel is fired. A total driven section length of 103 feet is attained with ten 10-foot sections and one 3-foot section which is connected to the conical nozzle. These sections have varying numbers of holes in their walls for the installation of pressure pickups, heat gages, and other instrumentation. Just before the entrance to the nozzle there are ten holes in the constant area section for measuring the shock velocity accurately and for determining the pressure and heat transfer behind the incident and reflected waves. All of the holes in the driven tube are identical in order to allow the pressure, heat, ionization, etc., gages to be placed anywhere on the tube.

## B. Support and Anchor

The entire shock tube is supported on a welded rail and I-beam structure which is anchored to the steel beam embedded in the floor. The tube itself rests on adjustable V-blocks and is held down with U-bolts attached to the V-blocks. At each end, the tube sets in split bronze bushings. These bushings keep the tube in alignment with the slip joints at the driver and nozzle. With this arrangement, a slight deviation in the alignment of the center portion of the tube is not critical. At the downstream end the tube is anchored to the floor with a 12-inch steel channel member (Figs. 2 and 8). A thick rubber slab is used between the channel member and the steel beam embedded in the floor to absorb some of the impact produced when the shock wave reflects from the nozzle entrance at the end of the tube.



Fig. 8 Driven section anchor, nozzle, and dump tank.

### C. Vacuum and Pressure

Provisions are made for evacuating the constant area section for low-pressure operations by means of a large vacuum pump. For operations where pressures above atmosphere are required, clean dry air is led into the tube from the building air supply. To measure the initial pressure in the shock tube accurately, a McLeod gage and a micromanometer are used for the pressure range of 1 micron to 8 millimeters of mercury. For intermediate pressure to atmospheric, both Bourdon-type gages and mercury manometers are utilized. For pressures above atmospheric, a Bourdon-type gage is used. It is important for shock tube operation to know the pressure and the temperature in the shock tube accurately before firing.

### D. Second Diaphragm Section

The 3-foot section at the end of the tube is fitted with a threaded movable collar for clamping the second diaphragm near the entrance of the conical nozzle (Fig. 9). "O"-ring seals between this collar and the outside of the nozzle permit the collar to be moved for diaphragm changing. When the diaphragm is clamped in place, these seals allow the tube to move or slip relative to the nozzle to allow for thermal expansion and contraction of the tube as well as the recoil caused by the reflected shock wave.

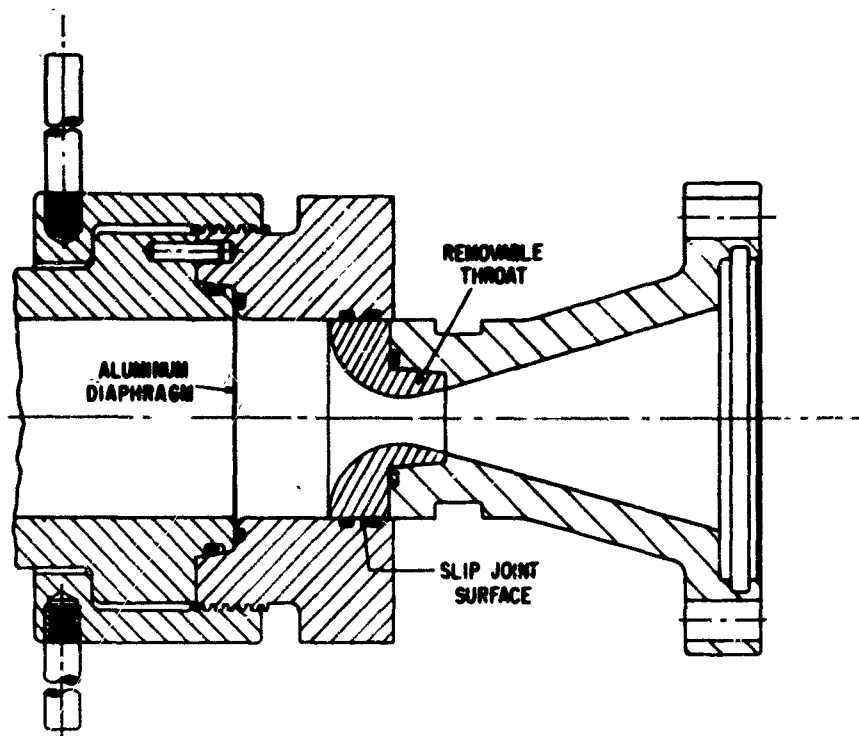


Fig. 9 Second diaphragm and slip joint assembly.

The second diaphragm, made of soft aluminum and cross cut like the driver diaphragm, is used to allow the driven tube and the nozzle to be at different pressures. Usually the nozzle and dump tank are evacuated to very low pressures to facilitate the establishment of flow in the test section, while the driven tube pressure is varied to control the reservoir conditions at the nozzle entrance. The bursting pressure is controlled by the material thickness and the depth of cut. The diaphragm must be heavy enough to prevent the leaves from tearing off, and the depth of cut is made so that the diaphragm is just strong enough to maintain the pressure differential and will open with very little resistance upon the arrival of the incident shock.

