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Gas Gun for Impact Studies*

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A detailed description of a 10.16 cm gas gun that has been designed and installed at Washington State University is presented. The design velocity is 1.5 mm/μsec; the maximum velocity achieved to date is 0.9 mm/μsec with an 1100 g projectile. Angular misorientation of the projectile with respect to the target surface is consistently below 0.5 mrad. Brief descriptions of ancillary instrumentation and equipment are also given.

INTRODUCTION

THIS paper describes the gas gun and associated instrumentation that have been designed and installed at Washington State University. One year was spent in design and construction of the gun.[1] It was installed at the beginning of the second year, and active research began some three months later after a number of shakedown experiments and minor modifications.

A gas gun was chosen as the principal experimental tool of the Shock Dynamics Laboratory for several reasons. A gun is capable of very precisely controlled impacts in which initial conditions of the projectile and target are well determined; the velocity range (up to about 1.5 mm/μsec) is adequate for the study of a wide range of physical phenomena including, for example, the study of phase transformations and constitutive relations; they are relatively safe and can be operated by a small number of personnel in a campus environment.

Although powder driven guns can be shorter for a given projectile velocity and are therefore less expensive, they are less suitable for precision impact studies because of problems of cleanliness and high recoil forces. Further, the problems of storage and handling of gunpowder in a campus environment are substantial inconveniences.

Some of the conceptual design considerations leading to the choice of length, diameter, operating pressure, and mode of operation are discussed in Sec. II. Section III includes detailed descriptions of the major features, and Sec. IV describes the instrumentation developed for use with the gun, while Sec. V describes the performance of the gun.

DESIGN CONSIDERATIONS

The major design parameters are length, diameter, operating pressure, and gas reservoir volume. Projectile diameter is probably the most important parameter. Good measurements of plane stress wave propagation can be obtained only while the stress wave is accurately one dimensional, i.e., before any signal from the lateral edges of the sample under investigation can influence the measurement. This restriction requires that the ratio of diameter to thickness of the sample be at least 3 and preferably 4 or more. If sample thicknesses up to 25 mm are to be studied, or if it is desired to compare two or more thinner samples under identical impact conditions, a projectile diameter of about 10 cm is necessary. The experience of other investigators with guns varying between 6.35 and 15.24 cm indicates that these are reasonable limits.[2–4] Previous experience of the authors with explosive experiments and with a 6.35 cm gun led us to believe that 10.16 cm diameter would give reasonable flexibility in operation at reasonable expense.

At 413 bars operating pressure, which is a convenient limit in terms of availability of compressors, gauges, and tubing, a barrel length of more than about 16 m does not materially increase the attainable projectile velocities. The length chosen for the gun was 14 m in order to fit conveniently into the room available. Figure 1 shows the projectile velocity as a function of barrel length for various values of the ratio of mass of driver gas to projectile mass. The length chosen for the gun is clearly well beyond the knee of these curves and is sufficient to extract nearly all the velocity possible from a given reservoir at the maximum operating pressure (413 bars).

The gas reservoir volume was chosen to give a maximum ratio of mass of gas to projectile mass (G/M) of about five. The maximum velocity increases very slowly with G/M beyond this value, as shown in Fig. 2, and higher reservoir volumes increase the cost of gas which, in the case of helium, is not trivial. For a projectile mass of 450 g, which is about the minimum weight that can be fired with adequate strength and rigidity, the corresponding reservoir volume for helium at 413 bars is 28.3 liters and this value was therefore adopted. The curves shown in Figs. 1 and 2 were taken from Seigel,[5] and were verified by similar calculations in this laboratory by White.[6]

Thus, within the bounds of reasonable practicality the gun is designed to give nearly the maximum velocity (~1.5 mm/μsec) and maximum diameter attainable in a single stage gun. Improved performance would result from use of hydrogen, but this gas was ruled out because of handling and safety problems.

Aside from the choice of operating parameters indicated above, the most important feature of the gun is the method for absorbing recoil. Detailed gas dynamical calculations indicate a maximum momentum of about 2×10^8 dynes·sec and a maximum unbalanced force of 3.36×10^5 N.[6]

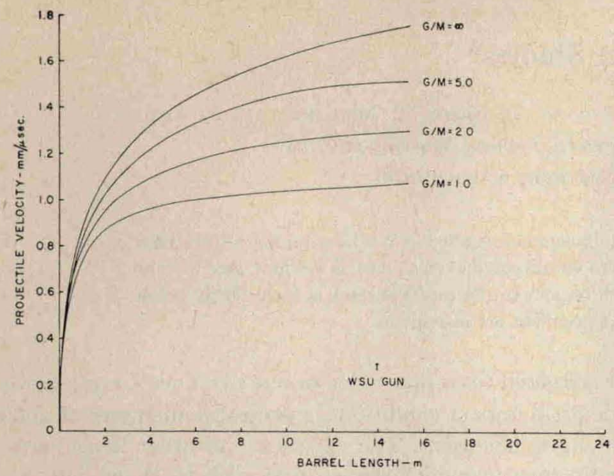

FIG. 1. Projectile velocity as function of barrel length for various ratios of mass of gas, G, to mass of projectile, M; helium gas at 413 bars (after Seigel[5]).

It was decided to let the gun slide freely while holding the target stationary, rather than to attempt to hold the gun rigidly with the target fastened to the barrel. The recoil forces are then substantially reduced and can be accommodated by standard shock absorbers. This has the additional advantage that no appreciable vibrations are transmitted to the target from the barrel. The principal concern with this scheme is whether sufficient control can be maintained of the tilt of the projectile with respect to the target. In order to fully utilize the time resolution available from our recording techniques a maximum tilt of ½ mrad must be maintained in a typical experiment. (Projectile velocity is 0.5 mm/μsec, active gauge diameter is 10 mm.) Consideration of the possible extent of misalignment during the approximately 2.5 cm of motion of the gun barrel before impact indicated, however, that significant bending or rotation would not be expected.[7] This conclusion has been subsequently verified by tilt measurements that are consistently below 0.5 mrad and are frequently much less.

Other advantages of the design are (1) capability for evacuating all sides of the target to avoid distortion, (2) breech mechanisms which can be precisely triggered and have fast opening times, and (3) quiet operation.

Two interchangeable breeches with different projectile firing mechanisms were designed and built because no single breech of an existing gun performs optimally throughout the desired velocity range (~0.1 to 1.5 mm/μsec). Several new concepts for a breech design that would accommodate the complete velocity range were considered, but were rejected in favor of two breeches on the basis of simplicity and reliability.

The need for fast breech opening times was shown by computer simulation studies performed by White.[8] The results show that, for maximum performance, the breech mechanism must provide unrestricted gas flow within a few milliseconds.

The low pressure breech (to 206 bars) is of the wraparound type developed by Muhlenweg at Sandia Corporation. This design is very convenient to use, employs no moving parts under pressure except the projectile itself, and is automatically fast opening. Its only disadvantage is that the projectile must be strong enough to withstand the initial pressure; the relatively large projectile mass provides the primary limit on the velocity attained with this breech.

A double-diaphragm breech, also patterned after a Sandia design, was built to operate to 413 bars. It imposes no limitation on projectile weight, but is more expensive and less convenient to operate since two burst diaphragms must be inserted between breech and barrel for each shot.

