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WADD TECHNICAL REPORT 60-511
PART I

INVESTIGATION OF THE HIGH SPEED IMPACT BEHAVIOR OF FIBROUS MATERIALS ,

PART I: DESIGN AND APPARATUS

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= USAF. WRIGHT AIR DEVELOPMENT DIVISION ,
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UNITED STATES AIR FORCE
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FOREWORD

This report was prepared by Fabric Research Laboratories, Inc. under USAF Contract No. AF 33(616)-6321. The contract was initiated under Project No. 7320, "Air Force Textile Materials," Task No. 73201, "Parachute Materials and Functional Textiles." The work was administered under the direction of the Nonmetallic Materials Laboratory, Materials Central, Directorate of Advanced Systems Technology, Wright Air Development Division, with Mr. Jack H. Ross and Mr. R. A. Wilkinson (succeeded by Capt. C. O. Little, Jr.) acting as project engineers.

This report covers period of work from 15 February 1959 through 15 June 1960.

Acknowledgement is given to United Engineers, Inc. of Boston, Mass., who in collaboration with Fabric Research Laboratories, designed the gas gun.

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ABSTRACT

A high speed impact test machine has been designed, constructed, and calibrated to test parachute components at high rates of loading. This instrument is capable of rupturing materials of up to 10,000 pounds static breaking strength at velocities of from 200 to 750 feet per second. The impacting force is applied by a free flying missile launched by a gas gun utilizing either nitrogen or helium gas at moderately low pressures. The gun has a bore of 2.5 inches and fires missiles weighing up to 10 pounds.

Pertinent data are obtained by means of multiple exposure photography using a multi-microflash lighting source which provides a maximum of fifteen separate flashes spaced at predetermined intervals of between 10 and 10,000 microseconds. The resulting photograph records the specimen and the impacting missile before, during and after the impact. Measurement of the distances between successive exposures yields information such as the breaking strength, the extension to rupture, and the energy absorbed by the specimen.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

C. A. Willis

C. A. Willis
Chief, Textiles Branch
Nonmetallic Materials Laboratory
Materials Central

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I. INTRODUCTION

"One of the common areas in which little effort has been expended in the past is the impact studies at high rates of loading of textile materials. Today, in an air age of supersonic speed aircraft, missile systems, and the advent of space vehicles a need for impact behavior data of textiles definitely exists. Evidence of this need is shown through several reports which have indicated that rupture or failure of parachute suspension lines has occurred during high speed tests of first stage recovery parachute systems. The data recorded revealed that failure of the suspension lines occurred although the total load was less than 50% of the total rated strength of the lines. These problems have steadily increased in number and complexity. Requirements for recovery **of missiles involve speeds up** to Mach 3, flight altitudes of 500,000 feet, and weights up to 10,000 pounds." (From WADC PR 07111 - 23 July 1958).

Part of the parachute design is concerned with the fabrication of various seams, splices and joints. These various configurations, commonly called overlap splices, skirt band joints, vent band joints, butterfly gusset and felled seams, are also subjected to impact conditions together with the webbings and suspension lines. While some preliminary data on nylon webbings tested at impact velocities of up to 750 feet per second have been obtained by the Textile Branch of the Materials Laboratory through the use of the rocket sled facilities at the Air Force Flight Test Center, Edwards Air Force Base, California, it has been determined that it is not feasible to obtain similar data on seams and joints of textile materials by the same method.

Consequently, this contract entitled "Research and Development Leading to the Design and Fabrication of a High Speed Impact Test Machine" was initiated to fulfill the requirement. It was the objective of the research to design and construct an impact test machine capable of rupturing specimens with static strengths of up to 10,000 pounds at impact velocities ranging from 200 to 750 feet per second. The breaking of the specimens at these velocities, however, is only secondary in importance to the collection of other physical data such as: the load-elongation curves, times to rupture, impact velocities, rupture energies, etc., which were heretofore difficult if not impossible to obtain from the testing performed on the rocket sled. All of these objectives have been successfully met.

II. GENERAL CONSIDERATIONS OF SYSTEM DESIGN

Impact testing at high rates of loading differs from static testing primarily from the essential consideration of the phenomenon of stress wave propagation in both the test specimen and the attachments.

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In static testing, the force applied to extend the specimen is uniform throughout the entire length of the test piece. At impact velocities there is a non-uniform increase in load which is a consequence of the stress wave; i.e., the applied force on one end of the specimen is not instantly measurable from the restrained or the clamped end. Failure to consider this phenomenon can lead to the use of force gauges with inadequate frequency response characteristics.

In textile materials, this stress wave phenomenon manifests itself at impact velocities in excess of 100 feet per second. The resistance offered by the internal inertia of the specimen to an applied impact produces stress waves which are reflected from end to end until the breaking stress of the specimen is reached. The fronts of these stress waves are step functions with rise times in the order of from one to ten microseconds. Thus, a true measure of the force in a specimen at any time requires the use of a force gauge with a resonant frequency of upwards of one megacycle ($f = 1/T$). Such gauges are not currently available.

If stress waves are not considered, calculations can be made to show that a load cell with a resonant frequency in the range of 25 to 50 kilocycles might suffice. Unfortunately, such load cells cannot give the stepwise force-time behavior which actually occurs.

The reason for discussing the stress waves and load cell design is that the system of rupturing the test specimens employed was tailored to the only measuring system known to be successful in obtaining useful data. It is, in fact, the measuring system which must be considered of paramount importance since it is the source of the desired information.

2.1 The Measuring System

In view of the foregoing discussion, load cells using either strain gauges or piezoelectric transducers either directly or as accelerometers, i.e., the principle of inducing reaction forces in a secondary system, were rejected because of their inadequacy to respond to the load rise times encountered. The system which is best suited for this problem is one which measures the impact force by the deceleration of a known impacting mass by the use of a high speed photographic technique described below. Rather than use high speed motion picture cameras of up to 10,000 frames per second which are expensive and difficult to operate and process, a multimicroflash technique is used. Separate ultra-high speed flashes spaced at given time intervals "stop" the motion of the test specimen as well as the impacting mass. These "stopped" motions are caught on a large (4" x 5") photographic film as a multiple exposure.