#### IV. NOZZLE AND DUMP TANK

##### A. Nozzle

The shock tunnel was designed for three possible nozzle arrangements:<sup>(18)</sup> straight-through configuration with the throat diameter equal to the shock tube diameter of 4 inches, converging-diverging or reflected shock wave configuration, and a straight-through double nozzle arrangement which removes the boundary layer. The reflected nozzle arrangement was selected for initial operation because the shock tube boundary layer effects are minimized and high nozzle stagnation temperatures are attained for a given driver pressure after combustion. Moreover, the large area ratios required for high flow Mach numbers can be achieved without a prohibitively large nozzle exit diameter or the complications of the double nozzle arrangement. Also, with the reflected method several nozzles can be attached to the end of the driven section at the same time. In this manner several models can be tested at one time under identical reservoir conditions which greatly increases testing capabilities per shot of the shock tunnel.

A conical nozzle with a total expansion angle of 30 degrees and with an exit diameter of 24 inches is connected to the end of the shock tube at the slip joint and is supported and partly housed inside the dump tank. For ease of operation and simplicity of construction, the nozzle consists of four parts. The exit part is made of aluminum in order to facilitate handling. The adjacent part, which is outside the dump tank, is a heavy brass casting. The short pieces (Fig. 9) for the throat and the part that connects the throat section to the brass section are constructed of tool steel and stainless steel, respectively, for strength and corrosion resistance. The area ratio for the conical nozzle is varied simply by changing the throat section. The throat diameter can



be varied from 4 inches to 0.05 inch. Throat diameters of 1, 0.33, 0.19, and 0.10 have been tested to produce flow Mach numbers in the test section for nearly perfect gas conditions of approximately 10, 16, 20, and 25.

### B. Dump Tank

A 200-cubic-foot dump tank houses the test section of the conical nozzle, as shown in Figs. 8 and 10. The large dump tank insures moderate steady state pressure in the facility even for maximum driver charges. Observation windows are located at the exit of the nozzle to permit optical investigations of the flow field around models. The windows are 1 1/4-inch-thick optically selected plate glass. The dump tank is firmly anchored to the floor to prevent movement and subsequent misalignment, from the recoil caused by the shock wave reflecting at the nozzle entrance.

The dump tank was designed for either horizontal or vertical installation. A vertical arrangement for the dump tank was selected initially to permit the shortest length for the model sting. Even in this position the unsupported sting length is 5 feet. Where the sting enters the tank a floating Lucite isolating flange is used (Fig. 10). This flange is clamped between two flanges with enough clearance between the flanges to enable the Lucite to move on sliding "O" ring seals. With

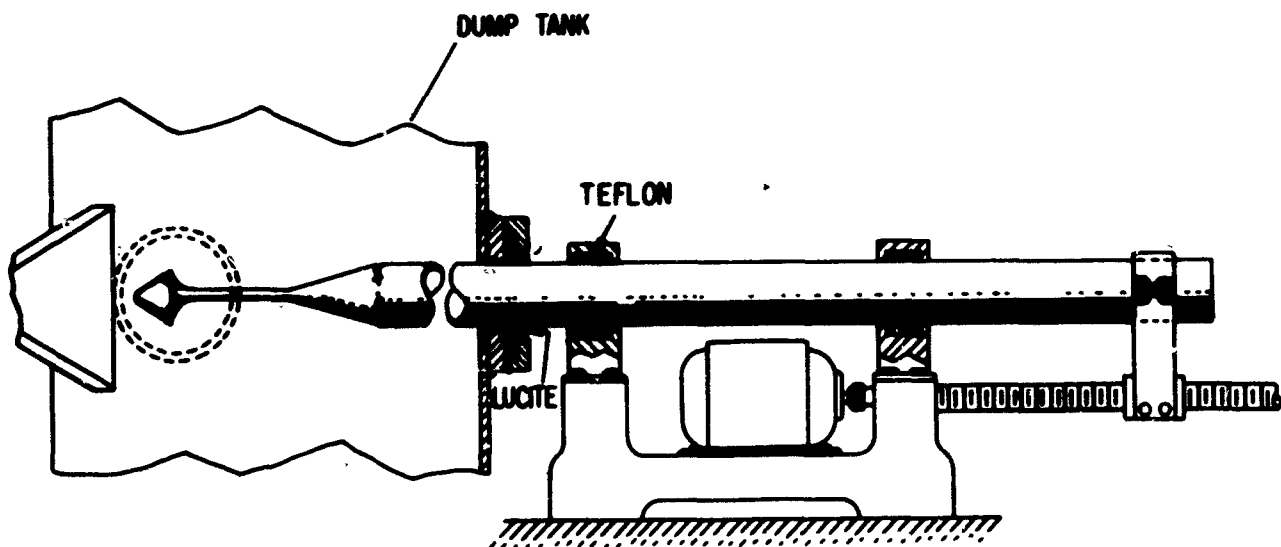


Fig. 10 Sting and model support assembly.

this sliding ability and the Lucite's natural damping qualities, most of the vibration setup in the tank by the shock recoil is not transmitted to the sting and model.