There was substantial concern about the acoustic noise produced by the gun inasmuch as it is located directly below a large lecture room. Partly to help control noise and partly for safety purposes, a catcher tank was constructed that contains all the fragments and gas. This tank, which incorporates a large evacuated target area, and the heavy concrete shielding around the muzzle, reduce the noise to surprisingly low levels. We have been able to fire at pressures up to 206 bars without disturbing classes in the room above.

DESIGN DETAILS

A. Location

The room in which the gun facility is located is a basement room in a large classroom and office building on the WSU campus, Sloan Hall. It is approximately 22.8×7.6 m and is partially below ground level. Inside this room we constructed a very heavy, doubly reinforced concrete muzzle room approximately 3.3×4.8×2.1 m. The walls, ceiling, and floor are reinforced and are 30 cm thick. The

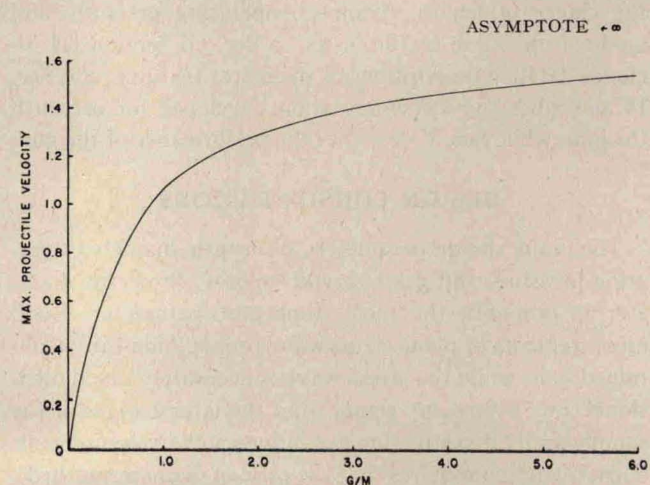

FIG. 2. Maximum projectile velocity as a function of G/M for 14 m barrel; helium gas at 413 bars (after Seigel[5])

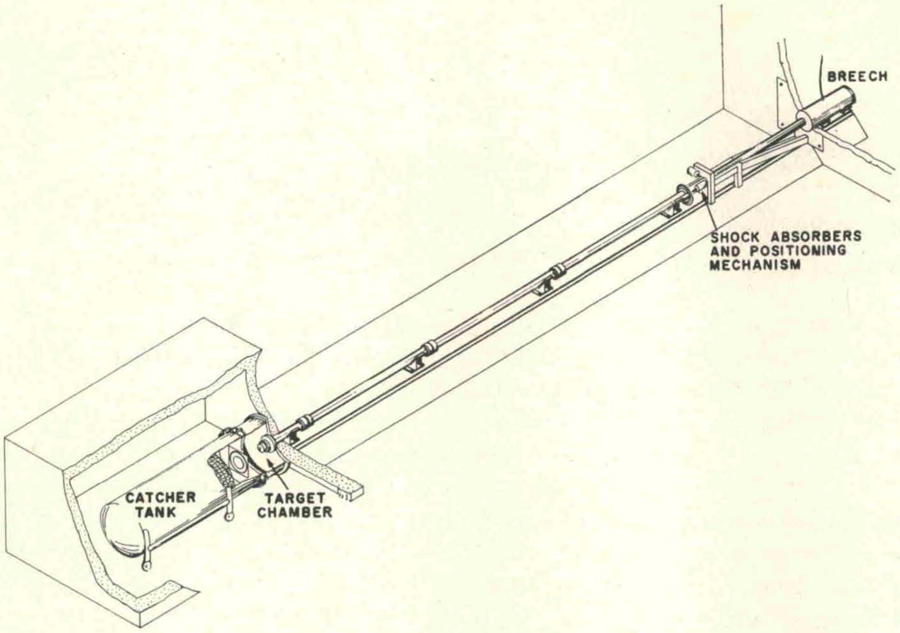

FIG. 3. Over-all view of gun and gun room.

door is 1.27 cm thick steel plate and weighs 272 kg. This room was designed to withstand the maximum overpressure of the gas in case of rupture of the catcher tank (approximately $\frac{1}{4}$ bars).

Concrete blocks with reinforcing rods were used to shield the breech and compressor room from the central part of the main room. The central portion, between the breech and muzzle rooms, is used as a working area and houses the instrumentation and the control console. The gun is mounted on an I-beam which in turn rests on a solid concrete foundation. A sketch of the layout is shown in Fig. 3.

B. Barrel

The barrel is constructed in four 3 m sections and one $1\frac{1}{4}$ m muzzle section. It was drilled from 4140 HT steel heat treated to 38 Rockwell C. The sections have bayonet joints at each end and are held together with flanges threaded onto each barrel section with buttress threads (Fig. 4). The flanges are in turn bolted together with eight 1.90 cm, high strength (Unbrako) cap screws.

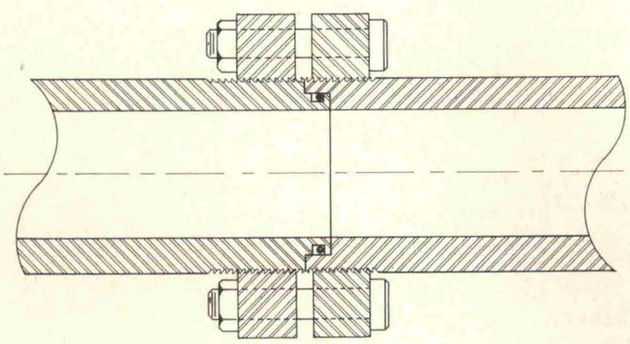

FIG. 4. Barrel joint detail.

The inside diameter of the barrel is 10.162 ± 0.002 cm; the muzzle section tapers slightly from 10.162 to 10.161 cm over the last 30 cm. This taper was initially greater but was honed out after test firings indicated excessive friction in the tapered section. The outside diameter is approximately 15 cm.

C. Barrel Supports

In order to minimize torque on the barrel while the projectile is in the gun, it rests on oiled porous bronze bearings constructed as caps for bolts threaded through V-blocks (Fig. 5). These are located at 3 m intervals along the I-beam. Some sagging of the barrel occurs between supports but it has apparently not affected performance.

The muzzle of the gun protrudes into the target chamber mounted on the muzzle room wall; a gas seal between tar-

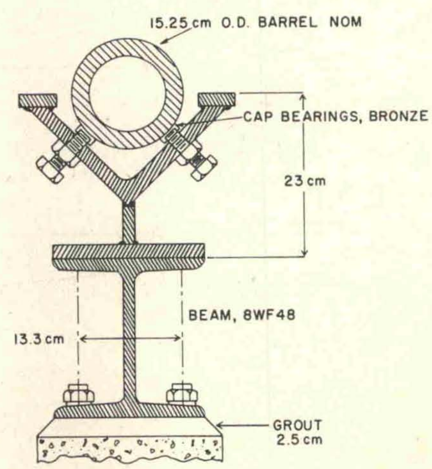

FIG. 5. Barrel supports. Scale: 1/4.

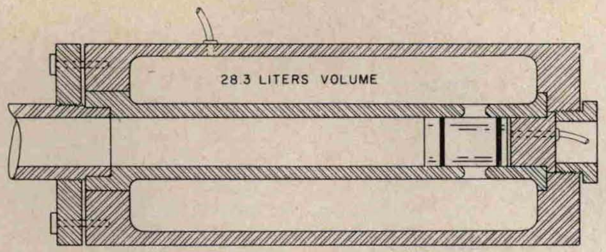

FIG. 6. Wrap-around breech assembly.