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Edgerton, Germeshausen and Grier, Inc. of Boston, designed and built a multimicroflash unit especially for this project. This unit, plus a standard open-shutter camera, provides sufficient data for the calculation of: (a) impact force as a function of time; (b) specimen extension; (c) effective gauge length; and (d) energy to rupture.

The deceleration as measured by double differentiation of specimen displacement in the photographic record is cross checked by the use of two ballistic pendulums. The displacement of the first pendulum, which also contains the specimen holder, gives a measure of the impulse delivered to the specimen. The impulse is defined by the integral of the force-time function and is measured by the change in momentum of the pendulum. The second pendulum catches the impacting mass after it ruptures the test specimen. The motion of the second pendulum is proportional to the residual momentum of the impacting mass. From the momentum, before and after impact, the energy lost by the impacting mass is calculated and checked against the energy absorbed by the specimen calculated by the photographic method.

2.2 The Impacting System

The impacting system, as mentioned previously, consists essentially of a free moving impacting mass whose deceleration is measured. Alternative impacting devices have been considered and rejected for a variety of reasons. For example: (a) Rotating systems seem plausibly attractive since it is thereby possible to get controlled velocities. Impact machines using rotating impact heads have been used at the National Bureau of Standards and Wright Air Development Division, as well as at Fabric Research Laboratories, Inc. However, in all these cases, impact speeds are well below 750 feet per second, and impact forces well below 10,000 pounds. At high speeds and high energy requirements, a rotary system was considered impractical for two reasons: (1) the potential hazards associated with rotary inertia, particularly when unbalanced forces are applied at impact; and (2) the long time required to accelerate and decelerate the heavy flywheels. (b) Mechanical systems such as stretched springs have been ruled out because it is not possible to get the required velocities by this means directly. The reason is that the inertia of the springs themselves restricts their motion and limits the ultimate velocity obtainable. It is true that a small mass could achieve a high velocity if it is first impacted by a large slower moving mass. However, a secondary missile system of this type was not considered practical. (c) Gravity systems are naturally out of the question since the required heights are much too great and terminal velocities of much less than 750 feet per second will be reached. (d) Hydraulic systems are even less feasible than the mechanical spring system since the mass of the piston involved creates similar, if not more severe, inertial problems.

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Thus the system of the freely moving impacting mass is the only feasible approach, wherein compressed gas is used to accelerate the mass and the deceleration of the mass is the primary means of measurement. The mass and/or velocity of the missile can be varied according to the requirements of the specimen and test.

2.3 The Specimen Holders

The clamping of textile specimens in tensile testing is a notoriously difficult problem. Capstan type grips are normally used when high strength webbings are tested. In spite of the difficulties produced by such grips, such as the determination of the effective gauge length, they represent the most satisfactory clamp system known. However, the mass of the capstan grips necessary to hold webbings with 10,000 pound breaking strength is considerable. If the impacting mass which has been described in the previous section were to include the mass of a capstan grip of this type, the thrust required to reach the desired velocities would be unusually large. A "V" shaped specimen configuration has therefore been adopted where the impacting mass will strike the specimen at the apex of the "V" while the two ends of the "V" are clamped in capstan grips mounted on the first ballistic pendulum.

III. DESIGN OF THE IMPACT TEST MACHINE

Figure 1 is a schematic diagram showing the major components of the impact test machine. It consists of the following:

(1) The gas gun or the impacting mass launcher

(2) The missile or the impacting mass

(3) Ballistic pendulum No. 1 with specimen holders

(4) Ballistic pendulum No. 2

(5) Pendulum deflection indicating devices

(6) Camera and the multimicroflash light source

(7) Control panel

Figure 2 is a photograph of the entire machine. The design, function and operation of each of the above items is given below.

3.1 The Gas Gun

3.1.1 Design Requirements

Since the primary function of the gas gun is to launch the impacting mass and propel it at the desired velocity with sufficient

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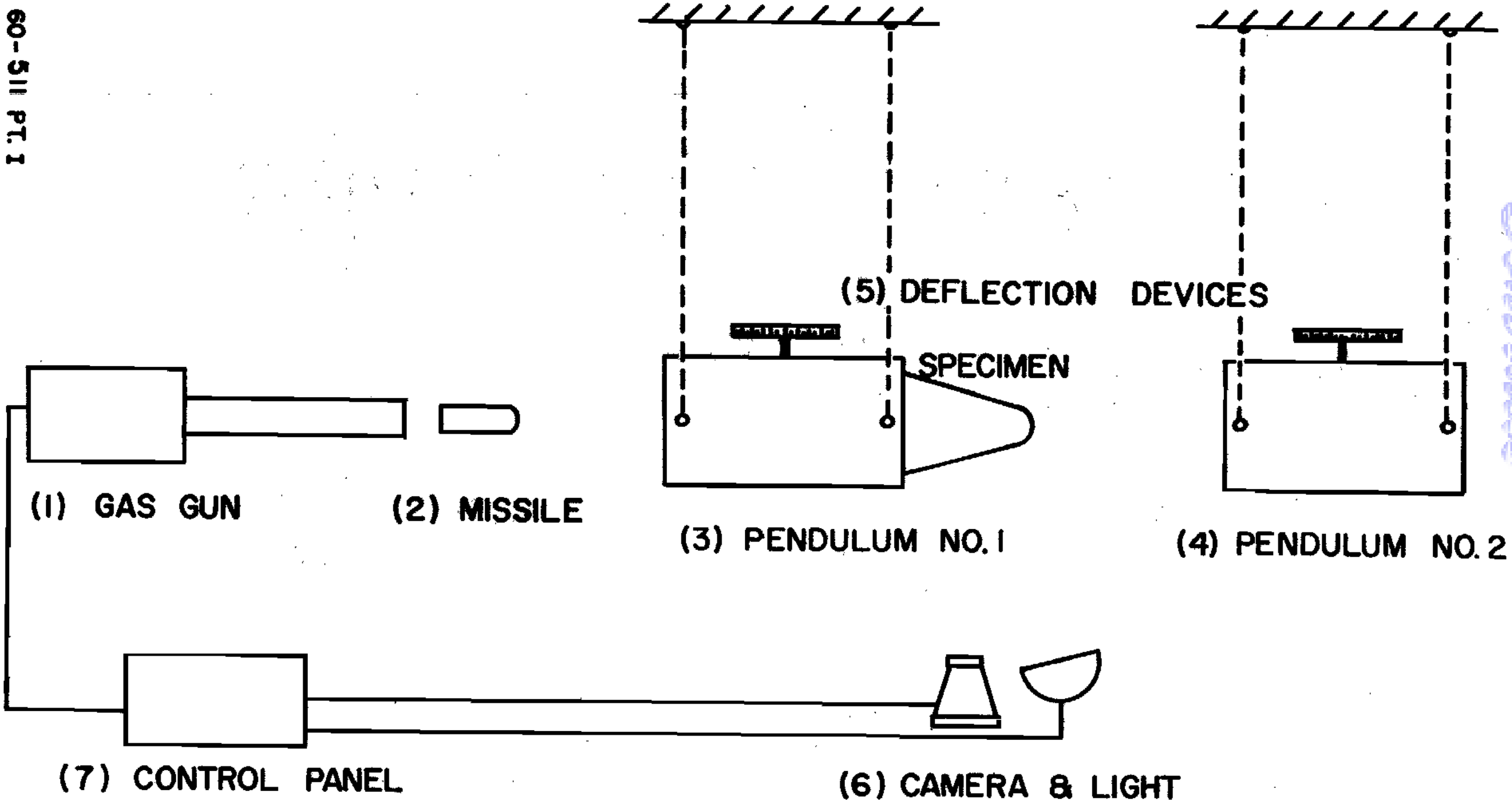