### C. Sting and Model Support

The sting is a 6-inch-outside-diameter stainless steel tube with a tapered nose that reduces to a 1-inch-outside-diameter tube behind the model (Fig. 10). The support structure for the sting is separate from the dump tank and is heavily weighted. The sting itself rides on Teflon bushings. With this combination of mass and Teflon bushings, a considerable degree of vibration isolation is achieved.

A lead screw, driven by a reversible d-c motor, is used to position the sting and model in the test section and has sufficient travel to completely withdraw the model from the tank. This greatly simplifies the installing and changing of models, and connecting of the electrical leads that pass through the hollow sting to the models.

### D. Vacuum System

Usually the dump tank and the nozzle are evacuated to low pressures in order to facilitate flow establishment in the test section. For very high flow Mach numbers of 20 and 25 the dump tank is evacuated to about 5 microns of mercury. At lower Mach numbers it is only necessary to evacuate to pressures below about 100 microns of mercury.

The vacuum system consists of two Consolidated Vacuum KS-200 diffusion pumps backed up by a Kinney KDH-150 mechanical pump. The mechanical pump is mounted on rubber pads, and there is a bellows section in the vacuum line between the mechanical and diffusion pumps to minimize the vibration from the mechanical pump being transmitted to the tank and model.

## V. INSTRUMENTATION

### A. Pressure Gages

Piezoelectric pressure gages<sup>(25)</sup> are used to measure pressure in the shock tube and on the models in the nozzle test section. The standard Kistler SLM quartz pressure pickups have been successfully used in most applications, but for many investigations with small models their large size and small output make their use difficult. Consequently,

small barium-titanate pressure pickups have been developed to meet these needs. This type of pressure gage, while considerably smaller than the Kistler (see Fig. 11), nevertheless has considerably greater output. These pickups are more sensitive to vibration than the Kistler and must be shock mounted in rubber. The response time of the barium-titanate gages is about 10 microseconds as compared to 50 microseconds for the Kistler gages. The barium-titanate crystals are more sensitive to heat than quartz; hence, the pickup is designed with a certain amount of heat insulation depending on the installation for which the gage is intended.

For pressures above 5 psia, the Kistler gages have very linear and consistent static calibrations. Below 5 psia both the Kistler and the barium-titanate are very sensitive to the installation in models. For higher pressures the Kistler and barium-titanate gages are fitted