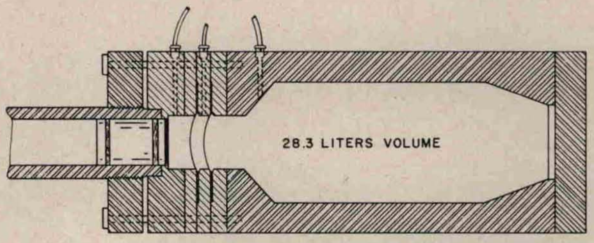

FIG. 7. Double-diaphragm breech assembly.

get chamber and muzzle is provided by a brass bushing and an O-ring. This bushing was initially made of steel, but it was found to seize to the barrel on occasion. No problems have been experienced with the brass bushing.

D. Breeches

Diagrams of the two interchangeable breeches are shown in Figs. 6 and 7. Each contains 28.3 liters of gas; the wrap-around model is designed for 206 bars, the double diaphragm for 413 bars; both have been tested to approximately twice the design pressures.

In the wrap-around design the projectile seals the ports between the barrel and the annular reservoir by means of O-rings at each end of the projectile. Firing is accomplished by injecting a small amount of high pressure gas behind the projectile, causing it to move past the ports. This design is convenient and reliable. Its only disadvantage is the restriction on projectile weight imposed by the requirement of sufficient strength to stand off the initial pressure. The minimum projectile weight we have attempted with this breech is 600 g with a projectile constructed of 7075-T6 aluminum.

For the higher velocity range ($\sim$0.9 to 1.5 mm/μsec) the double diaphragm breech is available. The diaphragms are selected to withstand slightly more than half the reservoir pressure and to open cleanly and quickly when subjected to full pressure. Firing is accomplished by exhausting the region between the diaphragms (initially pressurized to half-pressure) so that each diaphragm in turn experiences the full pressure. With this breech it is hoped that projectiles as small as about 450 g can be fired. It has not been tested at the time of this writing but no serious problems are anticipated.

E. Projectiles

In order to reduce the costs of the projectiles a standard design was chosen which could be made in quantity by a production shop (Fig. 8). The projectiles are machined from solid 6061-T6 aluminum, so there are no joints to leak or fail when used in the wrap-around breech. Moreover, the Hugoniot of this material is well known so that impedance match solutions can be readily obtained.[9] The wall thickness was chosen to withstand an outside pressure of

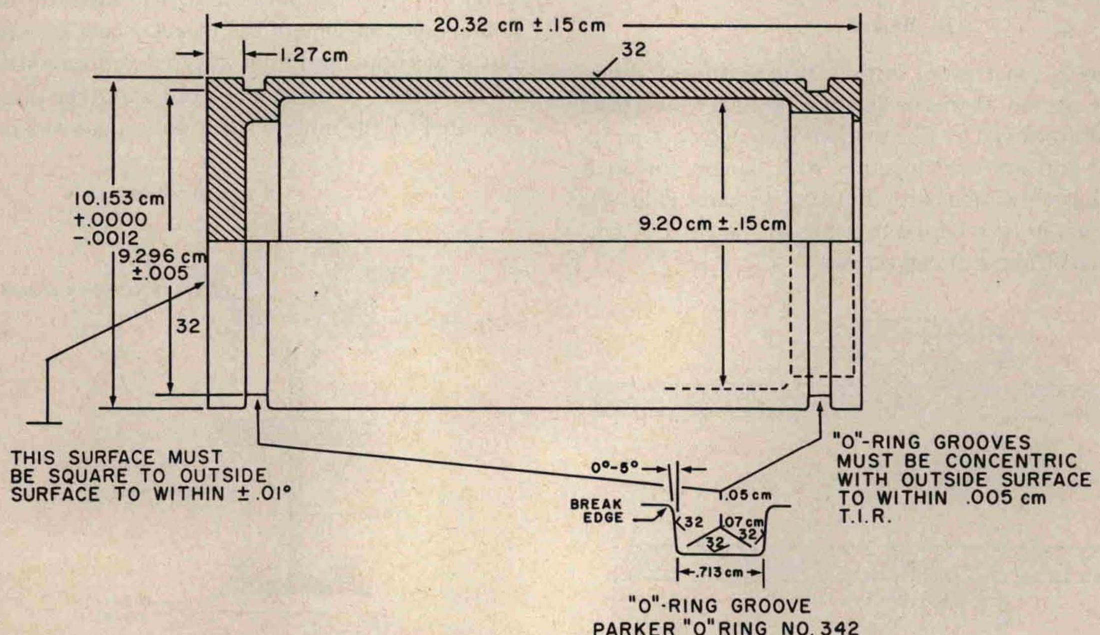

FIG. 8. Drawing of "standard" projectile. Material is 6061-T6 aluminum.

206 bars with a safety factor of 1.5; some of the projectiles have been tested to an outside pressure of 309 bars.

Projectile and barrel dimensions limit the angle between projectile and barrel axes to 0.5 mrad or less when the projectile contacts the target (i.e., when the projectile protrudes 5 cm from the muzzle). The O-rings help to center the projectile in the barrel, and close tolerances are held on these grooves, both in concentricity (0.002 cm T.I.R.) and size (± 0.002 cm). The O-rings are Teflon-coated Parker O-rings No. 2-342 made of buna-N rubber with a 70 durometer hardness.

The projectile weight of 1.1 kg limits the maximum velocity in the wrap-around breech to 0.6 mm/μsec with nitrogen as the driver gas and 0.9 mm/μsec with helium or 1.05 mm/μsec with special projectile.

The impacting surface of the projectile is lapped flat and brought into square with the axis of the projectile with a lapping machine. To check the impacting face for perpendicularity with respect to the axis of the projectile, the projectile is placed impacting face down on a surface plate and rotated against a reference pin. A dial indicator measures any runout of the top with reference to the pin. The runout is kept within 0.0012 cm. This means the impacting surface is perpendicular to the axis of the projectile to within 0.1 mrad. Any deviation is removed during the lapping process by eccentrically weighting the projectile.

F. Recoil and Catcher System

The most unusual feature of the gun compared to others of its type is that it is allowed to recoil freely until after impact has occurred; after impact the gun is decelerated by velocity sensitive shock absorbers. The target is mounted rigidly on the muzzle room wall and is therefore stationary. This arrangement essentially eliminates all problems of vibration of the target prior to impact. Further, standard shock absorbers can be used to stop the gun with maximum forces which are much less than the maximum unbalanced force on the gun during firing. Two shock absorbers of 17×10^6 g·cm capacity and 7.6 cm travel bear against one of the barrel flanges and against a steel frame that transfers the momentum to the I-beam (Fig. 3).

The catcher tank consists of two sections. One section

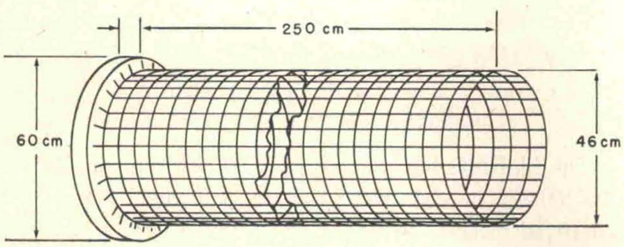

FIG. 9. Wire cage for stopping projectile. In operation the cage is stuffed with rags. Cage woven from 1.27 cm high carbon steel.