FIGURE I. SCHEMATIC DIAGRAM OF IMPACT TESTING MACHINE

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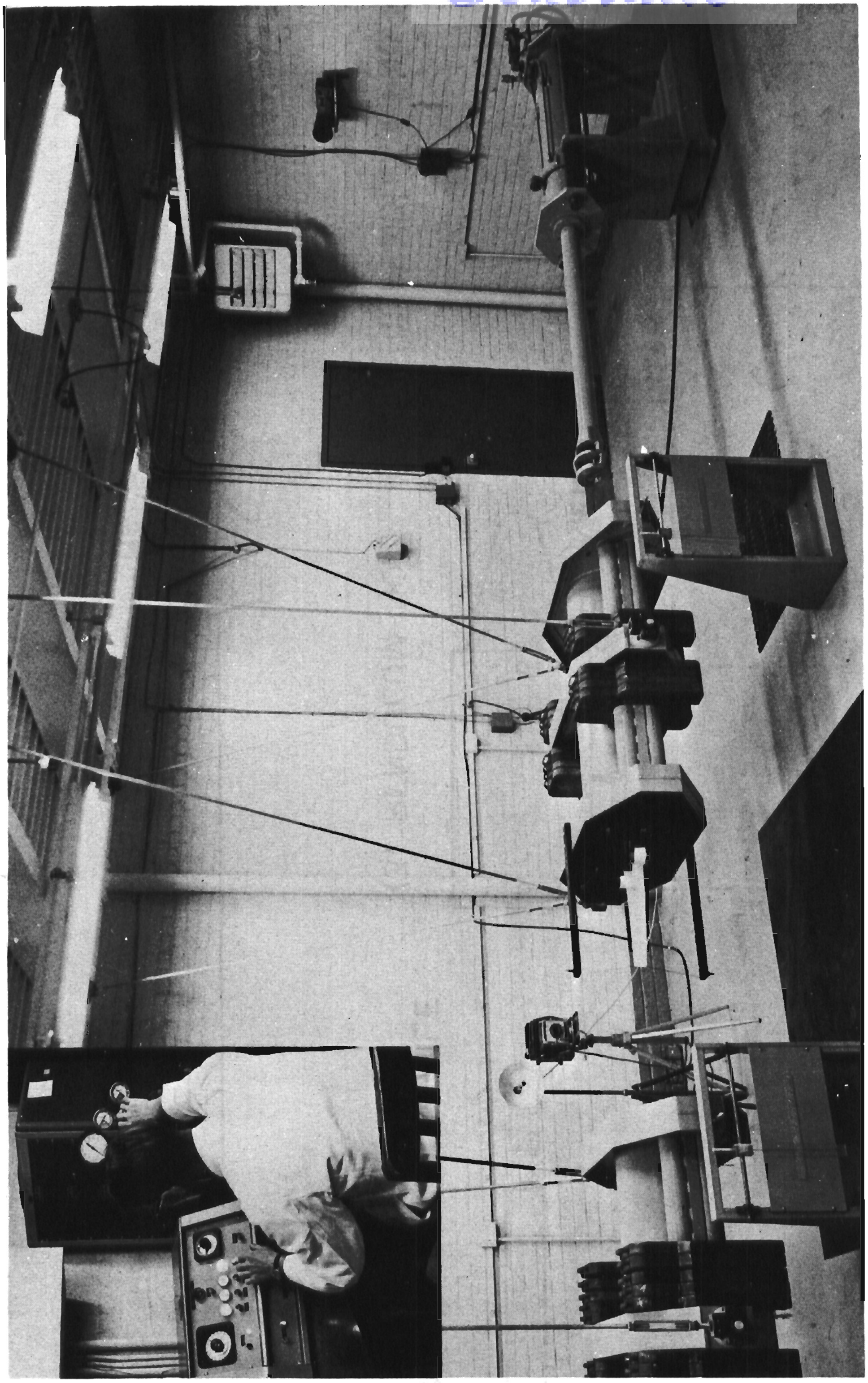

FIGURE 2. OVERALL VIEW OF IMPACT TESTING MACHINE

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energy to rupture the various specimens, the design has to be tailored to the elastic properties of the materials to be tested and their physical configurations. These are:

(1) Velocity Range - 200 to 750 feet per second

(2) Specimen Width - Up to 2 inches (webbings)

(3) Elastic Properties of Test Specimens:

  (a) Static Breaking Strength - Up to 10,000 pounds

  (b) Effective Gauge Length - Up to 48 inches

  (c) Specimen Extension - Up to 25 percent

3.1.2 Basic Computations

The kinetic energy of the impacting mass must be at least equal to the energy required to cause specimen rupture. If a linear load-elongation curve is assumed, the energy, E, is equal to one-half the product of the breaking strength and the extension; thus for a 48 inch long specimen

$$E = 1/2\ (10{,}000 \times 48 \times 0.25) = 60{,}000 \text{ inch-pounds}$$

$$E = 5{,}000 \text{ foot-pounds}$$

According to the kinetic energy equation:

$$E = 1/2\ MV^2 \qquad \text{Eq. (1)}$$

where

E = the kinetic energy in foot-pounds

M = Mass of the impacting mass in slugs

V = Velocity of the impacting mass in feet per second

Thus

$$M = 2E/V^2 = \frac{2 \times 5000}{(200)^2} = 0.25 \text{ slugs}$$

then the weight of the missile = 0.25 x 32.2 = 8 pounds.

The weight of the heaviest missile planned for this project is 10 pounds. This is 2 pounds more than the above calculations indicated; the extra weight is used for margins of safety as well as to provide sufficient residual energy left in the missile after impact for measurement purposes.

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For materials having static strengths of less than 10,000 pounds and/or tests performed at velocities greater than 200 feet per second, lighter missiles are used. However, regardless of the weight of the various missiles, they are all 2.5 inches in diameter in order to utilize a common gun barrel. The 2.5 inch diameter is dictated by the maximum specimen width of 2 inches.

The force, F, necessary to propel the missile is given by Newton's Law of Motion:

$$F = Ma \tag{2}$$

where

F = the propelling force in pounds

M = mass of the impacting mass in slugs

a = acceleration in feet per second per second

and

$$a = V/t \tag{3}$$

where

V = velocity of impact in feet per second

t = duration of applied force; i.e., the length of time the missile travelled in the barrel, seconds.

Also

$$F = PA \tag{4}$$

where

P = gas pressure in pounds per square inch

A = cross-sectional area of the barrel and of the missile in square inches

Combining Equations (2), (3), and (4):

$$PA = MV/t \tag{5}$$

Thus it can be seen that the gas pressure, P, required is inversely proportional to the duration, t. That is, with a long barrel (therefore high value of t) the working pressure could be relatively low and conversely, a short barrel requires much higher pressures. The actual

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length of the barrel, S, is five feet long; this dimension was selected for a number of practical reasons. Since the missile had to accelerate from rest to its maximum muzzle velocity, the time, t, may be taken as one and one-half times as long as if it had been travelling at constant velocity:

$$t = 1.5S/V \tag{6}$$

For the two extreme velocities of 200 and 750 feet per second:

$$t_{max} = \frac{1.5 \times 5}{200} = 37.5 \text{ milliseconds}$$

$$t_{min} = \frac{1.5 \times 5}{750} = 10.0 \text{ milliseconds}$$

Substituting these values in Equation (5), using $A = \quad (1.25)^2 = 4.91$ square inches, and the ten-pound missile travelling at 200 feet per second:

$$P = MV/At$$

$$P_1 = \frac{10 \times 200}{32.2 \times 4.91 \times 0.0375} = 337 \text{ psi}$$

The pressure required for a one-pound missile travelling at 750 feet per second:

$$P_2 = \frac{1 \times 750}{32.2 \times 4.91 \times 0.01} = 474 \text{ psi}$$

Attention is called to the fact that these are preliminary calculations with no consideration for any of the following pertinent factors:

(1) Frictional force between the missile and the barrel.

(2) Inability to discharge the gas into the barrel in zero time.

(3) Discharge coefficient of the gas entering the barrel from the source.

(4) Nature of the gas.

However, these factors notwithstanding, according to the calibration curve for the one-pound missile using helium gas (Figure 3), the pressure used was 550 psi in order to attain a velocity of 750 feet per second.

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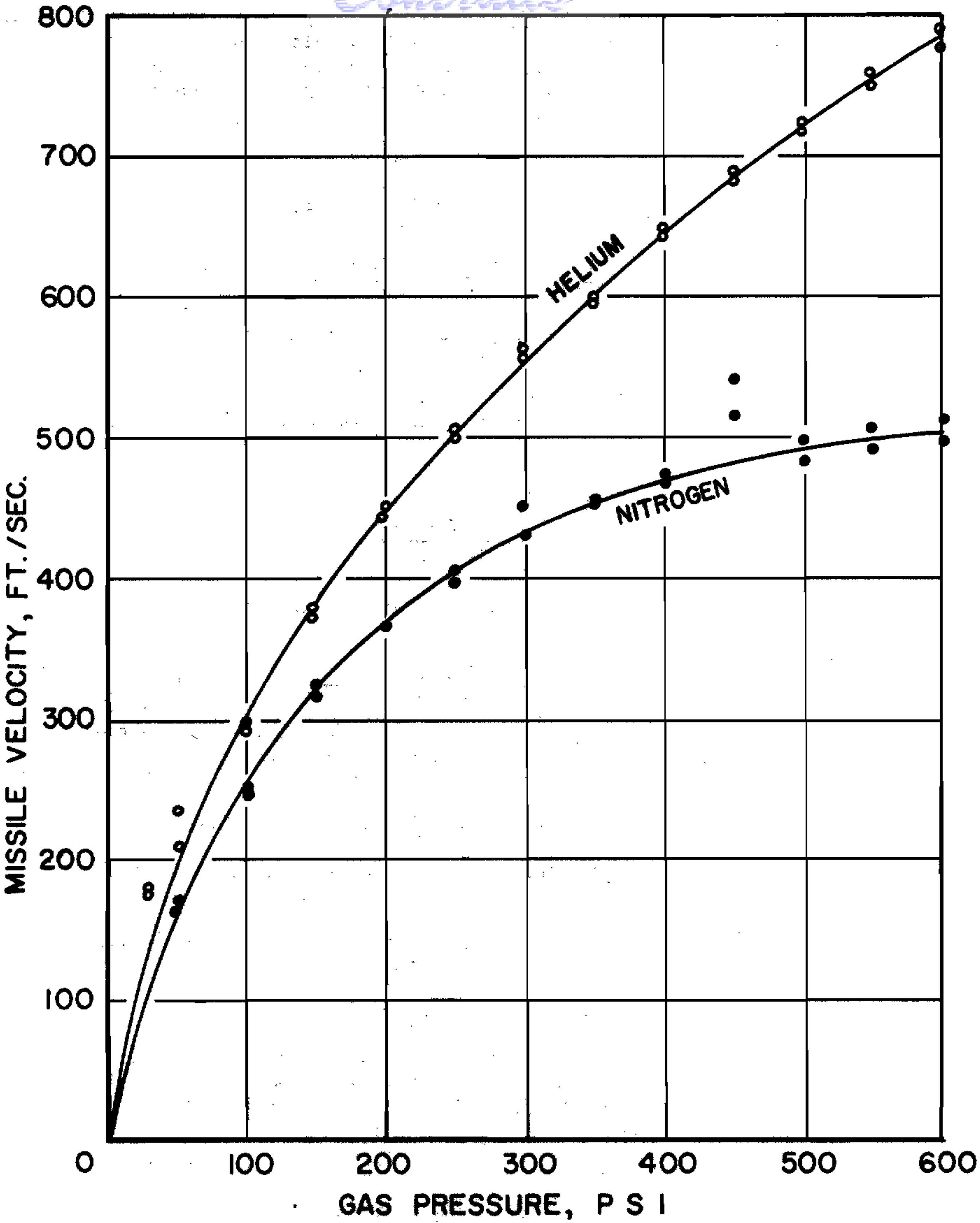