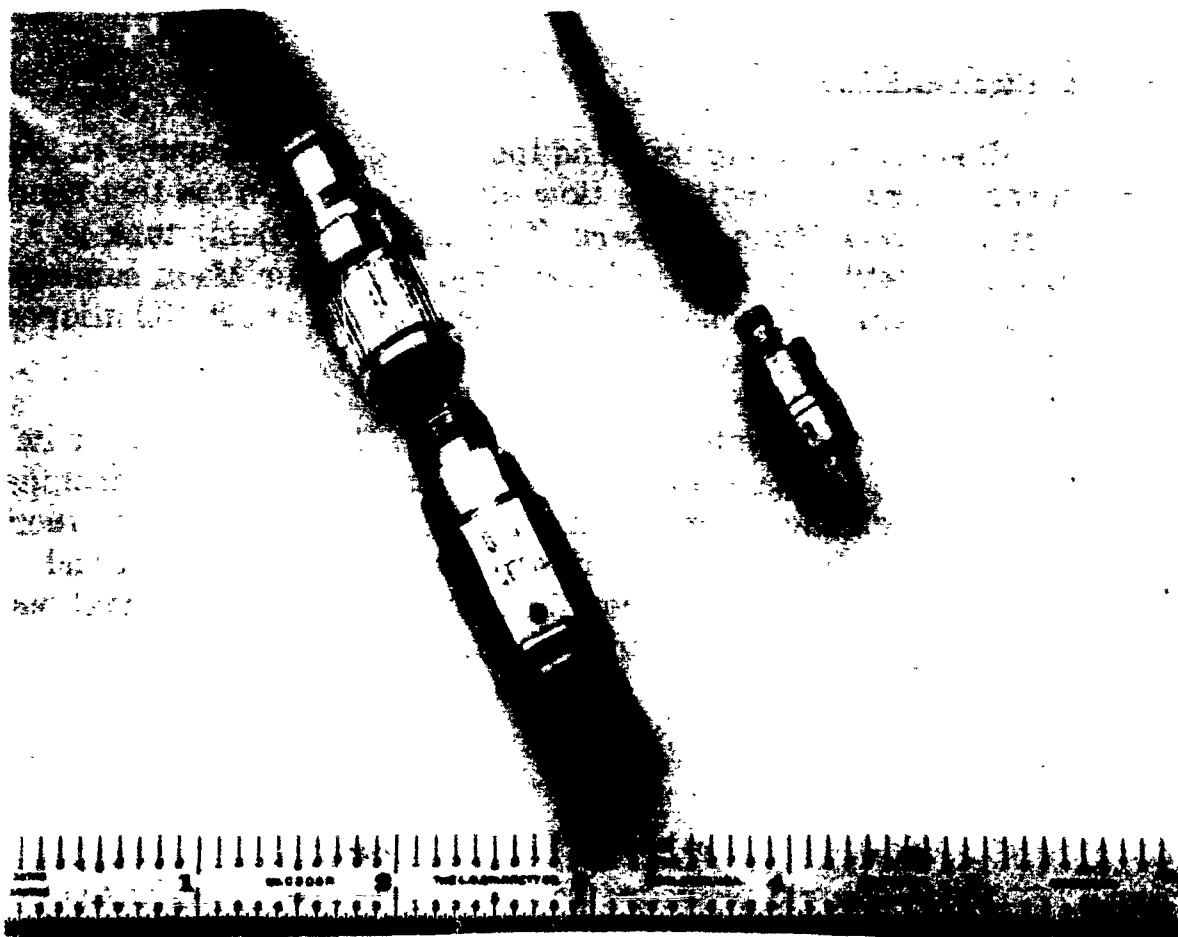


Fig. 11 Kistler (quartz) and barium-titanate pressure gages.

with adapters, which decrease the effective area on which the pressure acts. With these adapters it is possible to calibrate and use these gages above 10,000 psi.

Driver pressure measurements during the combustion process are taken with two Kistler SLM pressure indicators; the signals generated by these piezoelectric pickups are sent to two piezocalibrators whose outputs are connected to a Tektronix 535 oscilloscope. The discharging of the capacitor bank in the ignition system is used to trigger the sweep of the oscilloscope. A Polaroid scope camera is used to record the pressure traces. All cables for the ignition system and the pressure gages are shielded and carefully grounded to minimize the interference from the ignition process.

In the driven tube, both Kistler and barium-titanate gages are used to measure the pressure rise across the shock at various locations. For all runs, two Kistler gages are mounted near the end of the tube to record the reservoir pressure at the entrance to the nozzle.

For model pressure measurements, a dynamic calibration of the gages in their actual installations is made. This is accomplished by mounting the model at the end of the constant area driven section in place of the nozzle and subjecting it to the pressure increase behind incident or reflected shocks obtained with weak incident shock Mach numbers of about 1.5. In this manner very linear calibration curves for very small pressure increases have been obtained for both types of gages. A typical pressure-time trace for a Kistler gage and a barium-titanate gage is shown in Fig. 12.

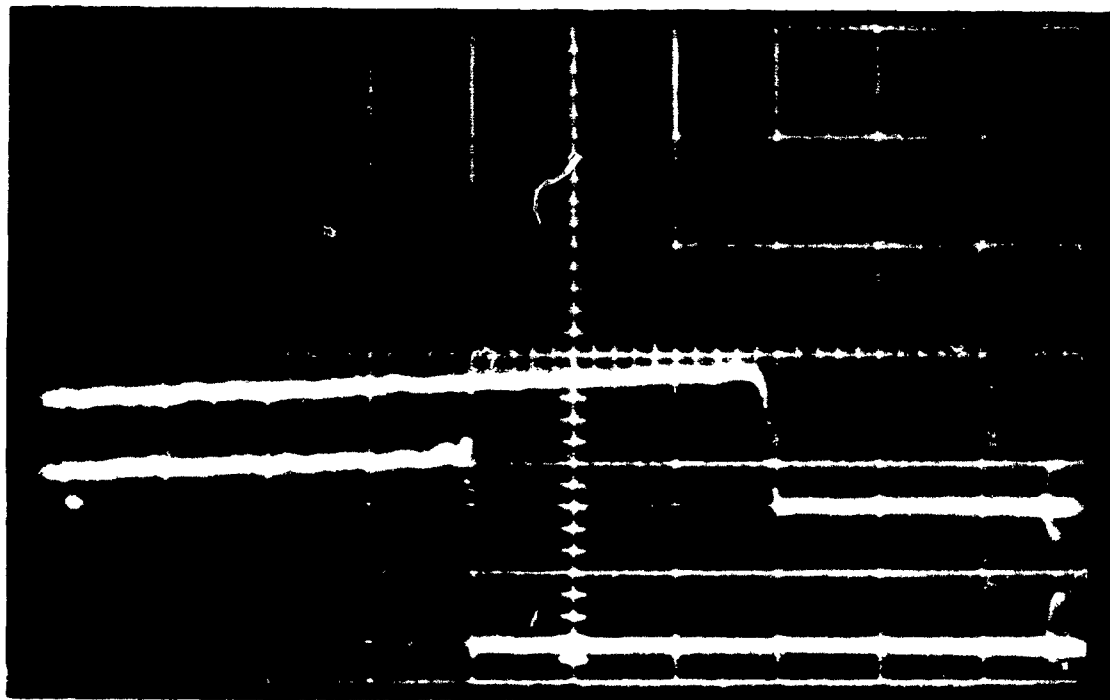


Fig. 12 Pressure time history for Kistler (top) and barium-titanate gages.

After calibration the model is attached to the sting and the gage leads brought out through the hollow sting to oscilloscopes. The actual method of recording the pressure traces is similar to that used in the driver and driven sections.

### B. Ionization Gages

A simple air gap with 300 volts d.c. between the center electrode and the outer wall is used as an ionization pickup (Fig. 13). The ionization of the air due to the strong shock wave breaks down the resistance across the gap and the resultant voltage change can be recorded. For a gap of 0.03 inch the response time of the gage is of the order of 1 microsecond.