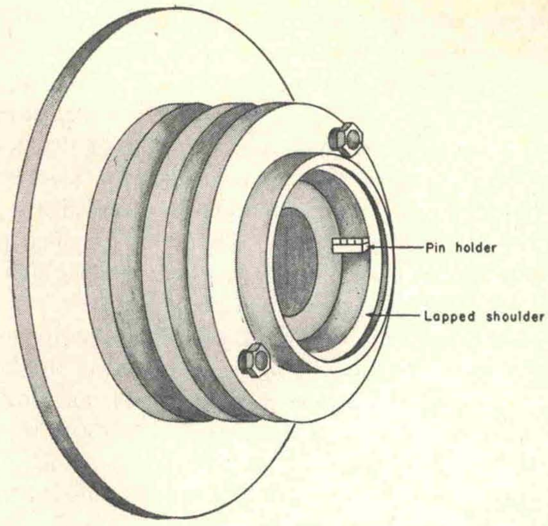

FIG. 10. Target holder.

(the target chamber) is permanently mounted to the wall of the muzzle room (Fig. 3). This section is evacuated prior to the shot. The second section is mounted on casters and joins the first section by means of quick disconnect devices. This section contains the projectile-stopping mechanism and is not evacuated. A Mylar diaphragm 45.7 cm in diameter and 0.018 cm thick provides an easily perforated seal between the two sections.

The projectile-stopping mechanism consists of a heavy wire cage, 45.7 cm in diameter and 2.5 m long, stuffed with nylon or Dacron rags (Fig. 9). At the rear of the cage is bolted a 10 cm thick by 61 cm diam steel plate weighing 225 kg; the total weight of the cage, rags, and steel plate is about 450 kg. This assembly is suspended on a rail and achieves a maximum velocity of about 2 m/sec when the maximum momentum of the projectile ($\sim10^8$ dynes·sec) is absorbed by it. The force required to stop the assembly within 7.6 cm of travel is therefore less than 31 000 N and is achieved with shock absorbers bearing against the rear of the tank.

G. Target Holder and Alignment Tools

The target holder is a ring with a lapped shoulder against which the target is held by small breakaway tabs (Fig. 10). Adjustment of the orientation of the target holder is accomplished with three differential screws that provide high strength and fine adjustment capability.

The tools used to align the target holder perpendicular to the axis of the barrel are a brass gauge plug and a gauging fixture which carries a sensitive dial indicator. The gauge plug is a 35 cm solid brass bar with the diameter machined 0.0025 to 0.0038 cm smaller than the exit diameter of the gun muzzle. A 5 cm tapered section is machined on the leading end to facilitate fitting the plug into the barrel. The gauging face of the plug is flat and perpendicular to the axis to within 0.05 mrad and is periodically checked with the same fixture used to check the projectiles. The gauge plug is solid to provide a heat sink so that handling does not change its dimensions or straightness.

The gauging fixture is simply a ring, ground flat, and large enough to mate to the target aligning surface. A sensitive dial indicator is rigidly supported through the ring to sweep a 9 cm diam circle on the face of the gauge plug. It measures the change in distance between the plane of the target holder and the face of the plug.

To align the target ring the gauge plug is positioned in the barrel and the gauging fixture is placed in the target holder and held with spring clips against the aligning surface. The dial indicator is then adjusted to touch the surface of the gauge plug and to give a null reading. The aligning fixture is then rotated and the dial indicator readings noted. The alignment nuts (differential nuts) are adjusted until a 360° rotation of the aligning fixture in both directions shows no greater than 0.0005 cm variation in readings. This corresponds to a misalignment of 0.06 mrad or less. The gauge plug is then rotated and the alignment rechecked.

H. Projectile Velocity Pins

Projectile velocity is measured with a series of four pins, spaced 1 cm apart, which make electrical contact with the projectile. To insure a good ground each pin has a companion grounding pin which is positioned to make contact shortly before the active pin. The pins are machined from 0.158 cm brass rod; a whisker 0.025 cm in diameter and 0.25–0.35 cm long is turned on one end. These eight pins are positioned in a block so that the projectile contacts one third of the whisker length.

The velocity pin block is designed to insulate each of the active pins (velocity pins) from each other and from ground and to provide a BNC connection for each (Fig. 11). The

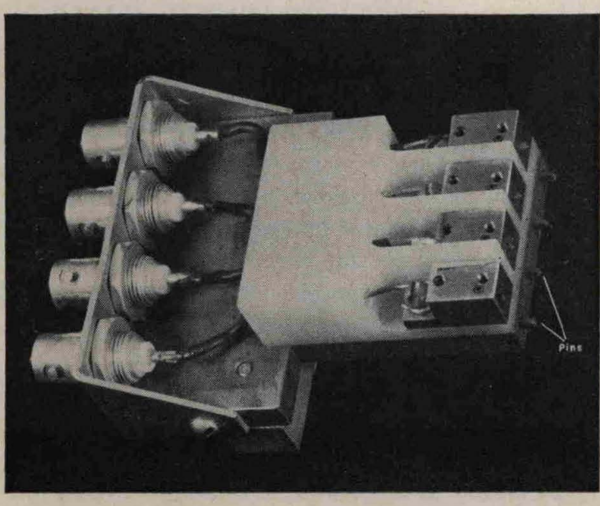

FIG. 11. Velocity pin holder.

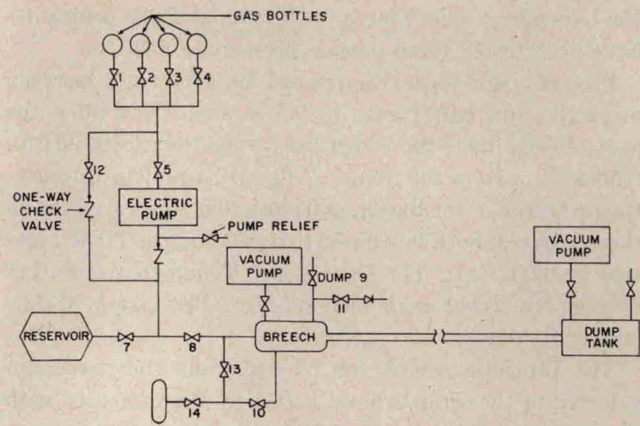

FIG. 12. Gas flow circuit.

velocity pins are stair stepped so that each pin makes contact with the projectile on fresh metal to insure accurate knowledge of spacing. The spacing of each pin pair is measured with a Gaertner toolmaker's microscope. The average of three sets of measurements yields an accuracy of $\pm 10\ \mu$, or about 0.1%.

Before firing, the velocity pin block is slipped into a close fitting hole in the target ring and the electrical connections are made. The first velocity pin makes contact with the projectile at a distance of 3.5 cm in front of the target and triggers the velocity measuring 'scope. The three intervals available provide redundant measurements of velocity and acceleration to provide a consistency check.

I. Control System

The control system was designed with the following criteria in mind:

(i) It must handle pressures up to 413 bars remotely.

(ii) It must be essentially failsafe, yet contain a minimum of interlocks.

(iii) It must indicate, at a glance from the operator, the complete status of the system at any time, particularly just before firing.

(iv) It must be easily adaptable to both breeches.

The above specifications were met by coupling two subsystems to the main high pressure system. A 110 V ac electrical system controls a low pressure (4 bars) air system, through the use of electrically operated three-way solenoid valves. These in turn control the actuators of the high pressure (413 bars) valves.