FIGURE 3. VELOCITY CALIBRATION CURVES OF THE 16-OUNCE MISSILE

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According to Equations (5) and (6), the velocity of the missile may be written as:

$$V = \frac{1.5\ PAS}{M}$$

Hence for the one-pound missile fired from a five-foot barrel with a bore of 2.5 inches, the velocity is:

$$V = 1.5 \times 4.91 \times 5 \times 32.2\ P = 34.4 \sqrt{P} \qquad (7)$$

Equation (7) implies that the impact velocity is proportional to the square root of the gas pressure; this is true only within certain limits. The geometry of the nozzle between the gas source and the barrel creates a choking effect when the pressure reaches a certain level. The limit velocity for nitrogen gas was found to be approximately 500 feet per second while the limit for helium is considerably in excess of 800 feet per second.

Based on empirical data, the velocity of the one pound missile may be approximately expressed as follows: (subject of course, to the limits mentioned earlier).

$$\text{For Nitrogen} \quad V = 23.8 \sqrt{P} \qquad (8)$$

$$\text{For Helium} \quad V = 31.6 \sqrt{P} \qquad (9)$$

where

V is in feet per second

and

P is in pounds per square inch

3.1.3 Working Principles*

Figure 4 is a schematic diagram of the gas gun which functions as follows:

(1) Gas at a predetermined pressure enters feed hose G through solenoid operated valve F (normally closed) and check valves X and Y to fill the three different compartments, C, A and R of the gun.

(2) Piston P and the valve needle N which are mounted on a common shaft keep the gas in the receiving chamber R from escaping into the barrel B.

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*The gas gun was designed by United Engineers, Inc. of Boston, Massachusetts in collaboration with FRL.

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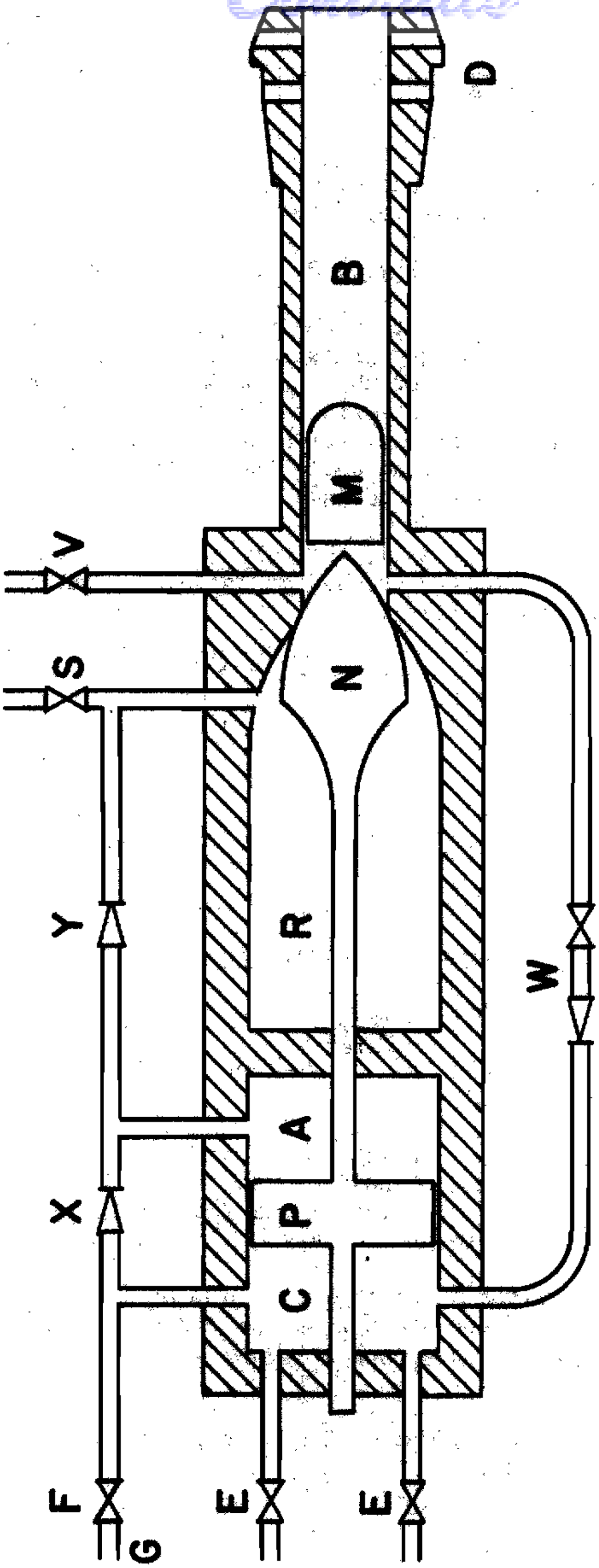

FIGURE 4. SCHEMATIC DIAGRAM OF GAS GUN

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(3) Vent valve V is solenoid operated and is normally open to allow any leaking gas to escape without the danger of accidentally firing the missile M and is closed when the gun is fired. The safety valve S prevents overcharging.