The ionization gages are used in the driven portion of the shock tube for determining the existence of ionization behind a shock, for time of arrival pickups for determining the shock velocity, and as triggers for starting oscilloscope sweeps and other instruments.

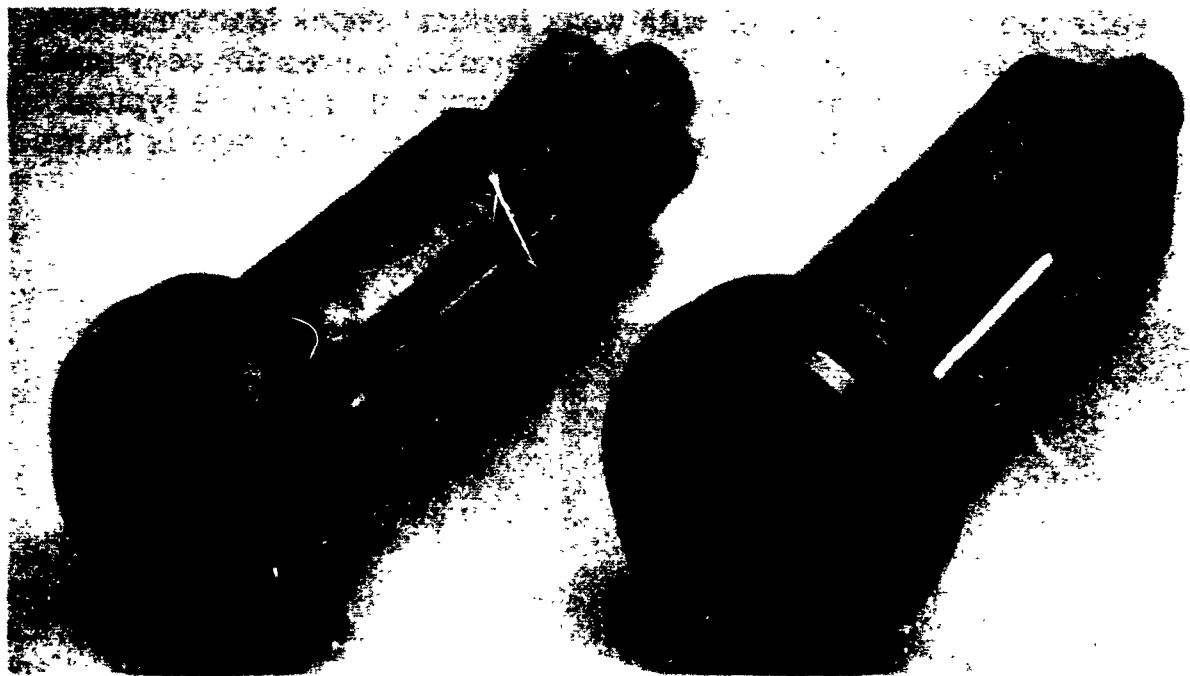


Fig. 13 Ionization and heat gage.

### C. Heat Gages

A thin platinum film, (26, 27) sputtered or painted, on a quartz or a Pyrex base acts as a resistance thermometer. The output of such a device, when a current is passed through it, is related to the surface heat transfer rate. This type of gage (Fig. 13) has been developed at various laboratories in recent years. (26-29) For these gages the resistance of the platinum film is usually about 40 ohms, and a current of 50 milliamps is used to detect a voltage variation produced by the change in film resistance. The thin sputtered heat gages have a response time of about 1 microsecond but are not as durable as the painted ones.

For shock waves too weak to ionize the gas in the shock tube, the platinum film heat gages are used to detect the arrival of the shock wave at stations along the shock tube. Similar heat gages are used on the models in the test section to measure the heat transfer at various stagnation temperatures. At very high temperatures for which the air becomes ionized, the heat gage must be coated with a very thin electrically insulating coating such as silicon dioxide. This coating prevents the ionized gas from short circuiting the platinum film.

### D. Raster (Shock Velocity Measurements)

The instrumentation used to determine the shock wave position as a function of time in the 100-foot-long shock tube consists of heat or ionization gages which serve as time of arrival pickups, a modified Tektronix 535 oscilloscope, a crystal-controlled raster generator, and a display chassis. The raster generator produces up to 500 cm of sweep length with a nearly vertical sawtooth or raster arrangement in which each vertical line represents a given time. The output of twelve sensing elements in the shock tube wall is fed into the display chassis which produces signals that are displayed as horizontal markers on the vertical sawtooth pattern. A curve of shock Mach number vs distance along the driven tube, obtained from raster data, is shown in Fig. 14. In normal operation of the shock tunnel, the shock velocity measurements are supplemented by a Berkeley counter, which measures the shock wave traversal time over the last few feet of the tube.