1. High Pressure System (Fig. 12)

The high pressure system is built entirely of 0.635 cm o.d.×0.276 cm i.d. 316 SS annealed tubing. Gas may be admitted directly from bottles to the reservoir through a bypass line from the pump inlet to the outlet (valve No. 12). A one-way check valve is inserted just before the

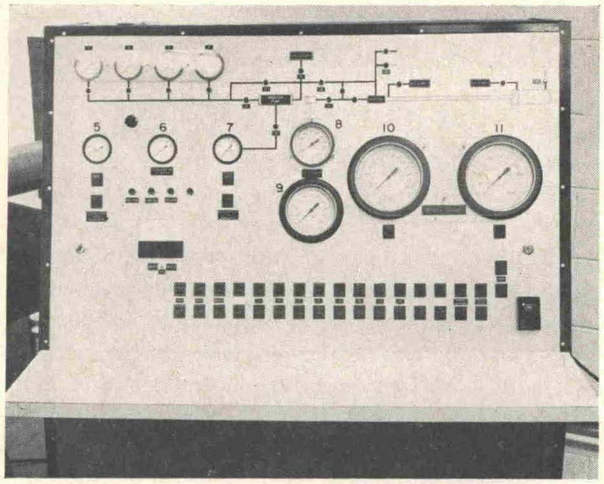

FIG. 13. Control panel.

entry of the bypass line into the high pressure side of the pump outlet to guard against the possibility of opening the bypass valve when the system pressure is above 135 bars.

The electrically driven pump accepts either N_2 or He at 31 bars or more and will compress it to 413 bars. If pumping is necessary, the operator may route the high pressure gas to a 28 liter storage reservoir for later use or pump directly into the breech reservoir.

It is normal procedure to fill the breech to 4 to 8 bars above the desired shooting pressure and then allow the gas pressure to stabilize at ambient temperature. Excess pressure is relieved through a normally open high pressure valve with restricted orifice open to the atmosphere. This valve (No. 11) is in parallel with the breech fill line. One other valve (No. 9) with a full orifice open to the atmosphere and also in parallel with the breech fill line is normally closed and is used for dumping the pressure in the breech in an emergency.

To facilitate the use of both breeches without having to make extensive changes in the system, valves No. 13 and 14 were incorporated into the system. Valve No. 10 is the firing valve for either breech. Valves No. 13 and 14 are on the same circuit and are operated in such a way that only one may be open at any time. By opening valve 14, valve 13 is simultaneously closed and the system is ready to accept the double diaphragm breech. With valve 13 open and valve 14 closed the system is used to operate the wrap-around breech.

2. *Control Panel*

The control panel (Fig. 13) is divided into two sections. One affords the control of operations and the other enables the operator to monitor the influence of the controlling action taken.

The control section, in the lower portion of the panel, consists of a double row of illuminated pushbuttons across the lower extremity of the panel face. The upper row is green and the lower red; one button of each pair activates a valve and the other deactivates it. These pushbuttons control all valves, both vacuum pumps, the projectile latch, and the oscilloscope camera shutters. The circuits are designed so that all lights must be green immediately before firing. This enables the operator to make a final check just before firing to be sure the system is "go." One pair of pushbuttons, at the right end of the row, is not in-line with the others. The upper of this pair is the dump actuating button. Upon depressing this pushbutton the previously mentioned dump valve is actuated and all other valve circuits are simultaneously opened, causing all other valves to close.

The upper section of the panel contains pressure monitoring gauges. Gauges 1–4 monitor the pressures in the supply bottles. Gauge No. 5 reads the regulated pressure of the bottle gas entering the high pressure pump. Directly below this gauge are two pushbuttons which actuate a motor driven pressure regulator, thus allowing for remote control of the pump inlet pressure. The vent gauge (No. 6) indicates the air pressure to the high pressure valve actuators. Gauge No. 7 reads the air inlet pressure to the pump. The two buttons below this gauge enable one to regulate the air inlet pressure to the pump.

Gauge No. 8 monitors the reservoir pressure; below this is No. 9, a thermocouple gauge readout which indicates the pressure in the evacuated barrel.

Breech pressure is monitored by the two large gauges on the right. Both gauges read to an accuracy of $\pm\frac{1}{4}\%$ of full scale. Number 10 is calibrated in 5 psi subdivisions and indicates pressures from 0 to 1500 psi. Number 11 is calibrated in 25 psi subdivisions and indicates pressures from 0 to 10 000 psi. These gauges are connected to the breech fill line by capillary tubing (0.317 cm o.d.$\times$0.071 cm wall 316 SS). Number 10 may be remotely switched into or out of the breech pressure line. If the low pressure gauge is left in the system above 98 bars, a burst diaphragm will rupture and a surge check valve will close, thereby isolating it from the system.

On the upper portion of the control panel is a schematic representation of the high pressure piping system. Each

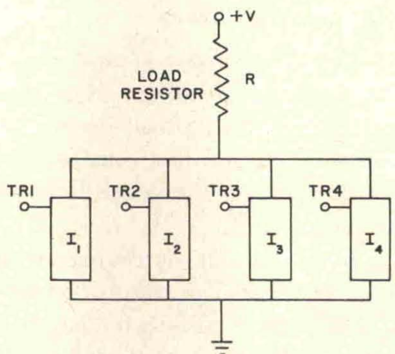

FIG. 14. Operational schematic of velocity and tilt circuits. TR1, TR2, TR3, TR4—trigger inputs.

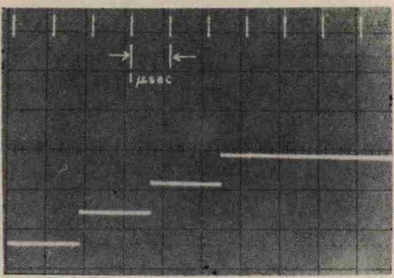

FIG. 15. Typical record for projectile velocity measurement.

valve in the system and its location with respect to the high pressure flow are denoted on the schematic by a numbered, red indicator light. The corresponding number is found between the two rows of pushbuttons. This feature reduces the possibility of actuating a critical valve at the wrong time.

INSTRUMENTATION AND ANCILLARY EQUIPMENT

In addition to the gun and control system, electronic instruments were either purchased or built to serve as recording devices. The principal instrumentation consists of 10 oscilloscopes. These include six Tektronix type 581/585, two Tektronix type 454, one Tektronix type 519, and one Tektronix type 555. These 'scopes provide 11 recording channels with a frequency response adequate for use with essentially all currently feasible measurement techniques.

The 'scopes are supplemented by a 100 MHz time interval counter, Hewlett–Packard type 5275A with crystal controlled oscillator, and a pulse generator, E-H Company model 120D. These are used principally for timing devices.

A number of electronic devices have been constructed by students to serve special purposes. These include timing and tilt pulse-shaping circuits, a quartz gauge calibration device, and a manganin gauge power supply. These devices are described in detail below.

In addition to electronic instruments other major auxiliary equipment includes a lapping machine, a toolmaker's microscope (which serves for measuring traces on films and other purposes), and a diamond cutoff saw.

A. Velocity and Tilt Circuits

Velocity and tilt circuits are identical in design and operation. The circuit for each consists of four triggerable constant current sources connected to a load resistor, as shown in Fig. 14. The trigger inputs for these constant current sources are the velocity pins for the velocity circuit and the tilt pins for the tilt circuit.