(4) When the gun is ready to be fired, either one or both of the solenoid operated exhaust valves E are opened, allowing gas in chamber C to escape. When this occurs, the pressure in chamber A is greater than the pressure in chamber C creating a pressure differential on the two surfaces of piston P which moves the piston toward the left and simultaneously withdraws the needle N from its seat.

(5) The gas in the receiving chamber R now rushes through the opening between the needle N and its seat thus forcing the missile M down the barrel B.

(6) Part of this escaping gas is piped through a flow and check valve W to chamber C to rebuild its lost pressure thereby cushioning the piston P and preventing it from slamming against the end of the chamber.

(7) The gas, both in front and behind the missile M is permitted to diffuse through the openings in the diffuser D to minimize the effect of the gas blast which may introduce erroneous readings on the pendulums.

3.1.4 Dimensions and Capacities

The gun is approximately ten feet long with a bore of 2.5 inches and a barrel length of five feet. Both the gas receiving chamber and the barrel were designed for a maximum working pressure of 5000 lbs. per square inch* with a factor of safety of five.

The volume of the gas receiver, (Chamber R, Figure 4) is approximately 600 cubic inches which is adequate to propel missiles of up to ten pounds in weight at velocities up to 800 feet per second using gas pressures of well below 1000 lbs/sq.in.

All rigid mechanical tubings and armored flexible hosings were designed to work at a maximum safe pressure of 4500 lbs/sq.in. However, all the valves used on the gun are only good for 1500 lbs/sq.in. This was largely due to the availability of the valves at the time of fabrication and the lack of needs to go to higher pressure.

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*Based on the Lame equations, pp. 5-65, Marks' Mechanical Engineers' Handbook, edited by Theodore Baumeister. Sixth Edition, McGraw-Hill Book Co., Inc. N.Y. 1958.

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3.2 The Missile

3.2.1 Mass of the Missile

Calculations for the mass of the missile have been presented in Section 3.1.2 for the extreme case; i.e., lowest velocity and strongest material. Missiles with smaller masses are required for other test conditions. However, it is not necessary to have a special missile for each combination of strength and velocity. Judicious selection of free gauge lengths will readily permit the use of four missile masses to accommodate all test variations. The four sizes are:

The A missile - 8 ounces
The B missile - 16 ounces
The C missile - 40 ounces
The D missile - 10 pounds

The kinetic energies, in foot-pounds, of each of these missiles at various impact velocities are:

	A	B	C	D
at 200 ft/sec.	311	621	1553	6211
at 300 ft/sec.	699	1398	3494	13975
at 400 ft/sec.	1242	2484	6211	24845
at 500 ft/sec.	1941	2882	9705	38820
at 600 ft/sec.	2975	5590	13975	55901
at 750 ft/sec.	4367	8735	21836	87345

Thus, for a given specimen, if the static strength, elongation, free gauge length, impact velocity, and the desired residual energy are known, it is very easy to select the suitable missile to perform the test. Typical of these are tabulated below:

Impact Velocity feet/second	Static Strength of Specimens, lbs.			
	1000	2500	5000	10000
200	B	C	D	D
300	A	B	C	D
400	A	B	C	C
500	A	A	B	C
600	*	A	B	B
750	*	A	A	B

3.2.2 Configuration of the Missile

The missile is cylindrical in shape with the nose machined in the form of a half cylinder whose axis is perpendicular to the axis of the missile. Upon impact, the cylindrical shaped nose fits into the curved portion of the "V" shaped specimen.

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*The "A" missile is too heavy for this application; a commercial tennis ball may be used instead.

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Each missile consists of four parts which are:

(1) The nose or the impacting surface which is machined from linen-inserted phenolic plastic selected for its superior impact properties.

(2) The body of the missile is a length of cylindrical material whose function is to provide mass. It can be solid or tubular and may be made of either metal or plastic, depending on the mass required.

(3) The sabot or tail piece which is again made of linen-inserted plastic.

(4) Teflon seal/bearings in the form of two "O"-rings are used between each of the three pieces mentioned above. These rings provide low-friction bearing surfaces for the missile to slide on and also seal against gas leakage.

Figure 5 is a photograph of a typical missile, the one pound "B" missile which is completely made of plastic and is approximately six inches in over-all length.

3.3 The Ballistic Pendulum

3.3.1 Function

The first ballistic pendulum is used primarily as a low frequency specimen mounting device. Additionally, if the mass were known and its displacement after impact were measured, the velocity and the energy of the missile can be calculated according to the equation of momentum transfer:

$$M_1 V_1 = (M_1 + M_2) V_2 \tag{10}$$

where

M_1 = mass of the missile

M_2 = mass of the first pendulum

V_1 = velocity of the missile

V_2 = velocity of the pendulum after impact

and the V_2 can be expressed as

$$V = dx/dt = 2\pi/T \left(D \cos 2\pi t/T \right) \tag{11}$$

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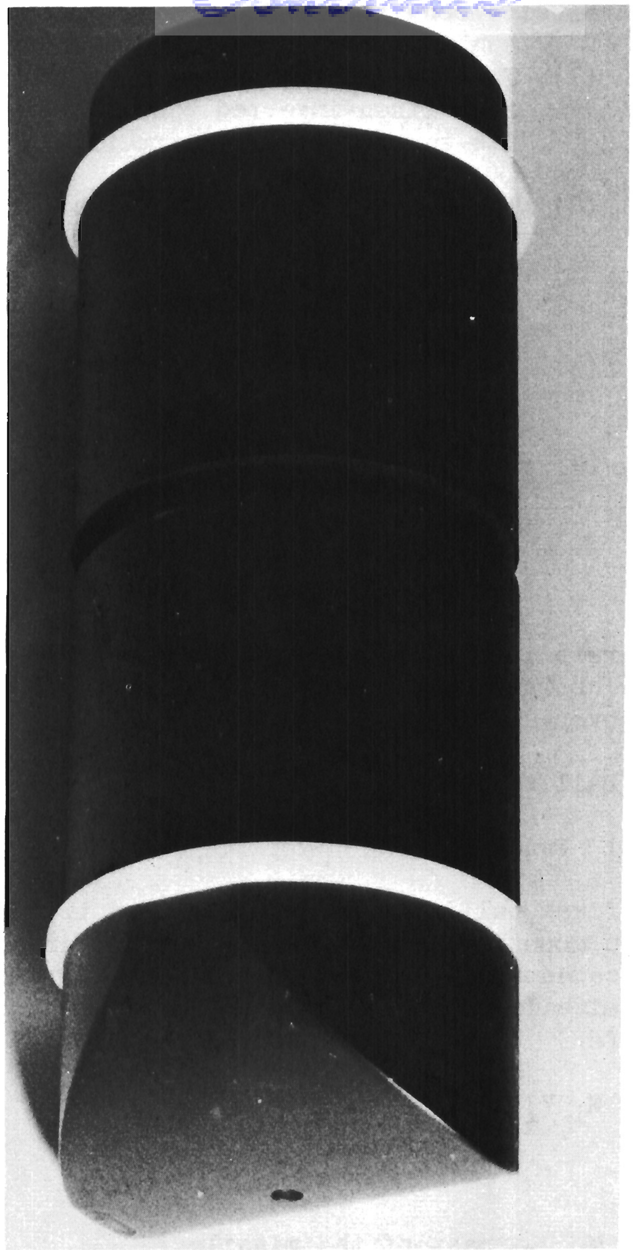

FIGURE 5. THE 16-OUNCE MISSILE

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where

dx/dt = horizontal velocity of the pendulum

D = displacement of the pendulum

E = period of the pendulum

t = time after impact

However, at the moment of impact, $t = o$

Hence $\cos 2\pi \; t/T = 1$

then

$$V_2 = 2\pi \; D/T \tag{12}$$

Combining Equations (10) and (12)

$$V_1 = 2\pi \; D \, (M_1 + M_2)/T \, M_1 \tag{13}$$

and according to Equation (1):

$$E = 1/2 \, M \, V_1^2$$

$$E = \frac{2 \, (\pi)^2 \, D^2 \, (M_1 + M_2)^2}{T^2 \, M_1} \tag{14}$$

Since the velocity of the pendulum, ds/dt, is assumed to be horizontal, the displacement must be small (say six inches or less) such that vertical components be kept near zero. To achieve this condition, the length of the pendulum should be as long as the height of the ceiling will permit as the mass, M_2, should be increased whenever the velocity V_1, is increased.

The second pendulum also serves a dual purpose. It is first a means for measuring, by its displacement, the velocity and the residual energy in the missile after rupturing the test specimen. And secondly, it is a low frequency shock mount for stopping and containing the missile after each test. Here again the mass is variable depending on the mass and the velocity of the missile.

3.3.2 Configuration of the Pendulum

Referring back to Figure 2, it is seen that the pendulums are fabricated from welded aluminum components. In the center is the body of the pendulum made of a length of 12" pipe through which the missile passes. On either side are two rails on which cast iron augmenting

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weights may be added to increase the mass of the pendulum. The augmenting weights are so designed as to maintain the center of percussion of the pendulum regardless of the number of weights added. Spaced evenly are three bulkheads whose purpose is to provide support for the aforementioned rails and attachments for the pendulum suspension system.

3.4 Photographic System

The equipment used to record the impact data consists chiefly of the Multiflash light source and a 4 x 5 view camera.

3.4.1 Multiflash Unit

The Multiflash Unit makes used of fifteen separate energy storing circuits (discharge units) and produces fifteen pulses of light, each with a duration of about one microsecond, an energy per flash of 1.5 watt-seconds, and a time interval variable from 10 microseconds to 10 milliseconds between flashes.

The system consists of the following basic units: a Power Supply, an Audio Oscillator, a Pulse Shaper Unit, a Junction Unit, fifteen Discharge Units, and a Flashtube and Reflector Assembly. All of the above equipment, with the exception of the flash tube assembly, is contained in one relay rack in which both front and rear panel space is utilized for the equipment mounting. The flashtube is remotely mounted on its own portable tripod. A photograph of the unit is shown in Figure 6.

3.4.1.1 Theory of Operation of Multiflash Unit*

The basic components in the discharge units are two thyratron tubes, a mercury tube, and a .03 mfd. 10-kv. capacitor. When all power switches to the rack have been turned on, the .03 condensers in the fifteen units become charge to 10 kv.

To set the time interval between light flashes, (that is, the rate at which the discharge units will be triggered), it is necessary to adjust the audio oscillator to the desired frequency. Since time is equal to one over the frequency ($t = 1/f$), the interval can be set between 100 cycles (10 milliseconds) and 100,000 cycles (10 microseconds).

The sine wave output of the audio oscillator is fed to the Pulse Shaper Unit, where it emerges as sharp rising timing spikes. These spikes are fed to the grid of a 5696 thyratron tube in each of the fifteen discharge units. The 5696's are so biased that these sharp pulses will not be of sufficient amplitude to trigger the thyratrons into conduction.

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*Taken in part from Instruction and Maintenance Manual for Multi-Micro-Flash - Edgerton, Germeshausen, and Grier, Inc.

