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HIGH VELOCITY SHOCK TESTING,
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HIGH VELOCITY SHOCK TESTING, EQUIPMENT AND METHODS

WALTER W. WALKER, 1613-2

ABSTRACT

The need for special high velocity shock testing is pointed out and equipment that has been developed to meet these needs is discussed. The concept of velocity-change and its importance in shock-testing technology is brought out. The three types of equipment discussed are: accelerated drop testers, pneumatic actuators, and air guns. Examples of each type and their capabilities and limitations are presented.

July 11, 1960

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HIGH VELOCITY SHOCK TESTING,
EQUIPMENT AND METHODS

There is now available, commercially, a limited variety of equipment for the simulation of shipping and handling shocks, and for developmental testing to military specifications. However, more and more laboratories are being faced with shock-testing requirements that go far beyond the capacities of available equipment. These requirements are generated by the stockpile-to-target sequence of modern weapons, both conventional and atomic. Some typical examples might include: launching shocks, violent maneuvers, counter-measures, and impact.

Velocities generated or dissipated by these shocks may be as high as 750-ft/sec. Time durations of these shocks may range from 300 microseconds to 100 milliseconds, or longer in the case of rocket launching. Acceleration levels may range from 15 to 7000 g's.

It has thus become necessary for some laboratories to design special equipment to perform high velocity shock-testing to these requirements. This is not necessarily an easy task, as some of the equipment will be required to generate and absorb energy equivalent to the energy generated by large caliber artillery. Some of this equipment must, because of its nature, be located in remote test areas, with adequate provision for protection of personnel and equipment. However, it is entirely possible to design equipment capable of generating velocity changes of 100-ft/sec or more that can be operated safely within the confines of a test laboratory.

To fully understand and appreciate the nature of this shock-testing equipment, it is necessary to be familiar with some of the basic quantities and definitions involved.

A mechanical shock can be completely described by specifying three parameters: peak g, time duration, and waveshape; "standard" waveshapes are square, half-sine, sawtooth, quarter-cosine and cubic. To completely encompass the capabilities of a shock machine, however, it is necessary to use two other parameters in addition to those already mentioned. These two are velocity-change and displacement.

Velocity-change is the total change in velocity undergone by the specimen during the shock pulse. Thus, for a shock pulse generated by impact, velocity change is the algebraic sum of the specimen velocity at first contact with the impact medium and the rebound velocity at separation from the impact medium. These velocities are in opposite directions. When there is no rebound from the impact medium, the velocity-change is the same as the initial impact velocity. Rebound increases the velocity-change obtainable with a given impact velocity, up to a maximum ratio of two.

The area within an acceleration-time plot such as figure 3 or 7, represents velocity-change, since, by definition, velocity is the product of acceleration and time. Velocity-change can be readily calculated for the standard waveshapes, and can also be directly measured by velocity transducers or by direct measurement of the area of an acceleration-time plot with a planimeter. Theoretically at least, any value of peak g or time duration could be realized separately with only a very small velocity-change: hence, velocity-change serves as a "limiting" parameter.

Peak g and time duration can be measured fairly accurately, but since there is no reasonably good way to measure deviations from specified waveshapes, velocity-change becomes another means of determining how closely a shock pulse is meeting the specification.

On an actuator or air gun, the velocity-change is the velocity at the end of the positive acceleration phase. The test specimen in these cases is traveling at terminal velocity at the end of the test pulse. Terminal velocities are then dissipated by gradual braking down the guide rail for the actuator, and down the barrel for the air gun.

Displacement is that physical distance required to generate a given shock pulse. If sufficient other parameters are known, then displacement can be calculated from the basic differential equations of motion. Displacements required are not always the same for shock pulses generated by impact, as they are for shock pulses generated by impulse.

For a shock pulse generated by an impulse device (actuator or air gun), if the acceleration-time plot can be approximated by a simple function, then it is relatively easy to integrate this function twice to get displacement. However, it is not necessary to resort to integration in those instances where it is possible to determine the average g value of the shock pulse. In those instances this average g value can be used in the simple equations; $V^2=2as$, and $S=\frac{1}{2}at^2$, where V is the velocity generated or dissipated, a is the average acceleration, t is the pulse duration, and s is the displacement. These average g values are .636 times peak g for a half-sine wave, and 1 times peak g for a square wave.

Displacement calculations are not as straightforward for shock pulses generated by impact, due to the variation in rebound that can occur. For the zero rebound condition displacement is calculated in the manner, just stated, for a shock generated by impulse. For 100 percent rebound, the displacement will be just one-half of that required for a similar shock pulse generated by impulse. For the various rebound conditions, the displacement will vary somewhere between these two limits. Since displacement is generally not a limiting factor on drop testers and since percent rebound varies considerably under different impact conditions, it is usually sufficient to calculate the limits of the displacement, and then determine the exact displacement experimentally.

A knowledge of the approximate displacement required is essential in setting up for an impact shock pulse, as the thickness of the impact material must be sufficient to accomodate this displacement while preferably staying within the linear portion of the materials stress-strain relationship.

Displacement is often a limiting parameter on an actuator, since the maximum physical stroke length is fixed.

Figure 1 is an illustration of some of these basic parameters and quantities as related to drop testers and actuators. Some of the basic equations for calculating the various parameters are included in the Appendix.

To avoid constant calculation of the various parameters, it is relatively easy to draw up a nomograph that charts these basic quantities on the basis of their theoretical relationships, so that when sufficient parameters are known, the rest can readily be determined from the nomograph. Such a nomograph is included in the Appendix of this paper.

Accelerated Drop Testers

Figure 2 is a photograph of an accelerated drop tester. This tester has a capacity of approximately 100-ft/sec velocity-change, including rebound. Components weighing up to 50 pounds, and up to a 12-inch cube can be mounted on the carriage surface. The normal range of testing for this machine is 50 to 2500 g's, with durations from 1½ to 50 milliseconds. Rubber pads of varying thickness, size, and hardness are used for general testing, but different materials can be substituted, e.g., lead pellets for sawtooth waves and honeycomb for square waves.

Repeatability of all parameters is well within ±10 percent and can be held to ± 5 percent if the pads are changed frequently and the machine calibration is checked several times a day. These pads can be reused following a suitable recovery period before it is necessary to throw them away. They do however heat up with use and will affect the calibration if not changed frequently.

Elastic cords are used for accelerating the carriage downward to obtain the high impact velocity. Maximum acceleration on the empty carriage at release is 16 g's, decreasing to 4 g's at impact. The carriage weighs 70 pounds, being built very rigid to withstand the high g levels, and to have the highest natural frequencies possible. The carriage rides on teflon bearings, on two 3-inch diameter tubes, providing a noise-free low friction guidance.

Square waves have been generated with this machine, using aluminum honeycomb as the impact material. Honeycomb with a 0.0015-inch wall thickness and 1/8-inch cell size, having a crushing strength of 360 pounds per square inch, lends itself best to this application. See Section C of the Appendix for detailed information on using aluminum honeycomb for square wave shock testing. Honeycomb has a limitation when attempting very long duration shock pulses, as buckling can occur if the piece is too long and narrow.

Figure 3 is a typical shock pulse generated by this machine. As can be seen, the pulse shape is not a true half-sine or triangle. Since many of our specifications call for half-sine pulses, it was necessary to correlate this shape with the half-sine in terms of equivalent test specimen excitation. Figure 4 is a plot of input g magnification required, versus the ratio of the pulse duration to one-half the natural period of a simple spring-mass system, in order to excite the system in the same manner as a half-sine wave. Thus, below the ratio of approximately 1.6, it is necessary to increase the g level input in order to obtain the same excitation. This adjustment is very important when attempting to excite a given frequency, or when testing very close to a natural frequency of the

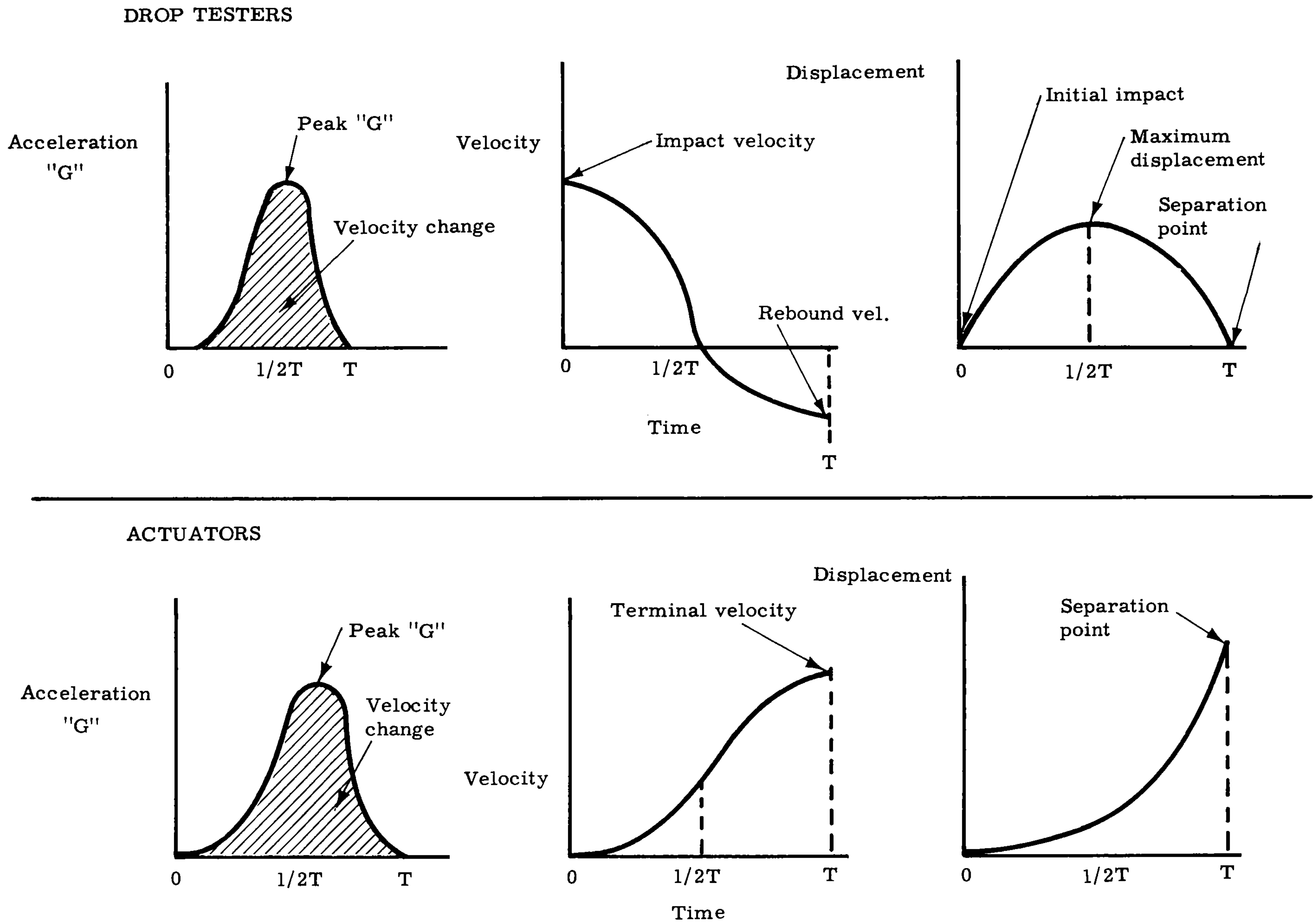


Figure 1 - Relation of shock parameters.