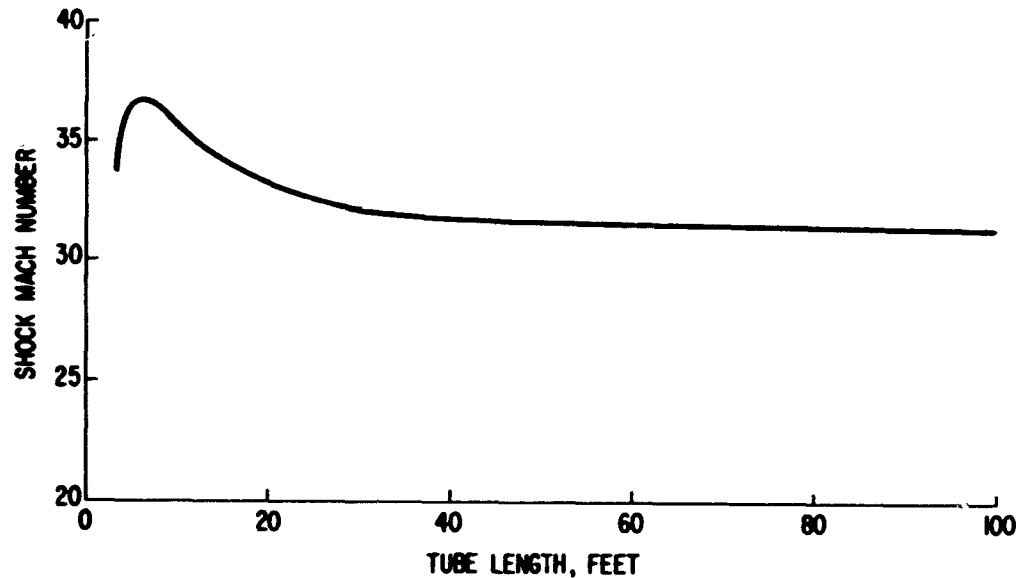


Fig. 14 Shock Mach number along the driven tube.

#### E. Optical Systems

A single-pass schlieren system with 6-foot focal length parabolic mirrors is used to obtain photographic records of the model flow fields (Figs. 15 and 16). For high-temperature conditions with a large amount of luminosity from the hot gas, an optical shield is placed at the knife edge to permit only small amounts of luminosity to reach the film. By permitting some of the luminosity to pass through the system, it is possible to photograph both the shock wave and the luminous gas region (Fig. 17).

The light source is provided by a 0.4-microsecond duration, 10,000-volt, capacitor discharge spark. For investigations of the flow phenomena as a function of time, schlieren photographs have been taken with a Fastex camera operating at 8000 frames per second using a 100-watt concentrated arc lamp for a steady light source.

Direct luminosity or "flash" photographs have been taken by leaving a camera open at the test section window during the test (Fig. 18). In this manner, color photographs have been obtained for the luminous region around blunt bodies. Direct photographs have also been taken with the Fastex camera.

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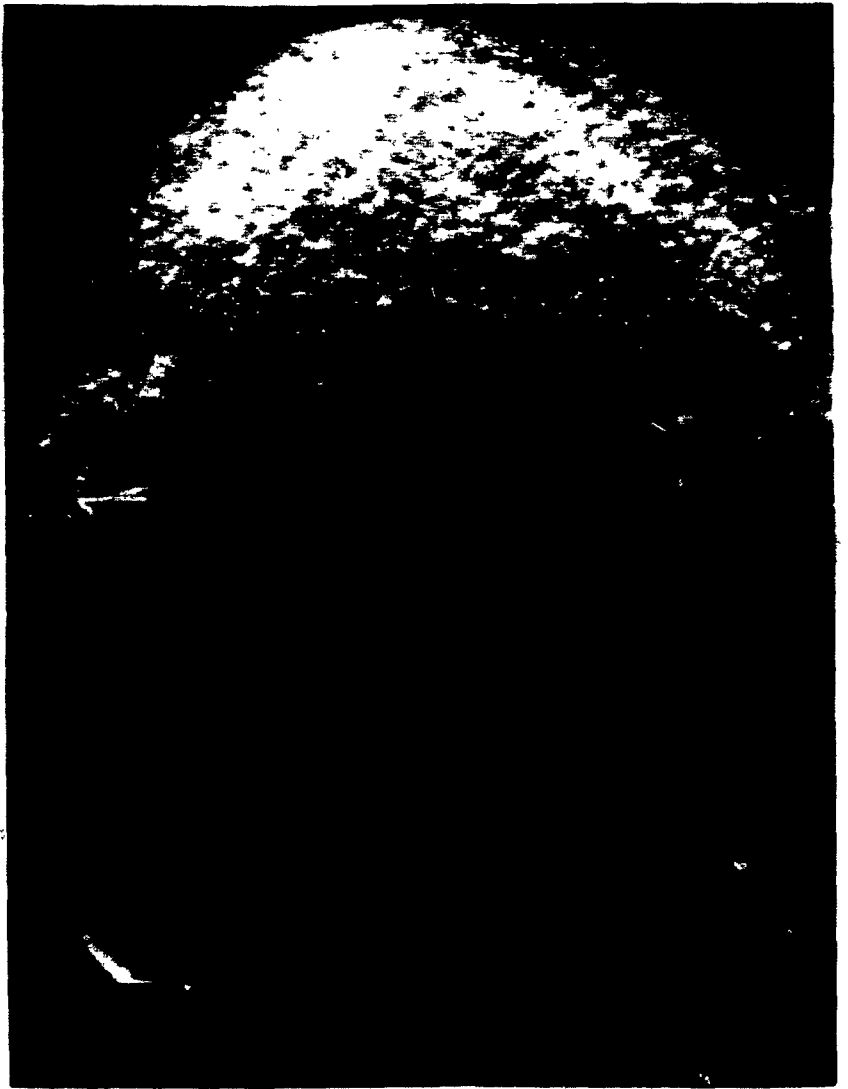


Fig. 15 Schlieren photograph of flow over a flat plate at Mach number 19.8,  $T_5 = 1400^\circ\text{K}$ .