Once triggered these constant current sources remain on until reset manually by the operator. This feature prevents any one of the current sources from turning on and then off due to a loss in the ground connection at the pin input. Thus, the voltage across the load resistor is given by

$$V(t)=R[I_1H(t-t_1)+I_2H(t-t_2)+I_3H(t-t_3)+I_4H(t-t_4)], \quad (1)$$

where

$$H(\xi)=0, \quad \xi<0,$$
$$H(\xi)=1, \quad \xi\geq 0,$$

and t_1, t_2, t_3, and t_4 correspond to the times at which pins 1, 2, 3, and 4 for either the tilt or the velocity circuit are grounded by the projectile. Further, the current ratios $I_1::I_2::I_3::I_4$ determine the relative voltages across the load resistor R for the respective pin shortings 1, 2, 3, and 4. In the case of the velocity circuit the ratios are all 1:1 so that the voltage steps are equal for all pin shortings. Figure 15 shows an oscilloscope voltage–time record for a typical velocity measurement.

For the tilt circuit the current ratios have been set at 1::2::4::8 for the circuit inputs 1, 2, 3, and 4, respectively, These ratios were chosen so that the sequence of pin closures can be determined in case any two or more pins short simultaneously; i.e., any additive combination of 1. 2, 4, or 8 will correspond to a unique voltage combination on the measurement oscilloscope. Tilt and velocity circuits do not have zero risetimes as implied by Eq. (1). The combined risetime of either circuit and a type 585A Tektronix oscilloscope normally used for the measurement is typically 10 nsec for any pin closure. A typical tilt record is shown in Fig. 16.

Figure 17 is a block schematic of both velocity and tilt circuits. When the input pins are all ungrounded the circuit may be placed in a "reset" mode by depressing the reset key. Any subsequent input pin shorting will change the circuit from the reset mode to the "set" mode. To the operator these two modes are distinguishable by the use of an indicator lamp, which is turned on when the circuit is in the reset mode (see Fig. 17).

Describing the reset mode more specifically in terms of circuit operation, each pin input is clamped on electrically by means of a 220 Ω resistor connected to the 3.6 V supply at the input of nor gates G1–G4. The nor designation means that the sign of the output of the gate is opposite to the input. The outputs of nor gates G1, G2, G3, and G4

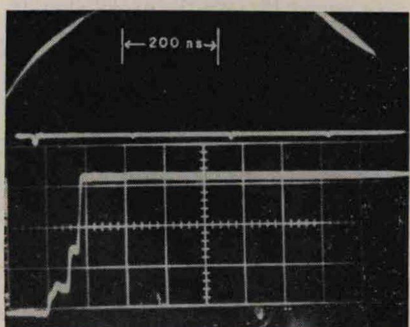

FIG. 16. Typical record for measuring tilt impacting surfaces.

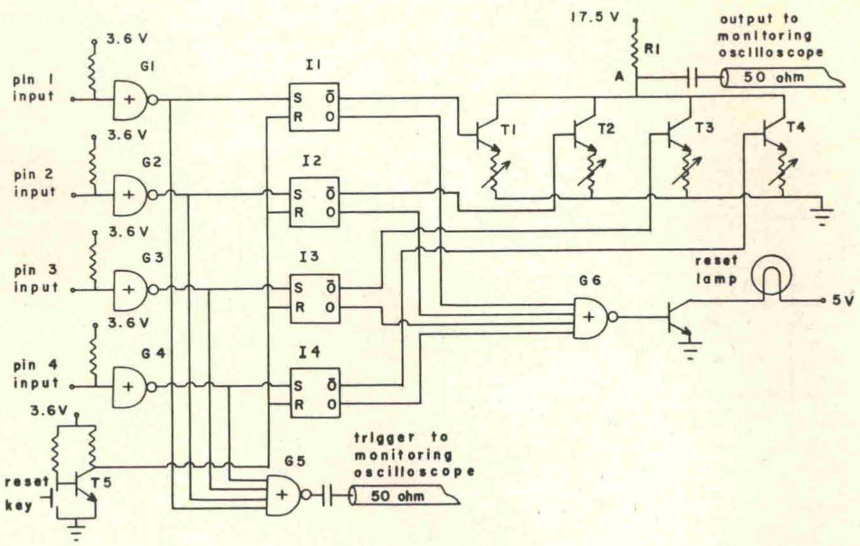

FIG. 17. Block schematic of velocity and tilt circuits.

are connected to the set terminals of gates I1, I2, I3, and I4, respectively. I1–I4 are properly designated as set–reset flipflops. It is the property of these gates that produces the set and reset modes in the circuit.

A set–reset flipflop is a bistable electronic device. A positive going pulse of amplitude greater than 0.7 V applied to the reset input will place the flipflop in reset state where it will remain until a positive pulse is applied to the set input. When a pulse is applied to the set input the device flips to the set state and remains there until again reset. The device has two outputs that will be designated here as 0 and $\bar{0}$.

When the reset key in the circuit is depressed a positive pulse from transistor T5 connected to the reset inputs of I1–I4 places the circuit in the reset mode. The 0 output of each flipflop is fed into G6, a four input nor gate, the output of which turns on a transistor to drive the reset lamp.

The $\bar{0}$ outputs of the set–reset flipflops I1, I4, I3, and I4 are connected to the base junctions of transistors T1, T2, T3, and T4, respectively. These transistors are then turned on when the circuit is in the reset mode. Each transistor acts as a current source and is connected to resistor Rl which sums the current from these four transistors. The variable resistor attached to the emitter of each transistor is used to adjust the current flowing through each transistor in order to provide the desired current ratios as previously mentioned.

The transistors T1–T4 then act as switches, either permitting or preventing the flow of current through resistor R1. These switches are all closed when the circuit is in the reset mode since all transistors will be held on by the $\bar{0}$ outputs of gates I1–I4. The voltage at point A in the circuit as shown in Fig. 17 will be, for the reset mode,

$$V_0 = 17.5 - 100(I_1 + I_2 + I_3 + I_4). \quad (2)$$

Now consider shorting input 1 of the circuit to ground. The voltage output of G1 will rise from 0 to 3.6 V. This positive pulse at the output of G1 flips I1 to the set position which turns off the reset lamp and turns off transistor T1. The voltage at point A will now be given by

$$V_1 = 17.5 - 100(I_2 + I_3 + I_4). \quad (3)$$

The voltage change at A appears as a step on the oscilloscope proportional to I_1, i.e.,

$$V_1 - V_0 = 100 I_1.$$

When input 1 is shorted to ground the positive pulse from the output of G1 also provides an input to G5 (a four input nor gate). This gate produces a negative going pulse which is used to trigger the monitoring oscilloscope.

Channels 2–4 all operate in the same manner as described above for channel 1. The complete circuit diagram for the velocity and tilt circuits is shown in Fig. 18.

The velocity circuit has one feature absent in the tilt circuit. Attached to each of channels 3 and 4 of the velocity circuit is a signal output circuit as shown in Fig. 18. When pin 3 or 4 is shorted, a negative pulse will appear at the respective auxiliary outputs. These outputs may be used to trigger external circuitry, i.e., manganin gauge current supplies, time interval counters, measurement oscilloscopes etc.