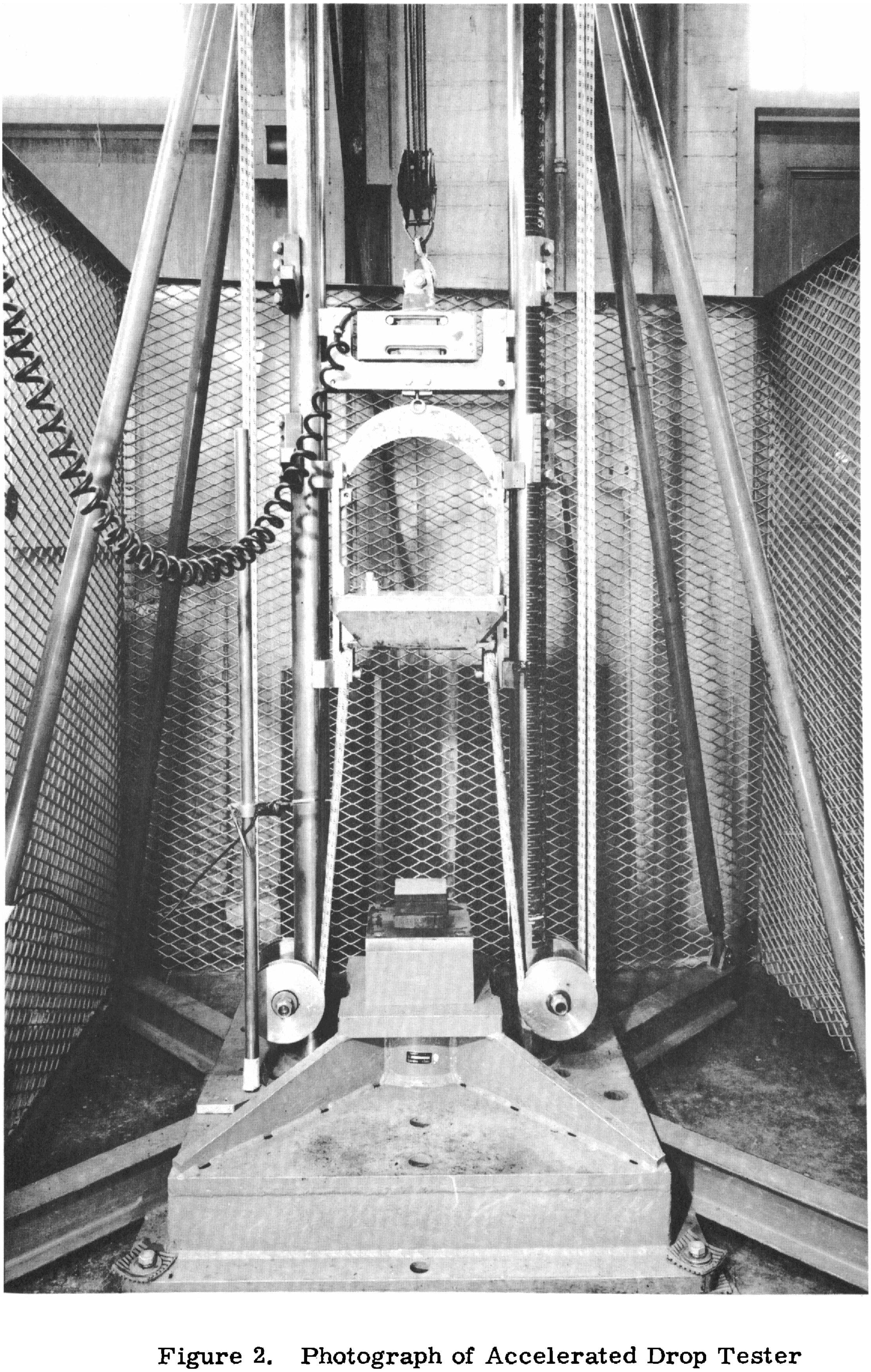
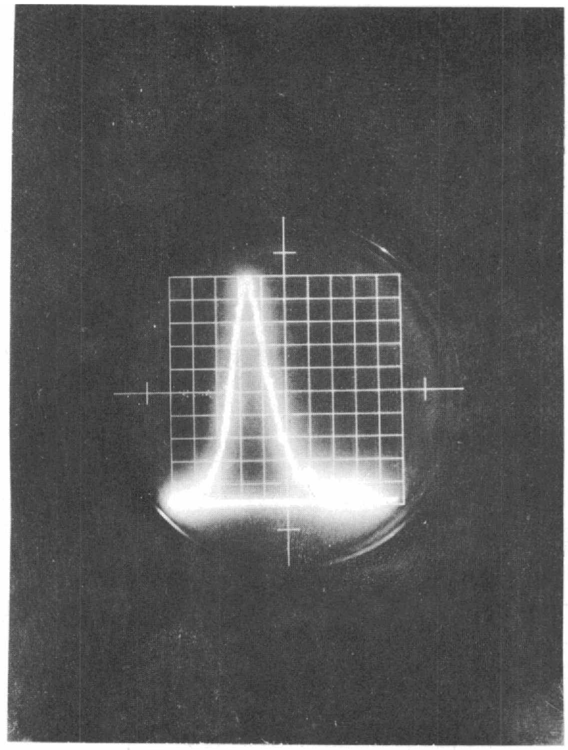


Figure 2. Photograph of Accelerated Drop Tester



Typical Oscilloscope Trace
Accelerated Drop Tester Output
(2000 g Full Scale) (1 millisecond-division)

(Recorded with Endevco 2214 Accelerometer, unfiltered, through Endevco 261A cathode follower and Tektronix 535 scope)

Figure 3-Typical Shock Pulse (Accelerated Drop Tester)

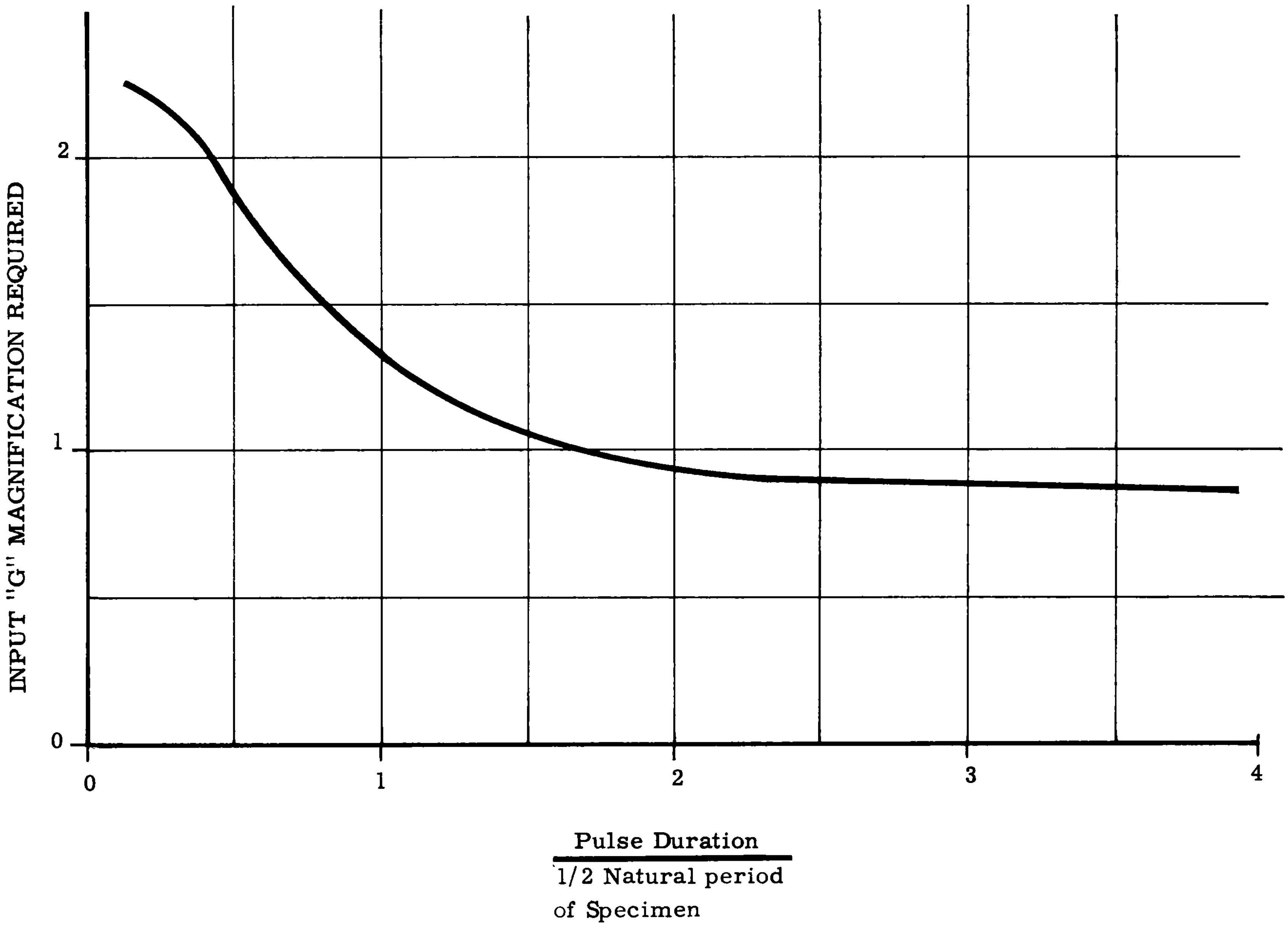


Figure 4 - Sine wave correlation (Accelerated drop tester)

specimen. As with other wave shapes, this shape factor becomes less important as the ratio of pulse duration to one-half the natural period becomes greater.

Correlations of this type for this and other waveshapes have been made and are compiled in Sandia Corporation Technical Memorandum 205-60-12 by W. J. Sieger.

Instrumentation for this facility is done with piezoelectric and strain-gage type accelerometers, amplifiers, and oscilloscopes with Polaroid cameras.

This accelerated drop tester is typical of its type, and most others that have been designed and built differ only in table size, drop height, or minor refinements. Figure 5 is a schematic drawing of another model of accelerated drop tester.

One last point should be brought out regarding this type of tester. Braking to prevent a second impact after rebound is difficult to achieve. This braking is quite important, since a second impact may increase specimen damage. The normal cam-operated braking devices have not proven satisfactory for braking the carriage against the cord load. Air operated friction brakes, with an inertia operated valve, are currently under development and show promise for this type of application. Fortunately, the rebound velocity is generally small, because of high damping in the impact medium, and the velocity-change of the second impact is not more than 10-15 percent of the original.

Pneumatic Actuators

There are now several models of actuators available on the market for a variety of testing conditions. A 3-inch actuator is rated at 10,000 pound maximum thrust and a 6-inch actuator is rated at 40,000 pounds maximum thrust. The standard actuators, by interchanging cylinder lengths and metering pins, can generate half-sine pulses from 5 to 50 ms in duration and g levels from 15 to 300. Velocity-changes up to 120 ft/sec can be generated with a 6-inch actuator. In addition, special kits are available for modifying the standard units to obtain square, sawtooth, and quarter-cosine pulses.