Fig. 16 Schlieren photograph of 50° cone-hemisphere in Mach 10 nozzle,  $T_5 = 1300^\circ\text{K}$ .



Fig. 17 Schlieren photograph of 50° cone-hemisphere in Mach 10 nozzle,  $T_5 = 4000^\circ\text{K}$ .

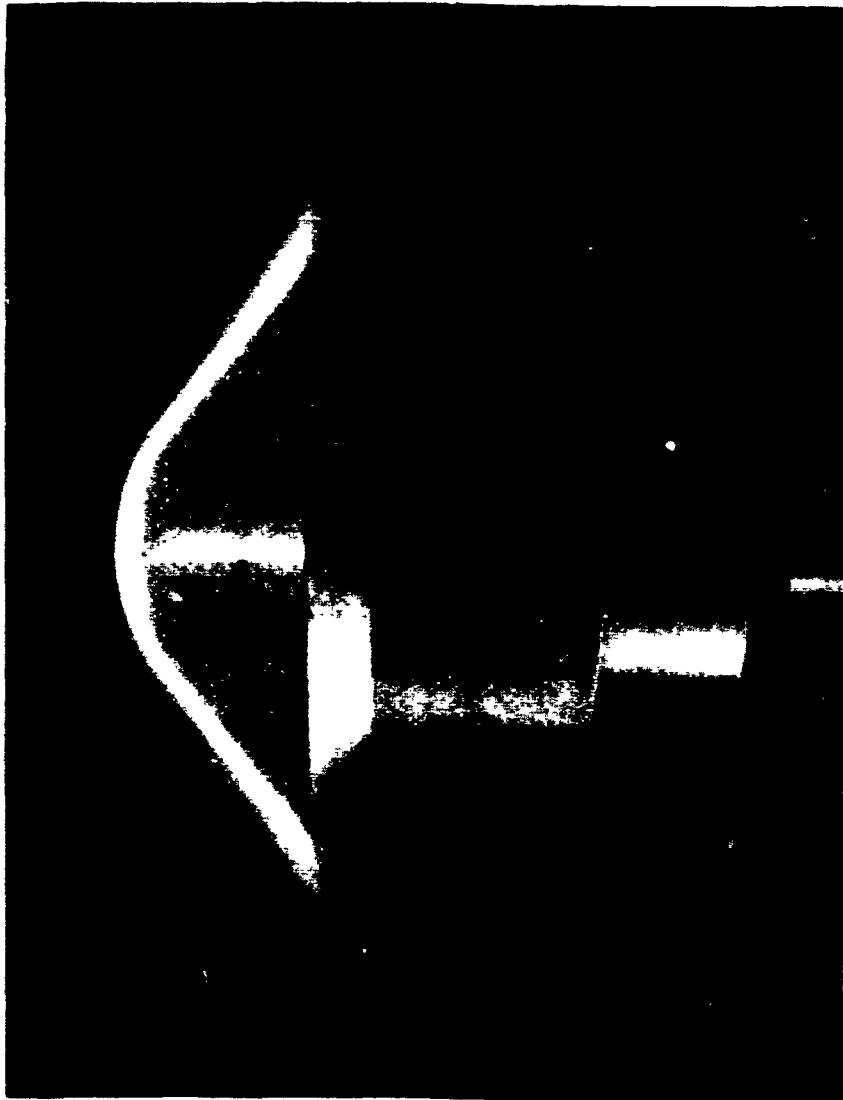


Fig. 18 Luminosity photograph of 50° cone-hemisphere in Mach 10 nozzle,  $T_5 = 5800^\circ\text{K}$ .

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For spectroscopic investigations of the heated gas after a shock wave, quartz windows may be inserted in the instrumentation holes in the shock tube walls. Some preliminary results have been obtained in the shock tube and in the test section.

Photomultiplier investigations of the hot gas region behind the shock wave may also be conducted through the quartz windows.

## VI. CONCLUSION

With the multiple-spark ignition system and with careful loading and mixing of the helium, hydrogen, and oxygen, it has been possible to obtain consistent and reproducible combustion in the hypersonic shock tunnel driver. In over 1000 successive test runs there has been no evidence of detonation.

The driver anchor and the slip joint at the transition section has minimized the recoil movement of the driver, and the transmission of this recoil movement and its associated vibration to the driven section. With this system the driver disturbance is a minor factor in successful shock tunnel operation.