B. Quartz Gauge Calibration Circuit

The quartz gauge technique is used to measure pressure profiles during shock compression. Based upon the piezoelectric properties of quartz, this gauge produces a current that is proportional to the stress difference across the thickness of the quartz.[10] For pressures below 30 kilobars the current–stress relation is accurately known and for a given current observed from the gauge the stress difference may be computed. Consequently, it is necessary to calibrate the measurement oscilloscopes directly to establish an accurate

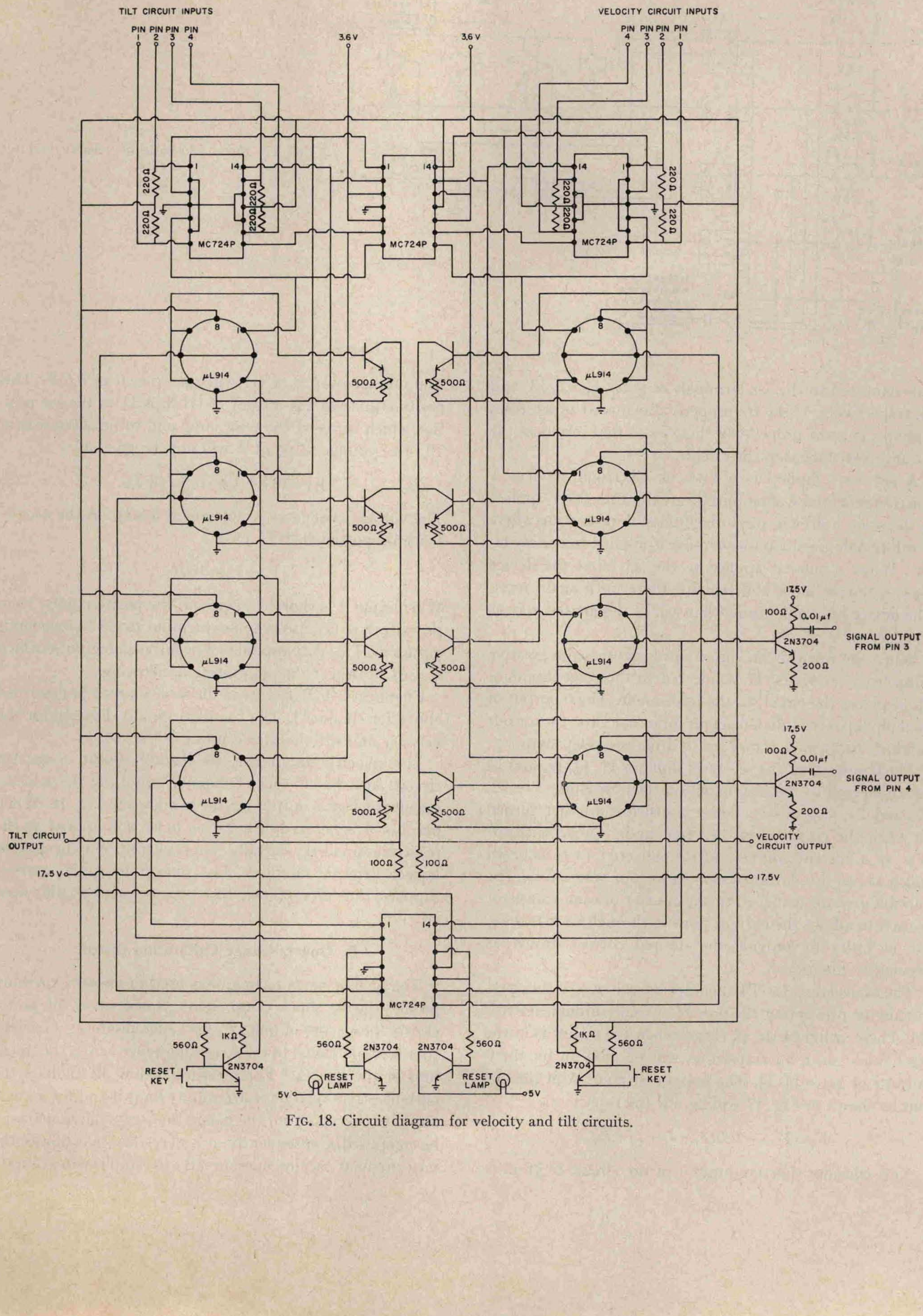

Fig. 18. Circuit diagram for velocity and tilt circuits.

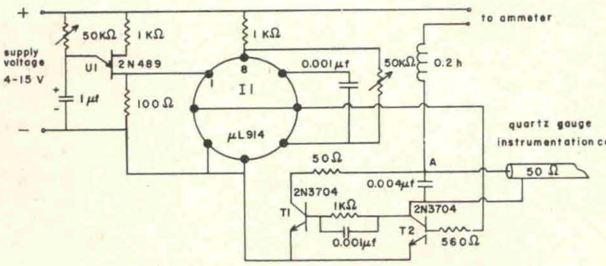

FIG. 19. Diagram of quartz calibration circuit.

relation between the 'scope deflection and the current output from the quartz gauge. A calibration circuit has therefore been developed to feed a pulse of known current amplitude through the instrumentation cable and to the oscilloscopes that are to monitor the output from the gauge.

The quartz gauge calibration circuit consists mainly of a unijunction pulse generator, a monostable multivibrator, and two switching transistors. Referring to the circuit diagram of Fig. 19, a unijunction transistor U1 pulses a monostable multivibrator I1 with a repetition rate of approximately 1 kHz. With each pulse from U1, I1 turns on and remains on for about 5 μsec. Initially, when I1 is off, current flows from point A in the circuit through transistor T1 to the negative supply voltage. As I1 turns on the current is switched to flow through transistor T2. This sends a current pulse down the instrumentation cable that is to be used in monitoring the quartz gauge output. The current before switching is measured accurately by the use of a precision digital ammeter. Therefore, the magnitude of the voltage step produced on the oscilloscope is related to an accurately known current value, since the inductor time constant is large compared to the 5 μsec time interval of the switched current pulse. The magnitude of the current step may be varied from 80 to 300 mA by varying the supply voltage from 4 to 15 V.

C. Manganin Gauge Pressure Transducer

The manganin gauge pressure transducer is a useful device at pressures in excess of those observable by quartz gauges or if the validity of the calculation necessary to eliminate the error due to impedance mismatch at the specimen–quartz interface is in doubt.[11] Auxiliary equipment needed for the manganin gauge technique consists of a constant current supply, an adequate gauge and mounting facility, and proper recording oscilloscopes and cables. The constant current supply has been described elsewhere.[12]

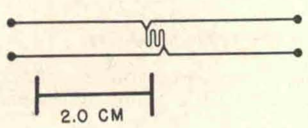

FIG. 20. Manganin grid for use as in-material gauge.

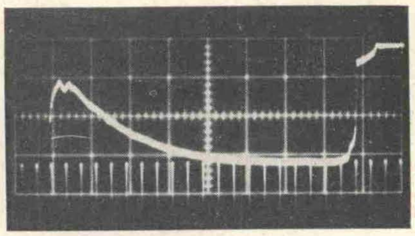

FIG. 21. Manganin gauge in aluminum with peak stress of 30 kilobars.

1. Gauge Construction

Gauges used are of the four terminal type, shown in Fig. 20. They are produced by a photoetch technique and are initially attached to a plastic film[13] from which they are easily removed by immersion in boiling acetone. The sensitive element lies within a 0.371 cm square while the gauge depth is approximately 0.002 cm. The aspect ratio (width/depth) is about 5 for the wire in the sensitive element. The resistance of the sensitive element is 2 Ω while that of the terminal leads is about 1 Ω.