Figure 6 is a photograph of a 6-inch actuator installation with the square-wave modification kit. The carriage is a special design to obtain optimum stiffness and weight. With this facility, square waves of 100 g's for 20 milliseconds can be generated on 100-pound specimens. Actuators of this type have proven themselves, over a period of several years, to be a very dependable and repeatable laboratory shock device, and they have certainly filled a big gap in the test-equipment field. Instrumentation used on this facility is usually a strain-gage type accelerometer, with amplifier, oscilloscope, and camera. Figure 7 is a typical oscilloscope trace of the square-wave output of a 6-inch actuator.

The 12-inch horizontal actuator (figure 8) is a special model, designed and built commercially to our specifications. This machine has a useable output of 160,000 pounds of thrust. The actuator was designed to generate half-sine pulses of 15 ms duration. An 800 g acceleration level can be generated on a total of 200 pounds. The thrust column and piston assembly account for 70 pounds, leaving a net of 130 pounds for carriage and specimen. Maximum velocity-change with a

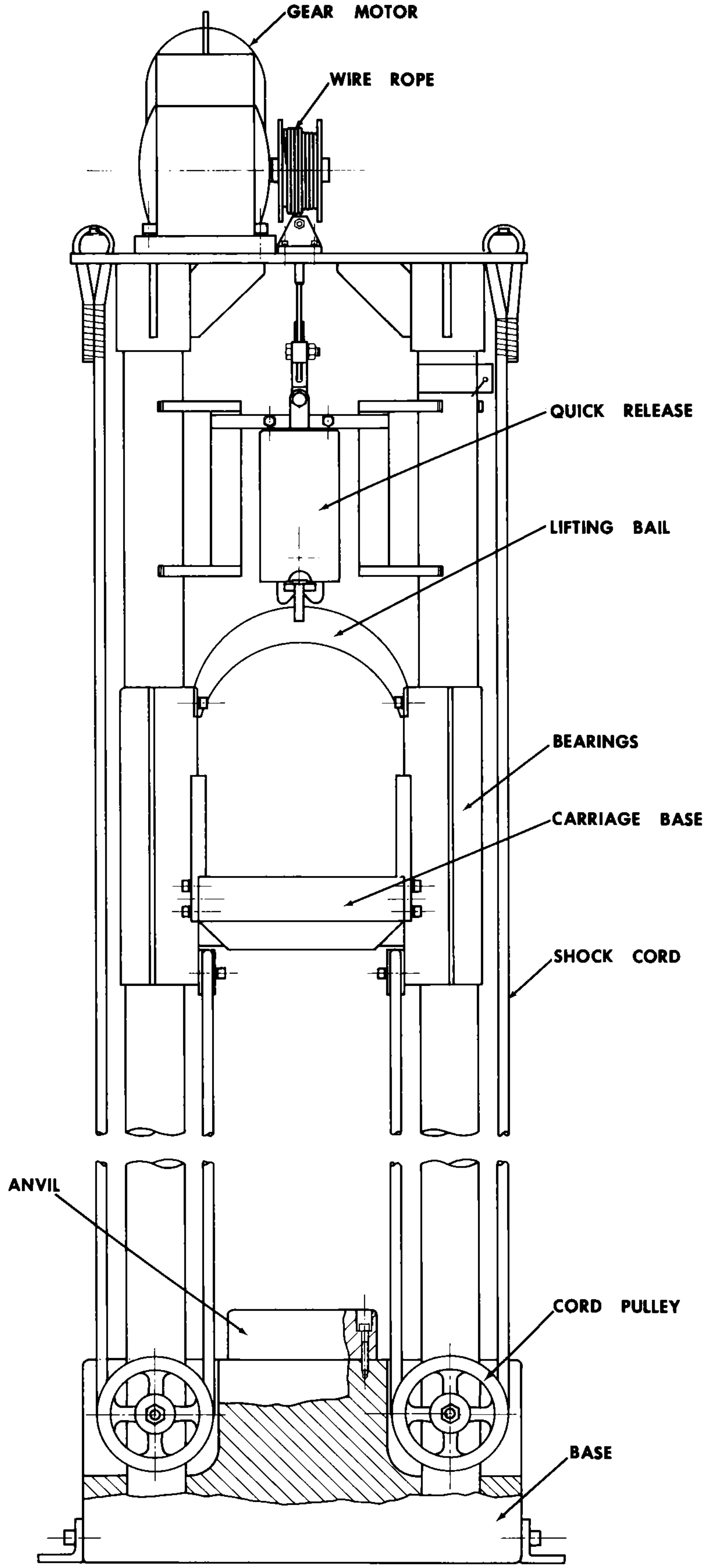


Figure 5. Schematic of Accelerated Drop Tester

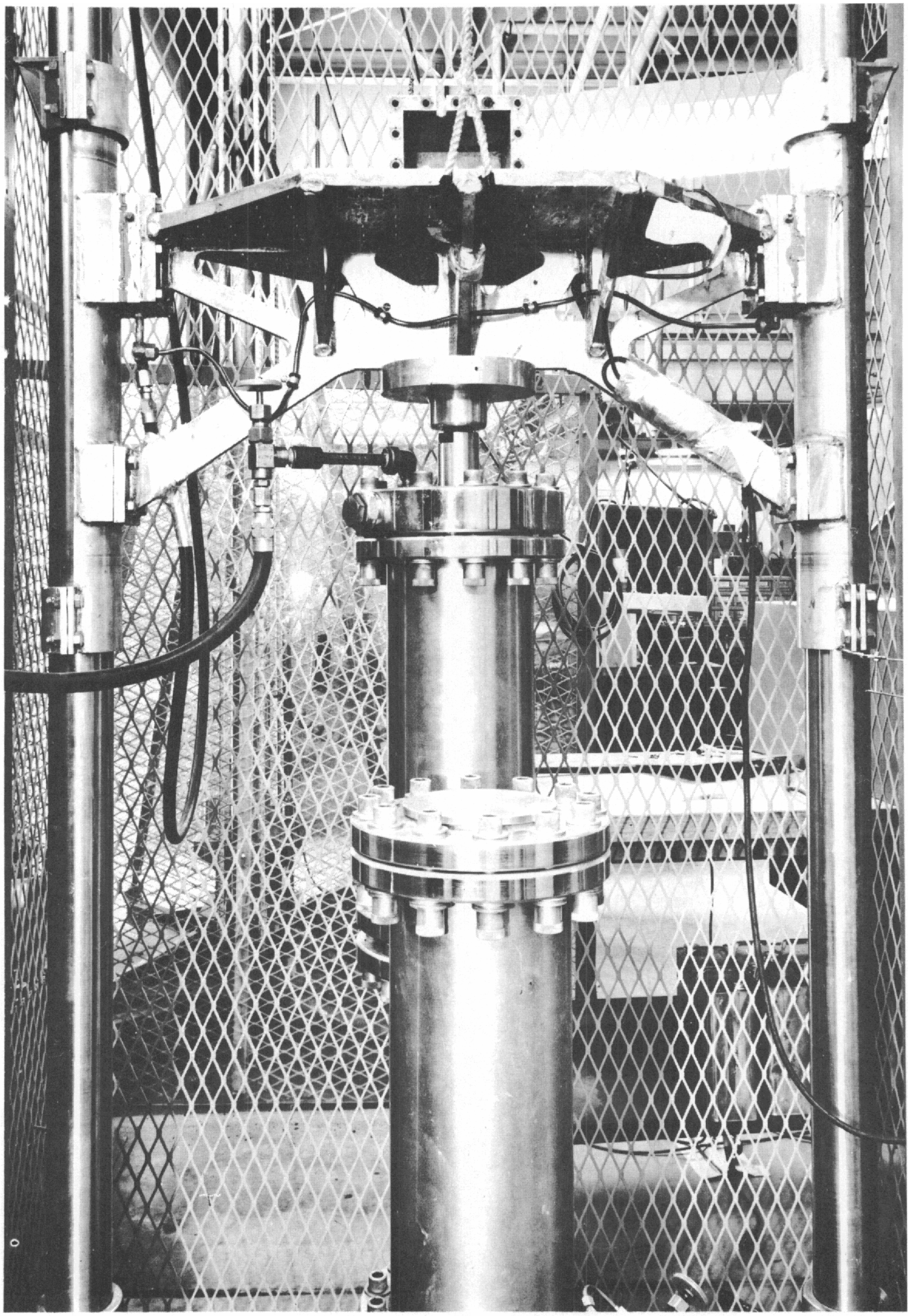
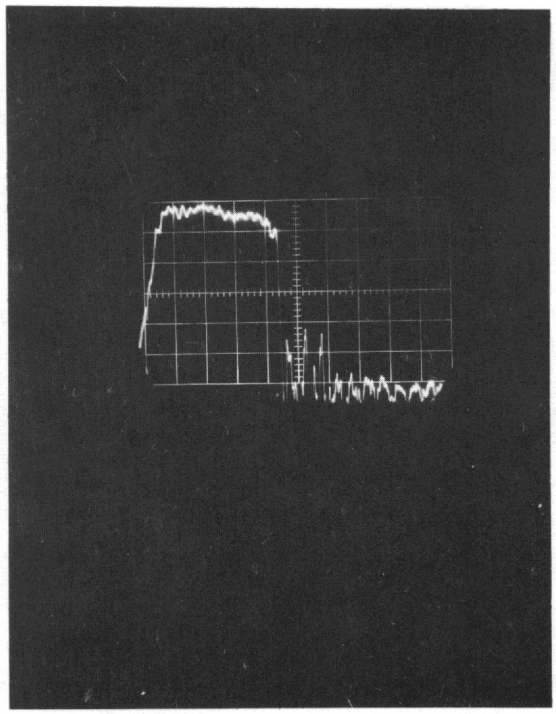


Figure 6. Photograph of 6-Inch Actuator



Typical Oscilloscope Trace
6-inch Actuator Square Wave Output
(100 G Fullscale) (5 milliseconds-division)

(Recorded with Statham accelerometer, through special amplifier and Tektronix 535 scope). (Vibrations following main pulse are due to shock excitation of carriage and fixture)

Figure 7-Typical Pulse (Square Wave) (6-inch Actuator)