The movable clamping section, that is actuated and held in place by the hydraulic pistons, has greatly simplified the changing and clamping of diaphragms. The two-groove method of diaphragm cutting has proven to be an inexpensive and reliable technique.

Boring and honing of the stainless steel driven section of the shock tunnel has reduced the shock wave attenuation along the tube. When this is coupled with the reflected shock technique at the nozzle entrance, a reservoir of high-temperature, high-pressure gas, relatively free from boundary layer effects is made available for expansion in the nozzle section.

The second diaphragm at the entrance to the nozzle makes possible a practically unlimited range of initial driven section and test section conditions. With the large dump tank initially evacuated to a very low pressure there is no interference, from pressure buildup in the tank, to the test section flow during the duration of the test.

The conical nozzle works very well for producing high Mach number flow in the test section. It is more versatile for the variation of Mach number and much simpler to build than a contoured nozzle.

The development of the instrumentation necessary for shock tunnel operation is sufficiently advanced to make the relatively short testing times of shock tunnels extremely useful.

The hypersonic shock tunnel is proving to be a very useful research tool for investigating the flow phenomena associated with the high flow Mach numbers and high stagnation temperatures encountered by hypersonic vehicles. The design features mentioned in this report have contributed to the simplifying and expediting of the fundamental investigations in the hypersonic field.

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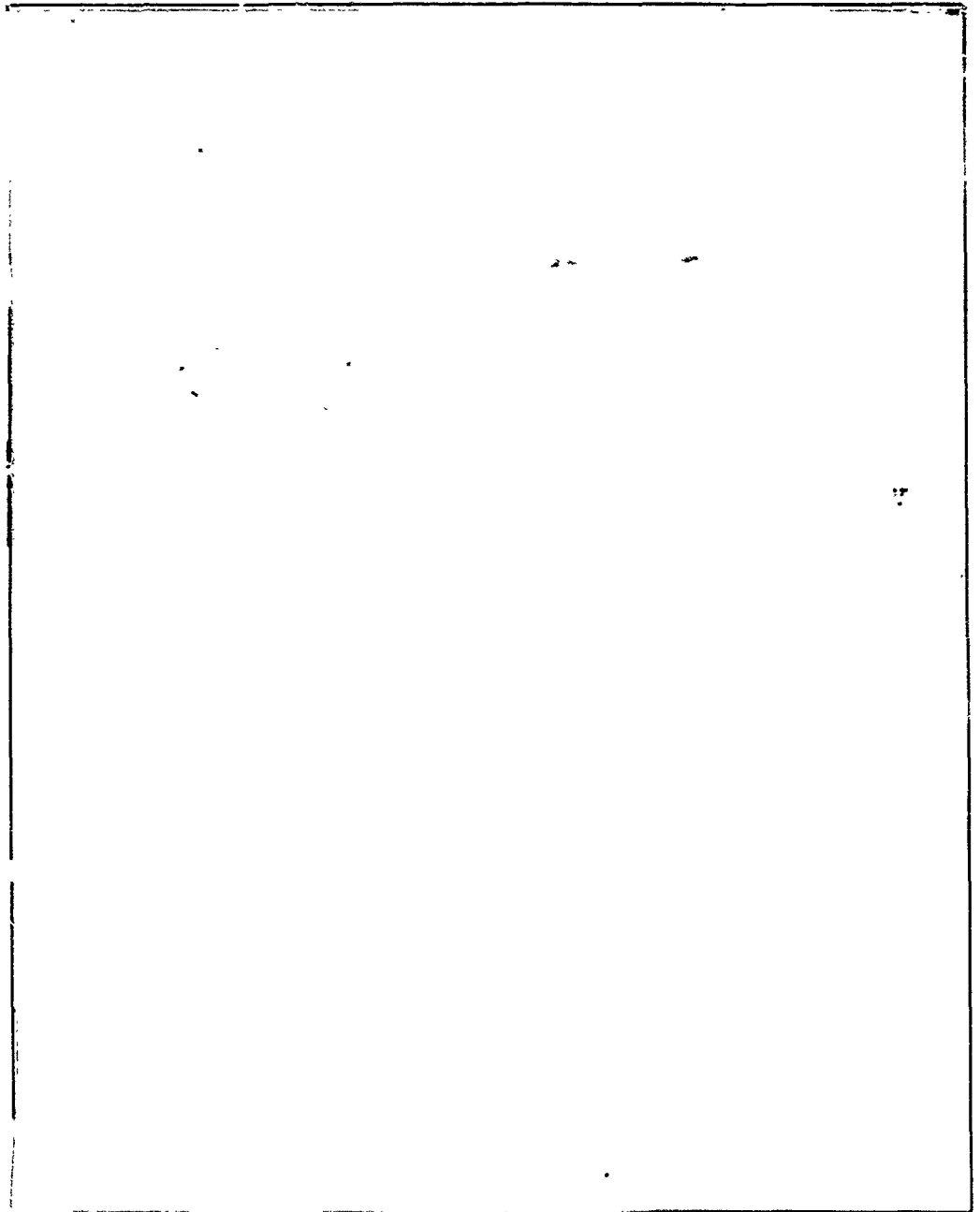
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