In target construction, the gauge is mounted directly between two slabs of the material under observation if that material is an insulator and does not produce a significant polarization signal. For conductors, the gauge is insulated from the material by a 0.00089 cm Mylar film. The bonding is effected by air evacuated epoxy. The dimension of the sandwich in the latter case is approximately 0.005 cm. Since the shock wave transit time of this sandwich is on the order of 10 nsec and since in general there is a sample–epoxy impedance mismatch, fidelity of the wave profile will deteriorate to an extent depending on the magnitude of the mismatch. Stress profiles at the 35 kilobars level in CdS have been observed by both the quartz gauge and manganin gauge technique. Allowing for the impedance mismatch with quartz they were found to be closely comparable. In constructions involving both conducting and nonconducting samples, the gauge terminal leads were brought out the sides of the sample. This allowed recording times of from 2 to 5 μsec before the gauge leads were either severed or shorted, disrupting the current flow. This recording time is sufficient for most applications. Figure 21 shows a representative record.

2. Recording Facility

The voltage time profile is recorded on a 585 Tektronix oscilloscope with the aid of a type 1A5 offset preamplifier plug-in unit. This unit allows observation of the profile which is superimposed on top of the voltage step developed across the gauge when the constant current supply is initially turned on. This voltage step, knowledge of which is necessary for data reduction, is measured during the preliminary setup. This measurement is performed using the comparison voltage available on the 1A5 plug-in unit and a precision voltmeter. The comparison voltage is used to

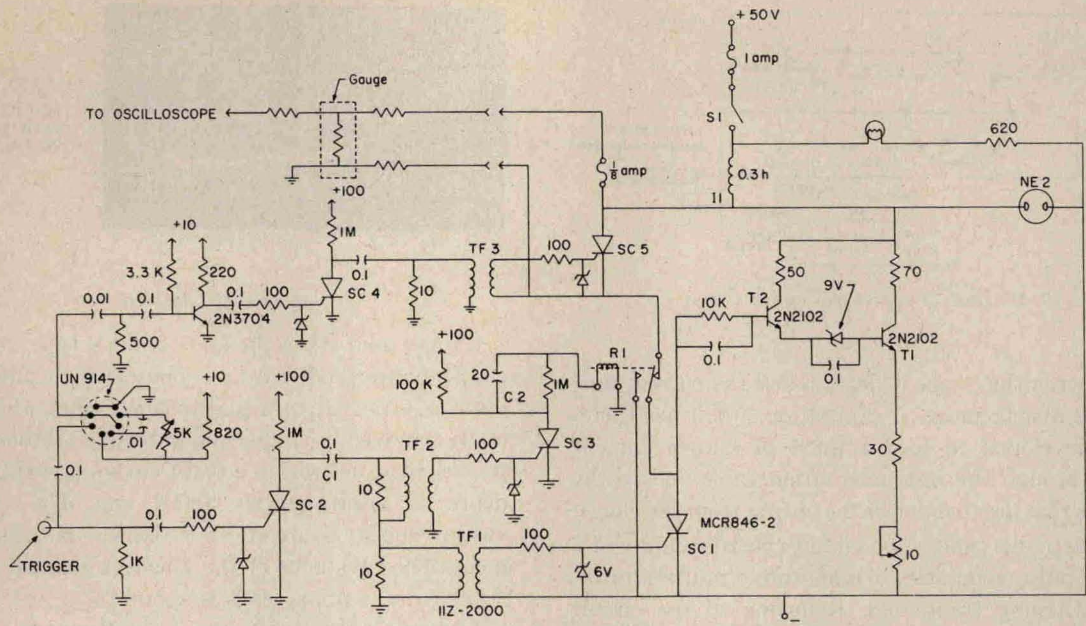

FIG. 22. Block diagram of constant current supply for use with manganin gauges.

nullify the voltage step while the comparison voltage is in turn monitored by the voltmeter. This measurement can be made to well within 0.5% accuracy.

Cable termination is carried out at the gauge rather than at the oscilloscope.[12] Figure 22 shows a schematic gauge with representative termination resistors. Termination at the gauge rather than at the oscilloscope eliminates the problem of a current shunting the gauge and therefore simplifies data reduction. In practice the gauge element will change resistance by about 1 Ω as the stress profile passes the gauge. The terminating resistance values should be selected so that proper termination is effected when the gauge resistance is in its final state.

GUN PERFORMANCE

A. Projectile Velocity

Predicted velocity curves for the gun as designed using nitrogen or helium are shown in Fig. 23. Also shown are representative data points derived from the approximately 100 shots fired to date at pressures up to 206 bars. The agreement is seen to be good for helium, but is less satisfactory for nitrogen. The reason for the discrepancy is not established; possibly throttling at the orifices connecting the breech to the barrel, which is more important for nitrogen than for helium, is the source of the difference. The reproducibility is very good, amounting to about ±1% at velocities above 0.2 mm/μsec.

B. Tilt

The major question with regard to this design is whether adequate control of the tilt of the projectile face with respect to the target face can be maintained. In order not to degrade seriously the time resolution of the recording instrumentation it is necessary that the closure time of the two surfaces (of 10.16 cm diameter) be less than about 50 nsec. The time required for the induced stress wave to sweep past a gauge whose lateral dimensions in a plane parallel to the impact surface is 10 mm or less will then be no more than 5 nsec. This time is comparable to the re-

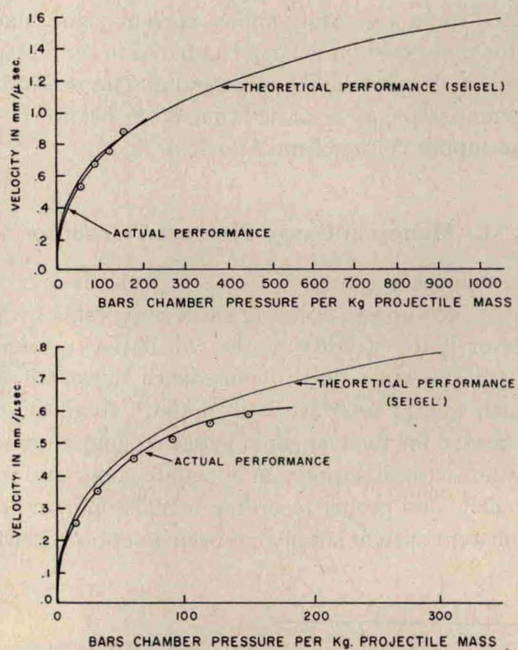

FIG. 23. Measured projectile velocities compared with theoretically predicted curves. Top, gun performance with helium driver gas; bottom, with nitrogen driver gas.

sponse time of the oscilloscopes in use (85 MHz frequency response).

The geometrical tilt required is thus a function of projectile velocity and varies between 0.2 mrad at a projectile velocity v of 0.1 mm/μsec to 2.0 mrad at $v=1.0$ mm/μsec.

Our experience to date shows that, with a few exceptions probably attributable to errors in initial alignment or to faulty target construction, the tilts achieved are frequently 0.1 to 0.2 mrad and are consistently below 0.5 mrad. This degree of tilt could arise solely from the allowed clearance (7.6 to 8.9×10^{-3} cm) between the projectile and the barrel. Thus the tilt is adequate for most experiments and, where it is demanded by an unusual experiment, improvements in tilt can probably be achieved with tighter fitting or longer projectiles.

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† Now at Physics International Company, San Leandro, Calif.

[1] Assistance with the design and construction was provided by Utah Research and Development Co., Salt Lake City, Utah. The barrel and breeches were machined by Clark & Wheeler Engineering Co., Paramount, Calif.

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