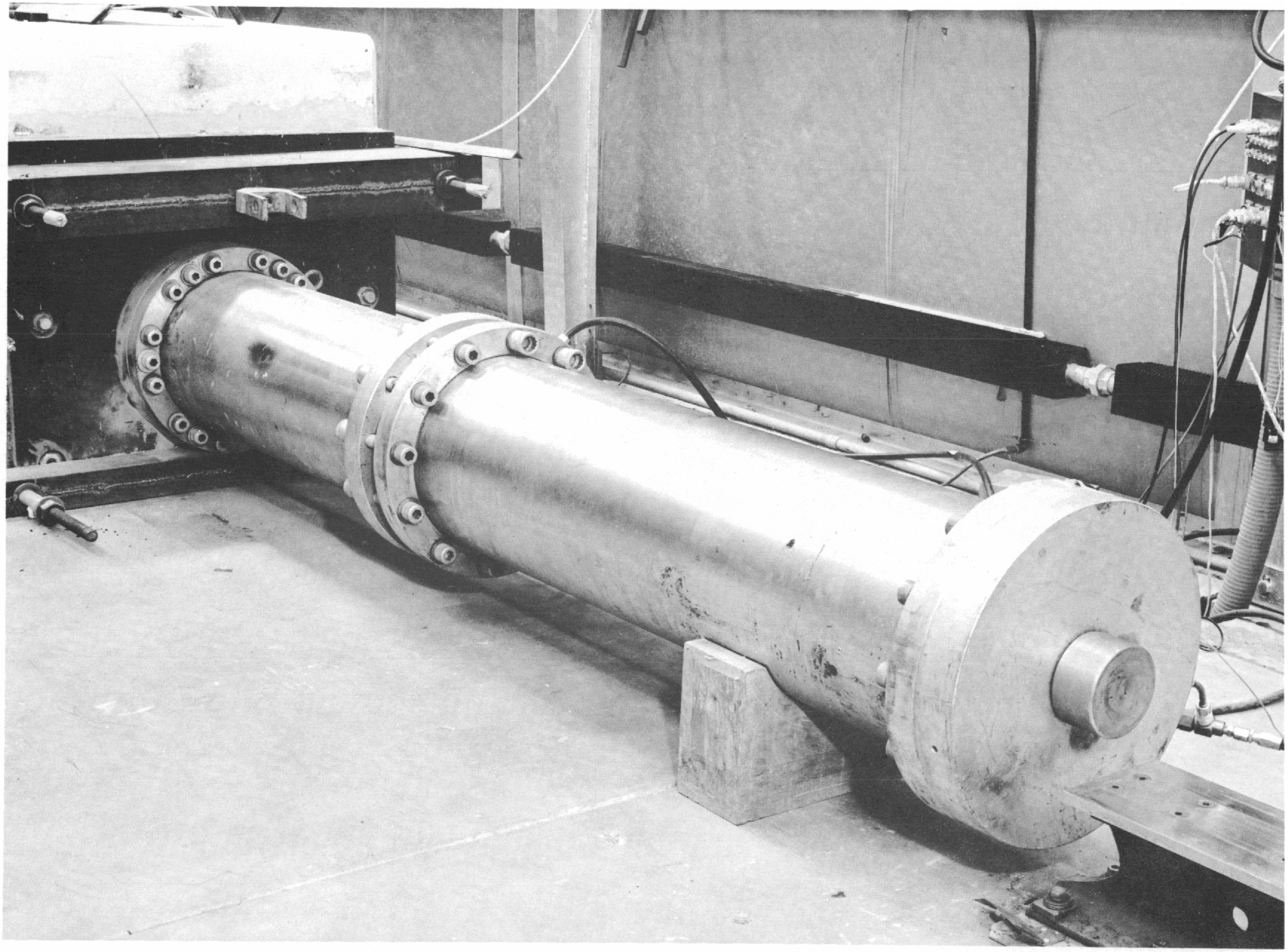


Figure 8. Photograph of 12-Inch Horizontal Actuator

40-pound specimen is approximately 240 ft/sec.

The carriage and rail system were designed and installed after delivery of the actuator, and were not purchased with it. The carriage rides on a flat-plate monorail, and incorporates an air-operated brake shoe on its underside, pressing against the monorail plate. The pressure on the brake shoe is pre-set before firing to bring the carriage to a halt in approximately 30 feet of travel. This maintains the deceleration level below 10 percent of the initial acceleration level. Figure 9 is an acceleration-time profile of a typical shot with this facility. Note the constant drag exerted by the brake shoe.

This facility was designed primarily for testing to a water-entry (two-phase) shock specification. Figure 10 shows the idealized specification. This consists of a short duration, high-g spike, followed by a "drag-phase" of 15 ms duration. To perform this type of test, it is necessary to add a "Janus" plate assembly to the main carriage. This is a mounting plate supported on guide rods from the vertical surface of the carriage. Figure 11 is a photograph of the Janus plate assembly installed on the main carriage. The plate is free to move along the rods in the direction of travel of the carriage. Thus, the main carriage can be accelerated to a desired velocity before it impacts the Janus plate. Spring-loaded latches hold the carriage and Janus plate together after impact, during the drag-phase and deceleration. A special rubber pad is placed between the vertical surface of the carriage and the Janus plate. The Janus plate is spaced from the rubber pads a short distance, depending upon the impact velocity required. Spacing required to generate a given velocity change on the test specimen and Janus plate can be approximated theoretically, but there are enough variables such as acceleration-time variations, friction, and the impact properties of rubber, so that it is generally desirable to calibrate on a trial-and-error basis, using accelerometer information and the following methods.

A crystal accelerometer is mounted on the main carriage body and its output fed to a high speed recording oscillograph. This results in a recording similar to Figure 12. It is then possible to measure, with a planimeter, the area under this acceleration-time trace, up to the point of impact with the Janus plate. The area reading is then converted to velocity. This is the velocity of the carriage at impact with the Janus plate. This value is used in the following equation to determine velocity change of the Janus plate. (See Appendix for derivation).

$$\Delta V = \frac{V_p\,(1+e)}{1+\frac{M_j}{M_p}}$$

V_p = velocity of main carriage at impact.

M_j = mass of Janus plate and specimen.

M_p = mass of piston, thrust column, and main carriage.

e = coefficient of restitution of rubber pad (determined experimentally on drop tester under similar conditions).

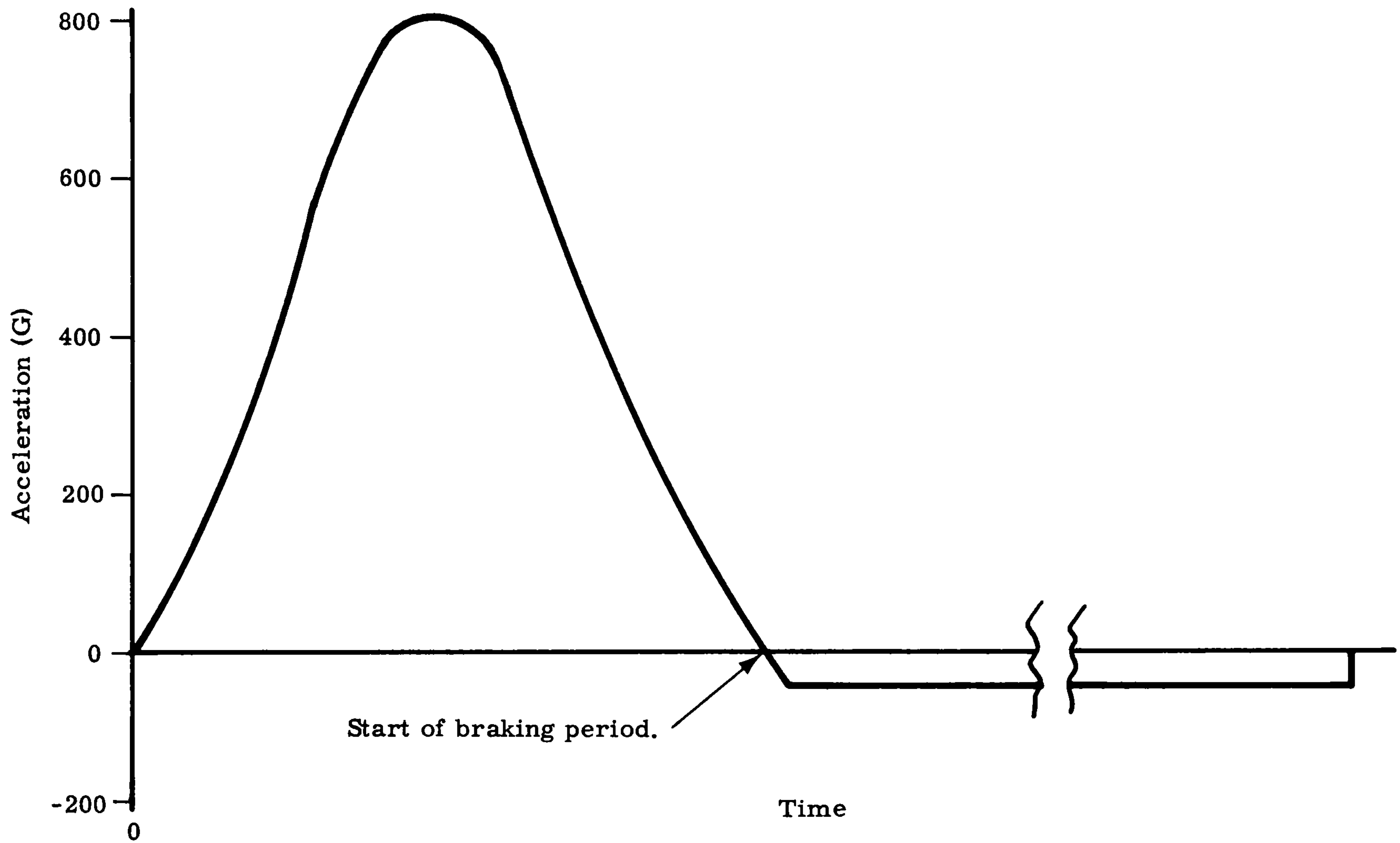


Figure 9 - Acceleration-Time profile 12" Horizontal Actuator

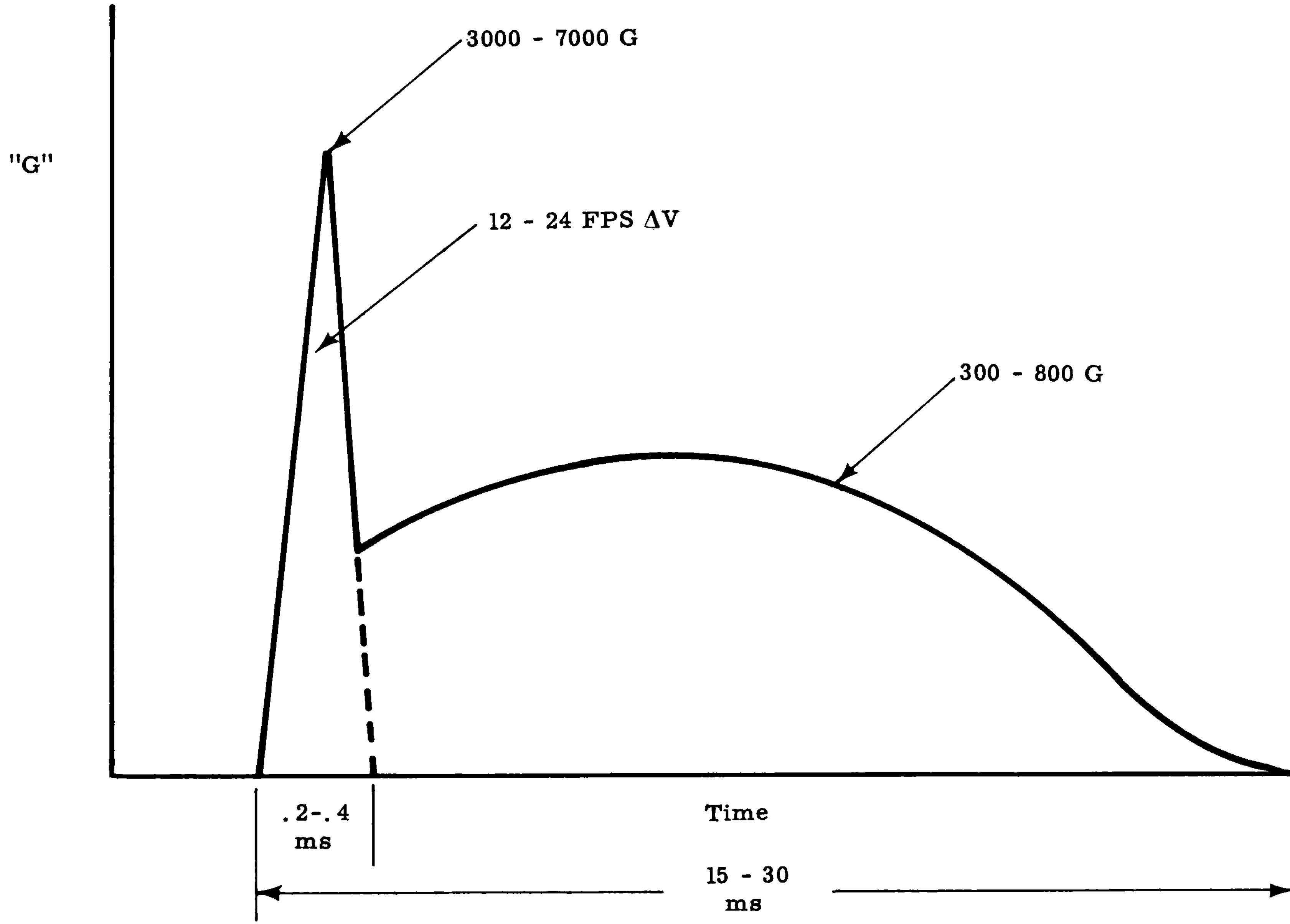


Figure 10 - Idealized water entry specification.

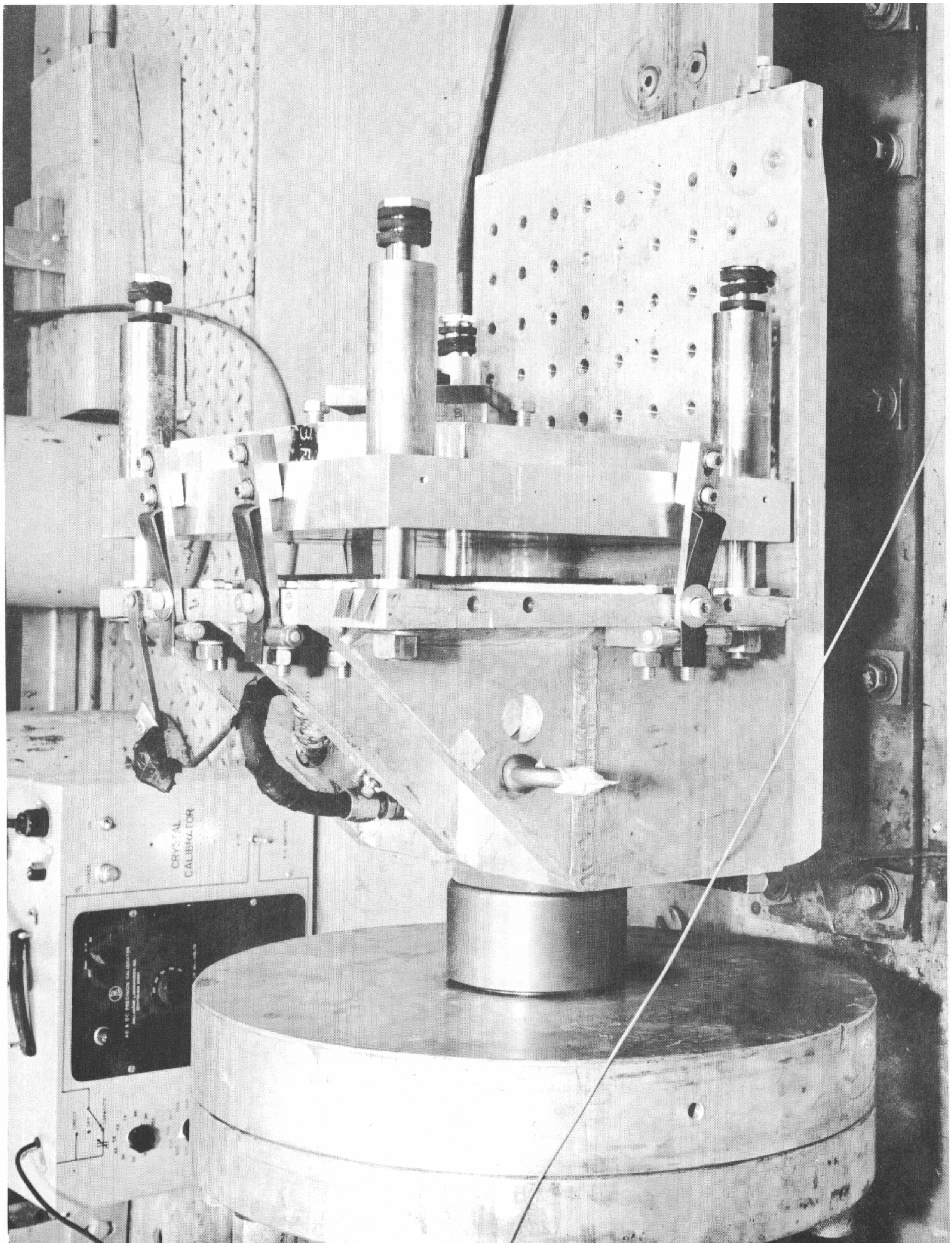
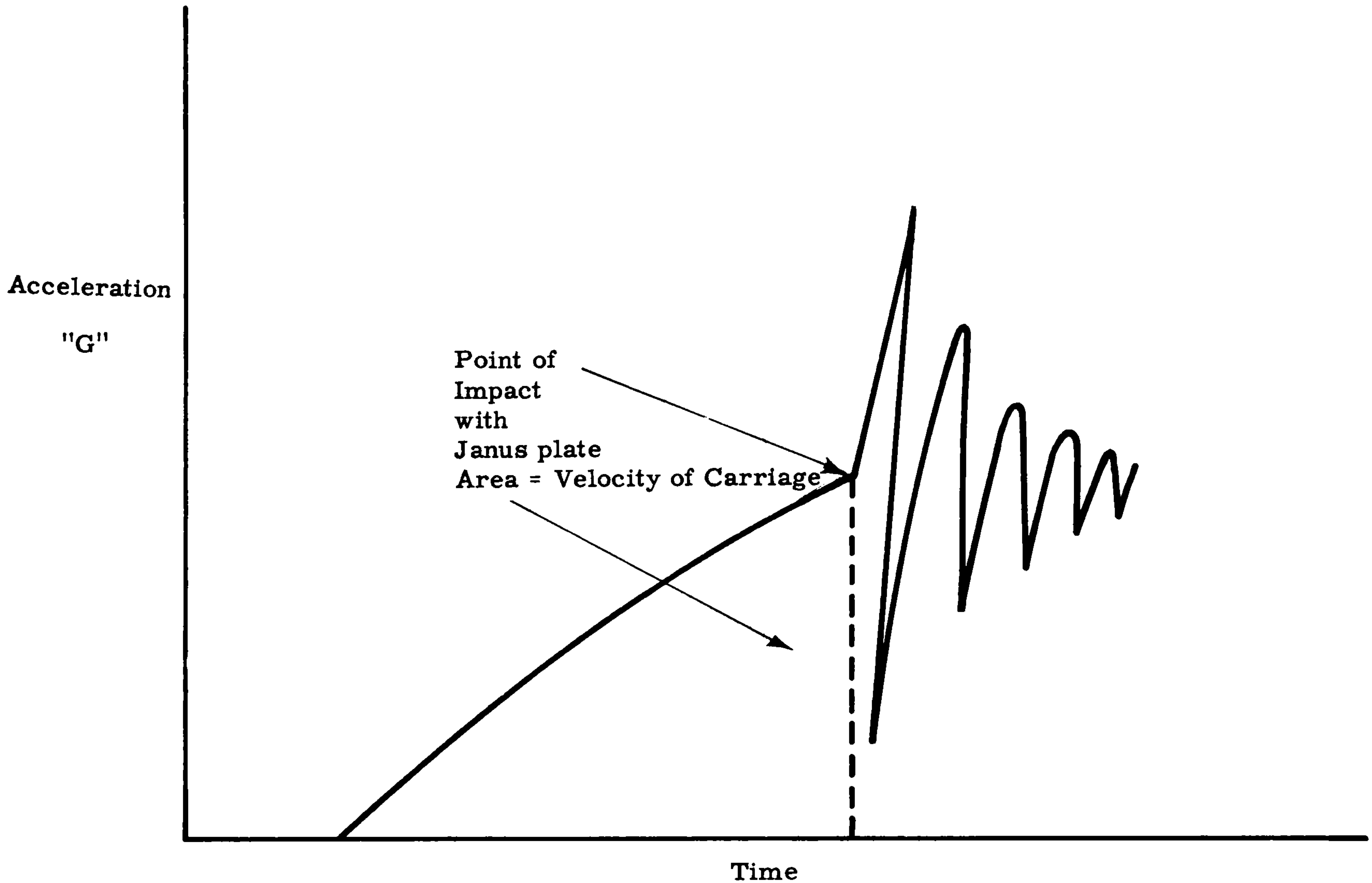


Figure 11. Photograph of Janus Plate Assembly on Carriage



$$\Delta V_{\text{(janus plate)}} = \frac{\text{Vel. (carriage)}(1+e)}{1 + \frac{M_j}{M_c}}$$

Figure 12 - Velocity Measurement Technique

The size and thickness of the rubber pad used is selected so that the deformation required to produce a spike of given duration will not exceed 50% deformation of the rubber.

It is estimated that the accumulated errors of measuring actual velocity change by this method may be as much as ±20%. However, considering that most water-entry shock specifications are somewhat speculative, this degree of accuracy cannot be too severely criticized.

An additional feature of the horizontal-type actuator is an impact testing capability. This is accomplished by placing a sizeable impact block at the end of the track and impacting a specially designed carriage into it. Here, as on a drop tester, impact conditions are controlled by pads of different material. This feature is especially useful for generating shocks in excess of 800 g, of short durations, where impact velocities up to 200 ft/sec are required. Figure 13 is an acceleration-time history of an impact shock generated by this facility.

As could be expected, this testing procedure also has its special problems. One of these problems is the necessity for maintaining the instrumentation cables intact through the impact. It is very difficult to maintain the cables intact when the velocity-change of the impact approaches 200 ft/sec, so this has proven to be a definite limitation on this capability. Another problem is rebound; the carriage rebounding from the impact material with velocities up to 100 ft/sec. The carriage must be stopped before it returns to the actuator. This is accomplished by the use of an inertia-operated air valve in a small tank bolted to the impact carriage. The tank is pressurized to the desired braking pressure before firing. Upon impact, the inertia forces open the air valve, releasing the tank pressure onto the carriage brake shoe and decelerating the carriage as it slides back along the rail. An important consideration, but not necessarily a problem, is the necessity for the initial acceleration of the carriage in a direction opposite to that desired. This, of course, is necessary to get the carriage up to the velocity desired for the impact. The effect of this initial acceleration on the test specimen must be taken into account when contemplating an impact test with the actuator facility. Figure 14 is a picture of the impact portion of the 12-inch horizontal actuator facility, showing impact block, impact carriage, and impact pads.

Air Guns

Air guns were originally developed more than 10 years ago as devices for simulating water-entry shock conditions. With the development of large pneumatic actuators, the need for air guns has diminished, as the actuators can meet most of the water-entry specifications, and are much cheaper and easier to work with. An actuator is really just a modified air gun, with refinements in the areas of releasing and pulse shaping. They have a great advantage over an air gun in that the carriage and specimen are exposed and are readily accessible.

In the basic air gun, high pressure air is used to propel the piston containing the specimen down a closed barrel, compressing the air ahead of it until the piston comes to a stop. This generates a pulse with a rapid rise time and a long gradual decay. Figure 15 is an illustration of a typical air gun shock pulse. Release of the piston is accomplished by either a mechanical holding

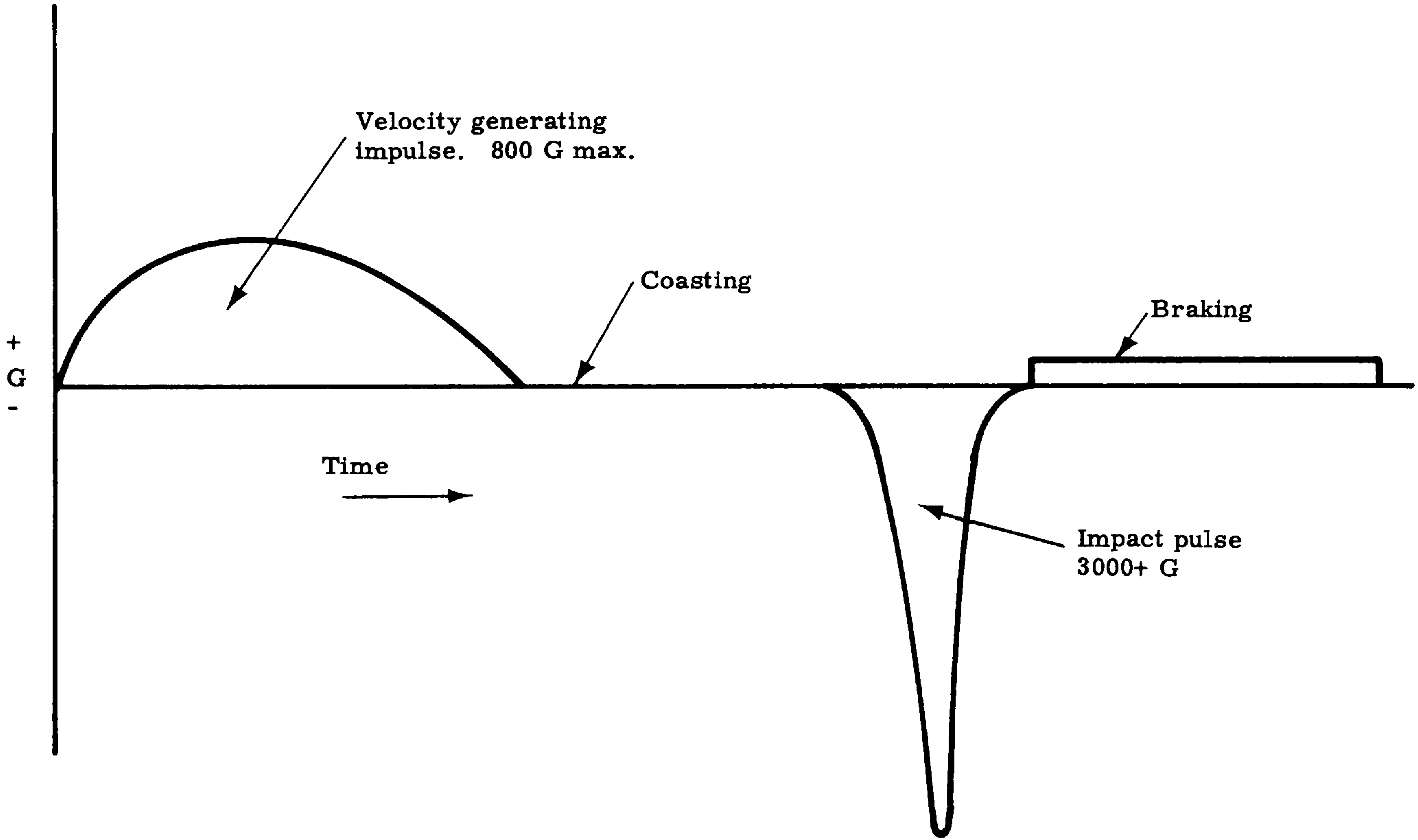


Figure 13. Typical Acceleration - Time History, Impact Shot. 12-Inch Horizontal Actuator Facility

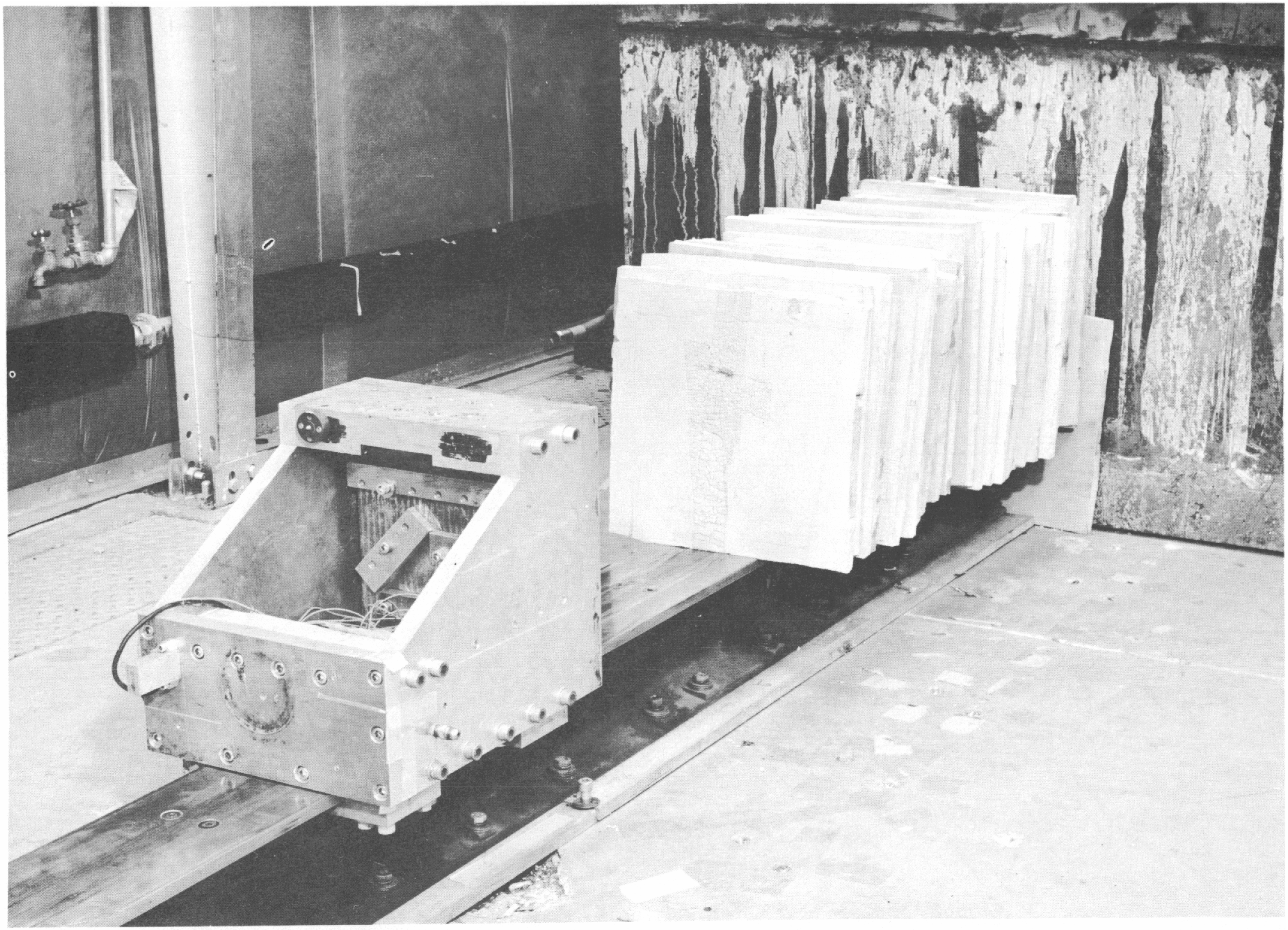


Figure 14. Photograph of Impact Portion, 12-Inch Horizontal Actuator Facility

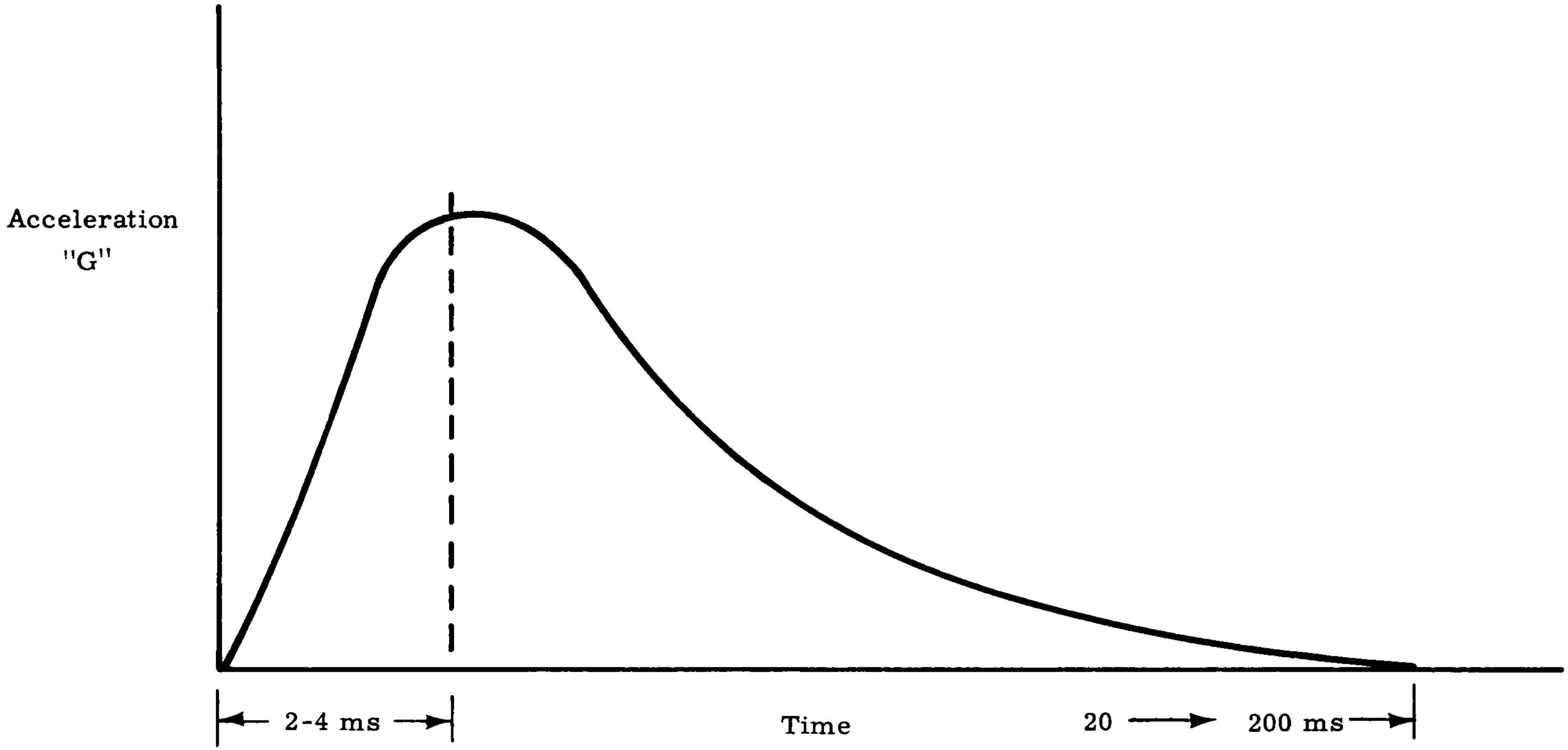


Figure 15. Typical Air Gun Pulse

device or by means of an air seal. The air seal is cheaper, more predictable, and maintenance free, and therefore has been used on most air guns designed in the last few years. Air guns are still quite useful for generating shock pulses of high velocity-change, such as 500-1000 ft/sec. They are also useful for very high g pulses (2000+ g's), but if the velocity change required is not great, it is more convenient to do this with an actuator or drop tester. Figure 16 is a schematic of a typical air gun. The major elements are: breech, release device, piston, muzzle, muzzle tank, and flap valves.

The test specimen is inserted in the piston, which may or may not be pressure sealed, and the piston is positioned in the release device. The muzzle pressure is then built up to a value predetermined to meet the necessary test conditions. Breech pressure sufficient to generate the required acceleration level is then built up. Release is accomplished by admitting high-pressure air behind the piston, forcing it out of the release device, and allowing the breech pressure to act on the back of the piston. As the piston travels down the barrel, it compresses the muzzle air ahead of it, forcing the air into the muzzle tank through the flap valves. As the piston comes to a stop and starts back toward the breech, the flap valves close, trapping the compressed air in the muzzle tank, thereby greatly reducing the magnitude and number of subsequent oscillations. The muzzle tank is a very important element of an air gun. Without its energy absorption, the piston and specimen would sustain a series of shocks each only slightly diminished from the preceding one, since the piston would be essentially rebounding back and forth between two elastic springs.

In general, the elements of the air gun having the most effect on the various test parameters are as follows:

Peak g	----------	Breech pressure
Time duration	----------	Breech volume and muzzle pressure
Rise time	----------	Release system
Deceleration	----------	Muzzle length and pressure

Two-phase testing is done on the air gun in the same manner as on the actuator, utilizing a Janus plate and latching system.

An example of a special-purpose air gun is shown in figure 17. This gun was designed to test components under 26 inches in diameter and weighing up to 1000 pounds, to acceleration values up to 1000 g and velocities of 500 ft/sec. The pulse shape generated is shown in figure 15. Most air guns have a relatively fixed rise time; however, it is possible to vary the rise time of an air gun pulse by metering the air flow from the breech. Physically this is done by extending the gun tube into the breech chamber with a removable sleeve. The sleeve is perforated with a predetermined pattern of holes, so that as the piston is released and starts moving, it uncovers these holes and increases the air flow from the breech chamber as a function of displacement. This would be similar to using a metering pin, as is done in actuators; however, using a sleeve has the advantage that the weight of the metering device is not added to the weight that is being accelerated. A 5.5" diameter air gun utilizing this principle has been built and successfully operated, and is reported on in SCTM 220-60-16 by H. D. Sivinski.

The problems associated with instrumenting the test vehicle on an air gun are severe and constitute the main disadvantage of air guns. There have been several approaches to the problem; however, none of these has ever been completely satisfactory.

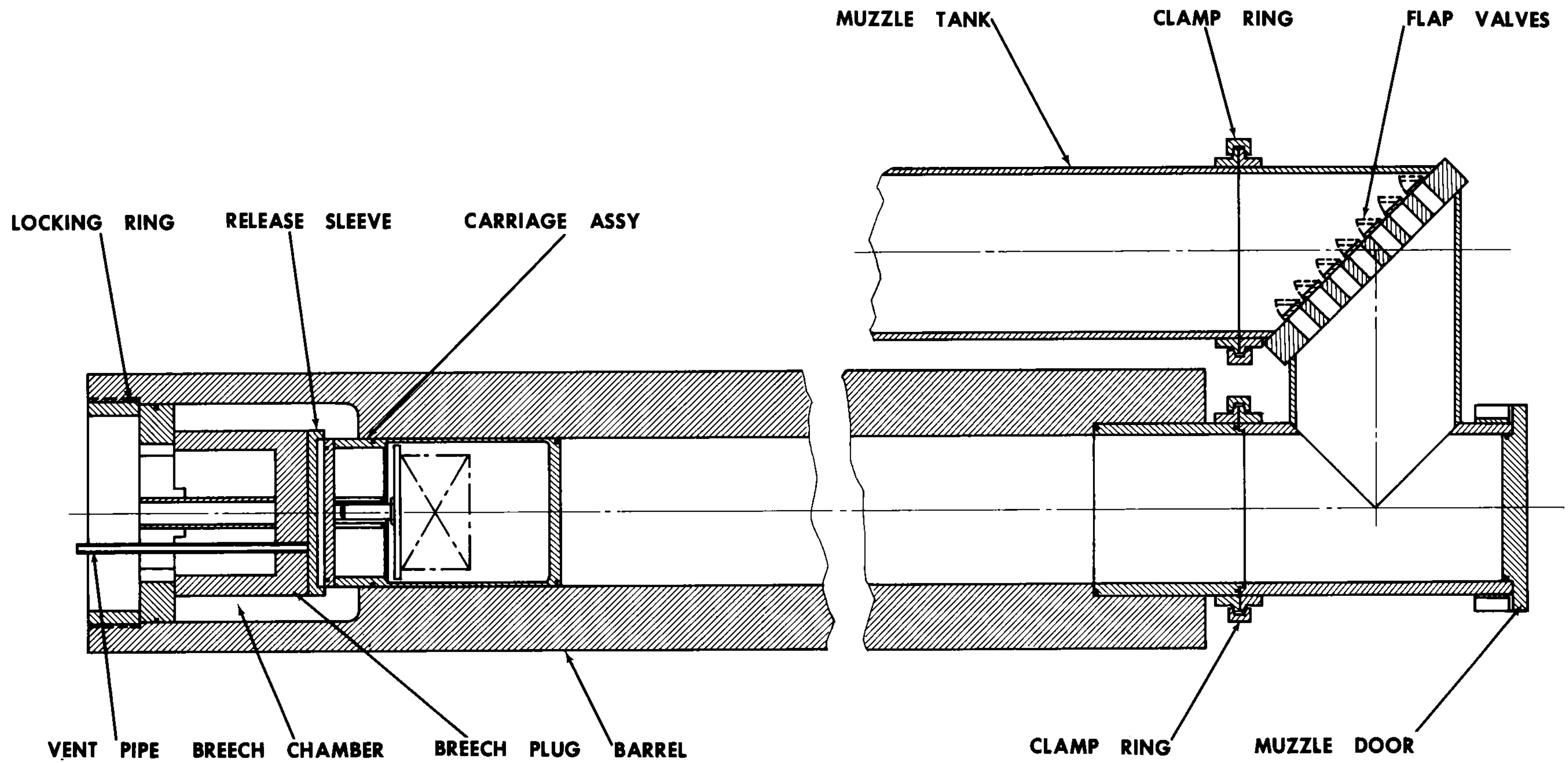


Figure 16. Air Gun Schematic

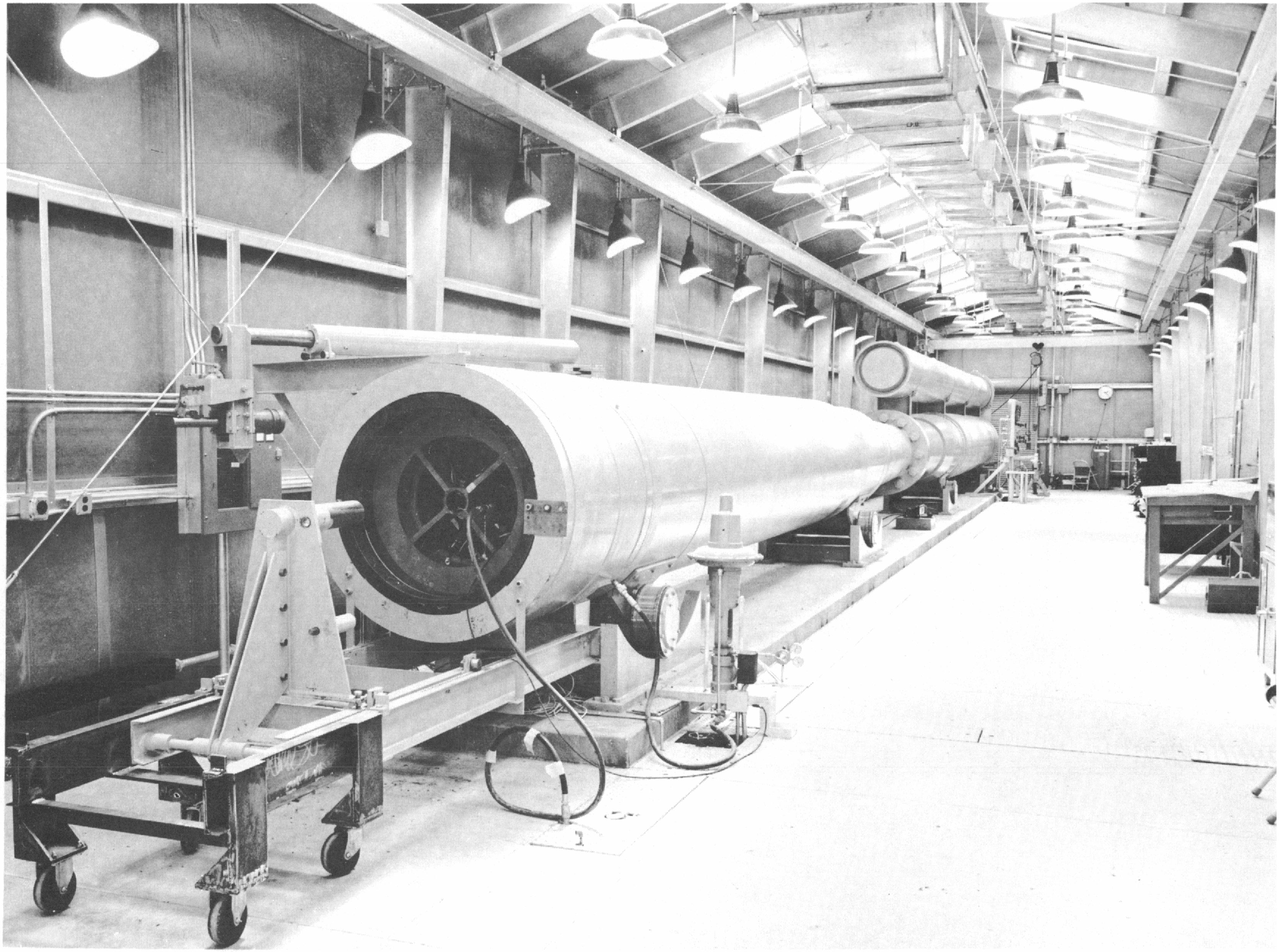


Figure 17. Photograph of 26-Inch Air Gun

One approach has been to use "on-board" recorders. These recorders are rugged devices that ride with the test specimen in the piston and record directly the outputs of the accelerometers and other transducers. These recorders are necessarily limited in frequency and amplitude response, and their resolution is very poor. They frequently exhibit intermittent and unreliable operation, especially at higher g levels. Also, they must be started at the right time, and this usually requires a direct-wire hookup.

Another method, used earlier but fading out with the development of better devices, is the copper ball accelerometer. This device, when designed properly and used under the right conditions, can be used to measure peak acceleration or velocity-change. Accuracy of this device is questionable, especially when vibrations of unknown frequencies are present on the piston.

The method that has proven the most successful, though still having considerable limitations, has been the direct-wire recording method. In this method, the accelerometers and other instruments are connected by direct wire, through pressure-tight connectors in the piston and muzzle door, to high-speed recording oscillographs. The wires are taped or wrapped to a tensile member, such as a nylon rope, fixed to the piston and muzzle door, and stretched out ahead of the piston along the barrel. As the piston moves down the barrel, it pushes the rope ahead of it. When the piston stops and reverses direction, the tensile member then pulls the instrumentation cables back, keeping the strain off the cables. However, the cables frequently fail on the return stroke as the rope tries to uncoil violently. Aside from the expense of replacing the cables, this is not a major problem, since all of the primary shock pulse and deceleration have already been recorded. This expense can be reduced considerably, where many tests must be recorded, by using a pressure feedthrough in the barrel at the point where the positive acceleration phase is complete. The wires are fed through small holes in the side of the barrel by means of a pressure tight instrumentation cap. As the piston passes this point, a sharp leading edge shears off the wires, expending only the length of wire between the piston and cap.

Summary

These three types of equipment represent the most common means of generating high-velocity shock pulses. The accelerated drop tester can be operated quite safely in the test laboratory with only a safety fence around it to guard against objects that may come loose. A vertical actuator can also be operated safely in the test laboratory, but it should be completely enclosed in a safety screen. A properly designed air gun can be operated safely in the test laboratory if no launching of projectiles is to be done. The complete enclosure of the piston and specimen by the barrel is adequate protection against failures of either of these items.

Accelerated drop testers, such as those mentioned in this paper, can be fabricated and put into service with a total outlay of $5000 to $8000. A basic 6-inch actuator, complete with console, carriage, and rail system, but without compressor, storage tank, or installation, would cost approximately $12,000. This cost would be increased if capabilities other than the half-sine wave were desired. A small air gun, such as a 4 to 8-inch diameter bore, would cost

$15,000 to $25,000, not including instrumentation, compressor, storage tank, or installation.

As testing requirements for high velocity applications become more widespread through industry, equipment of the types mentioned in this paper will no doubt be further developed and improved upon. With the exception of the basic actuators, the equipment discussed in this paper is not available commercially and must be specially designed and developed. The wide-range versatility and relative low price of the accelerated drop tester will no doubt make it a popular piece of testing equipment with environmental test laboratories and industries with production shock test requirements.

APPENDIX

APPENDIX

A Derivation of velocity-change equation for two-phase impact.

The basic energy equations for elastic impact of two masses:

(1) At moment of maximum deformation

$M_cV_c+M_jV_j = (M_c+M_j)V$

(2) At moment of separation

$(M_c+M_j)V = M_cV_c^1+M_jV_j^1$

M_c = Mass of carriage
V_c = Velocity of carriage (before impact)
M_j = Mass of Janus plate
V_j = Velocity of Janus (before impact = 0)
V = Resultant velocity of both masses (after impact)
V_c^1 = Velocity of carriage after separation
V_j^1 = Velocity of Janus after separation

Equating (1) and (2)

(3) $M_cV_c+M_jV_j = M_cV_c^1+M_jV_j^1$

Initial condition $V_j = 0$

By definition: $e = \dfrac{V_c^1 - V_j^1}{V_c - V_j}$ (coefficient of restitution)

Since $V_j = 0$ $\quad V_c^1 = V_j^1 - eV_c$

Substitution in (3)

$M_cV_c = M_c(V_j-eV_c)+M_jV_j^1$

Rearranging terms

$M_cV_c = V_j^1\ (M_c+M_j)-M_ceV_c$

$$V_j^1 = \frac{M_cV_c+ M_ceV_c}{M_c+M_j}$$

Divide through by $\dfrac{M_c}{M_c}$

$$V_j^1 = \frac{V_c(1+e)}{1 + \frac{M_j}{M_c}} \quad \text{- - - - - - - - - -} \quad \Delta V \text{ of Janus plate}$$

B Calculations for velocity-change of shock pulses. (ft/sec)
(G = maximum "g" units, t = pulse duration in seconds)

Square wave $\Delta V = G \times t \times 32.2$

Triangular wave (Sawtooth) $\Delta V = \frac{G \times t \times 32.2}{2}$

Half-sine wave (approximation) $\Delta V = \frac{G \times t \times 32.2}{1.57}$

The only reasonably accurate way to determine velocity-change with a "non-standard" wave shape is to measure the actual area with a planimeter and convert the area reading to velocity-change.

C Aluminum honeycomb for square-wave pulses.

Material: Aluminum honeycomb, hexcell, 1/8-inch cell size x .0015-inch wall thickness. Average crushing strength = 360 psi.

(1) Determine total weight of carriage, specimen, and jig.

(2) Multiply this total weight times maximum "G" units required:
$W_t \times G$ = crushing force required.

(3) Divide crushing force required by 360 to get number of square inches of impact area required.

$$\frac{\text{Weight (lbs)} \times G}{360\ (\text{lbs/in}^2)} = \text{in}^2 \text{ required}$$

Use a square cross-section of the area required.

(4) Length determination

$S = \frac{1}{2} at^2$ = maximum displacement (inches)
S = displacement in inches
a = "G" units x 386 (in/sec^2)
t = time duration in seconds

After determining S required, add one-third more, to avoid abrupt bottoming of honeycomb.

(5) Sample calculations:
Pulse required: square-wave, 100 g, 20 ms.
Wt = assumed = 100 lbs.

$\frac{100 \times 100}{360} = 27.7$ in^2 required area

Length:

$S = \frac{1}{2} at^2 = \frac{100 \times 386 \times .020^2}{2} = 7.72''$

$7.72 + \frac{7.72}{3} = 10''$ approximate length

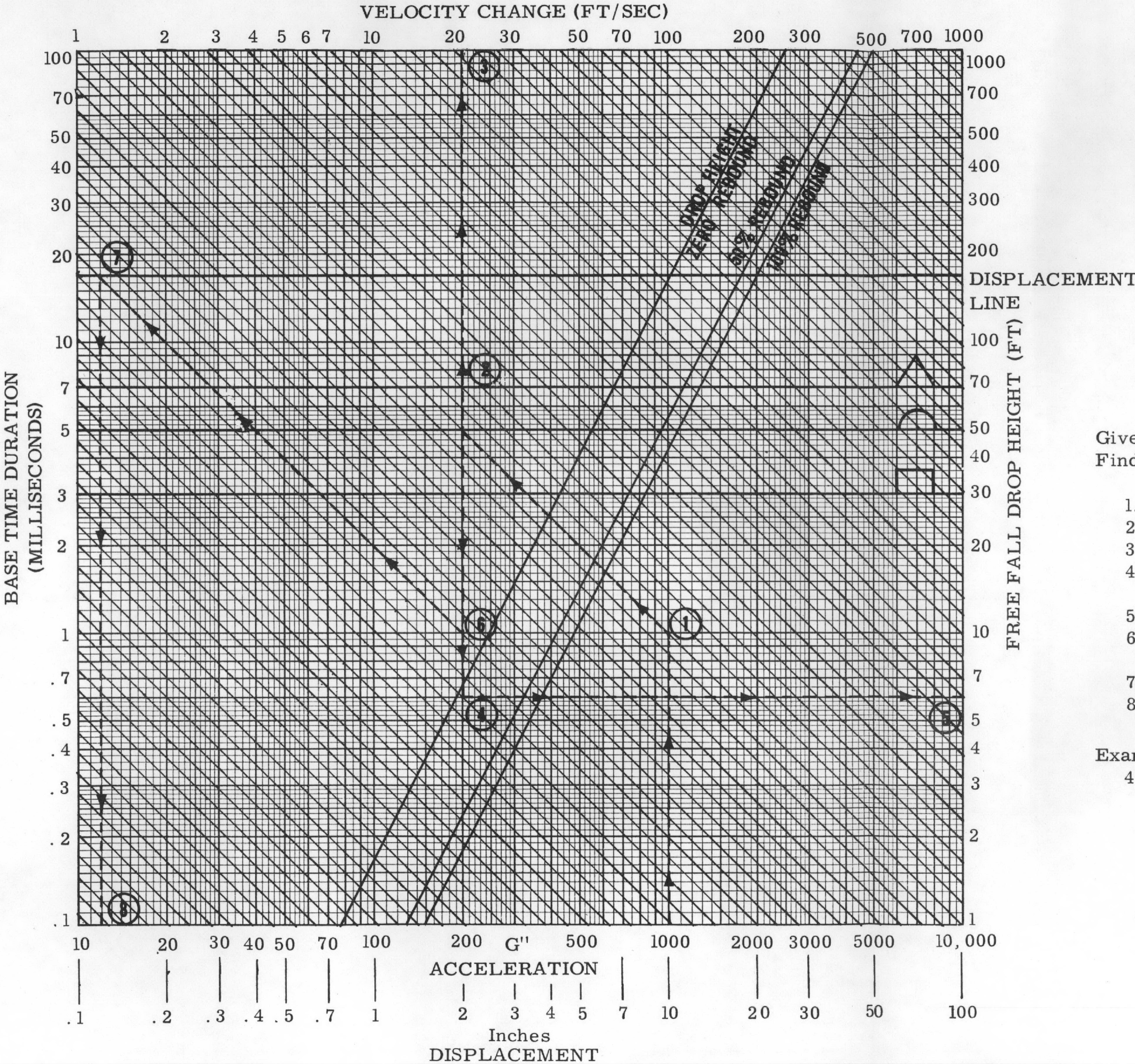
D Acceleration, velocity, and displacement functions for half-sine wave.

$$a = F_o \sin wt$$

$$V = \frac{-F_o}{w} \cos wt + \frac{F_o}{w}$$

$$X = -\frac{F_o}{w^2} \sin wt + \frac{F_o}{w} t$$

t = pulse duration (seconds)
w = equivalent rad/sec



Given: Peak G, base duration , and wave shape
Find: Velocity change, displacement, & drop height.

1. Find G & T intercept.
2. Follow diagonal grid to intersection with line for wave shape desired.
3. Read velocity change on top scale vertically from intersection 2.
4. To find free fall drop height drop vertically from velocity change to drop height line.
5. Read drop height on right scale horizontally from intercept 4.
6. To find displacement drop vertically from velocity change, to intercept with original T (time) line.
7. Follow diagonal grid from intercept 6 to displacement line.
8. Read displacement on bottom scale vertically from intercept 7.

Example:

4. 1000 G, 1 millisecond sine wave has a velocity change of 20 FT/SEC. Displacement is .12 inches. Free fall drop height is 6 FT.

Figure 18. Shock Nomograph

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