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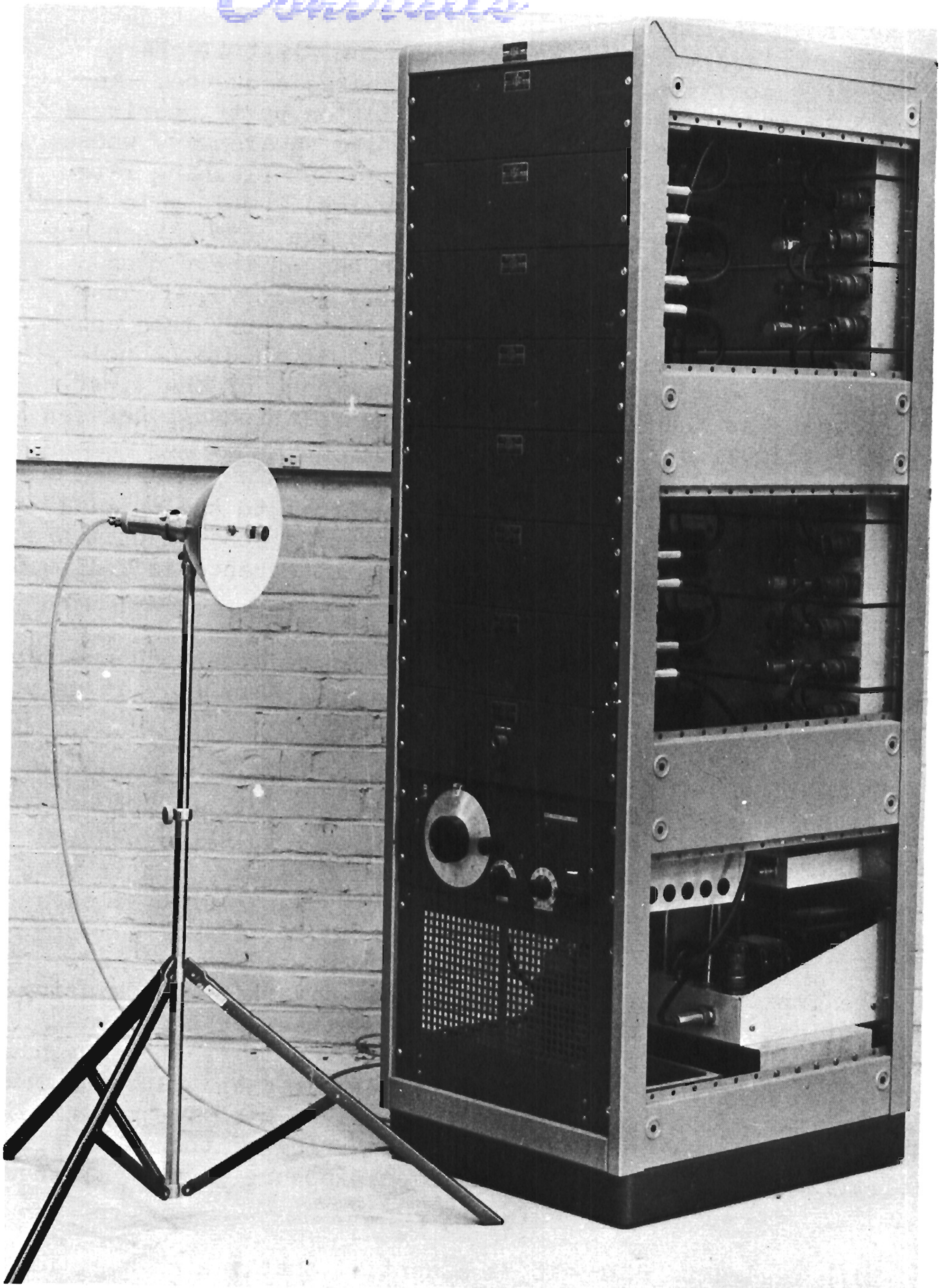

FIGURE 6. THE MULTI-MICROFLASH WITH SIDES REMOVED

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As shown in the block diagram of Figure 7, a gating pulse must be provided to drive the grid of the first discharge unit sufficiently positive to start the discharge sequence. An external or internal trigger initiates the action by triggering a gate tube. This gate tube generates a positive square wave whose minimum duration is at least as long as the lowest flashing rate used; in this case, 10 milliseconds (100 cycles). This gate is fed to the grid of the 5696 in the first discharge unit. When any portion of the gate pulse is coincident with one of the timing signal pulses, it drives the grid sufficiently positive to cause plate conduction of the 5696 and to trigger the mercury tube and discharge the first unit into the flash tube. It should be noted that the time between triggering and the occurrence of the first flash is variable, as there is no direct time relationship between the initiating trigger and the timing pulses.

Circuitwise, the 5696 stage is identical to the initial gate tube, so it becomes the gate for the second discharge unit and is coincident with the next timing pulse. This sequence is followed until all fifteen units are discharged.

Since the thyratrons are self-recovering, the sequence may be repeated again almost immediately. It is necessary to wait only until the .03 capacitors are again fully charged.

3.4.2 Camera

The camera used in conjunction with the Multiflash Unit need be of the simplest design. The only basic requirement is that the camera lens be of sufficiently good quality in order to insure getting a properly exposed and focused negative.

The impact photographs are taken in a darkened room using only the light emitted by the Multiflash Flashtube. The camera shutter is used on its "Time" setting which means it is opened manually a few seconds before the Multiflash is triggered and closed a few seconds after the test is completed. There is no need for synchronizing the opening of the shutter with the triggering of the light since very little film "fogging" occurs from over-exposure in the darkened room.

With regard to film, it is essential that a high-emulsion speed film be used with the Multiflash. The duration of the light (1 microsecond) and its resulting intensity are such that maximum film speed is essential. Films which have been used in increasing order of satisfaction include Eastman Kodak Tri-X, Superpanchro Press-Type B, Royal Pan and Royal-X-Pan. Also investigated were Ansco's Hypan and Super Hypan. Kodak's Royal-X-Pan has proven most satisfactory for the impact work because of its combination of high emulsion speed and moderate "grain" level.

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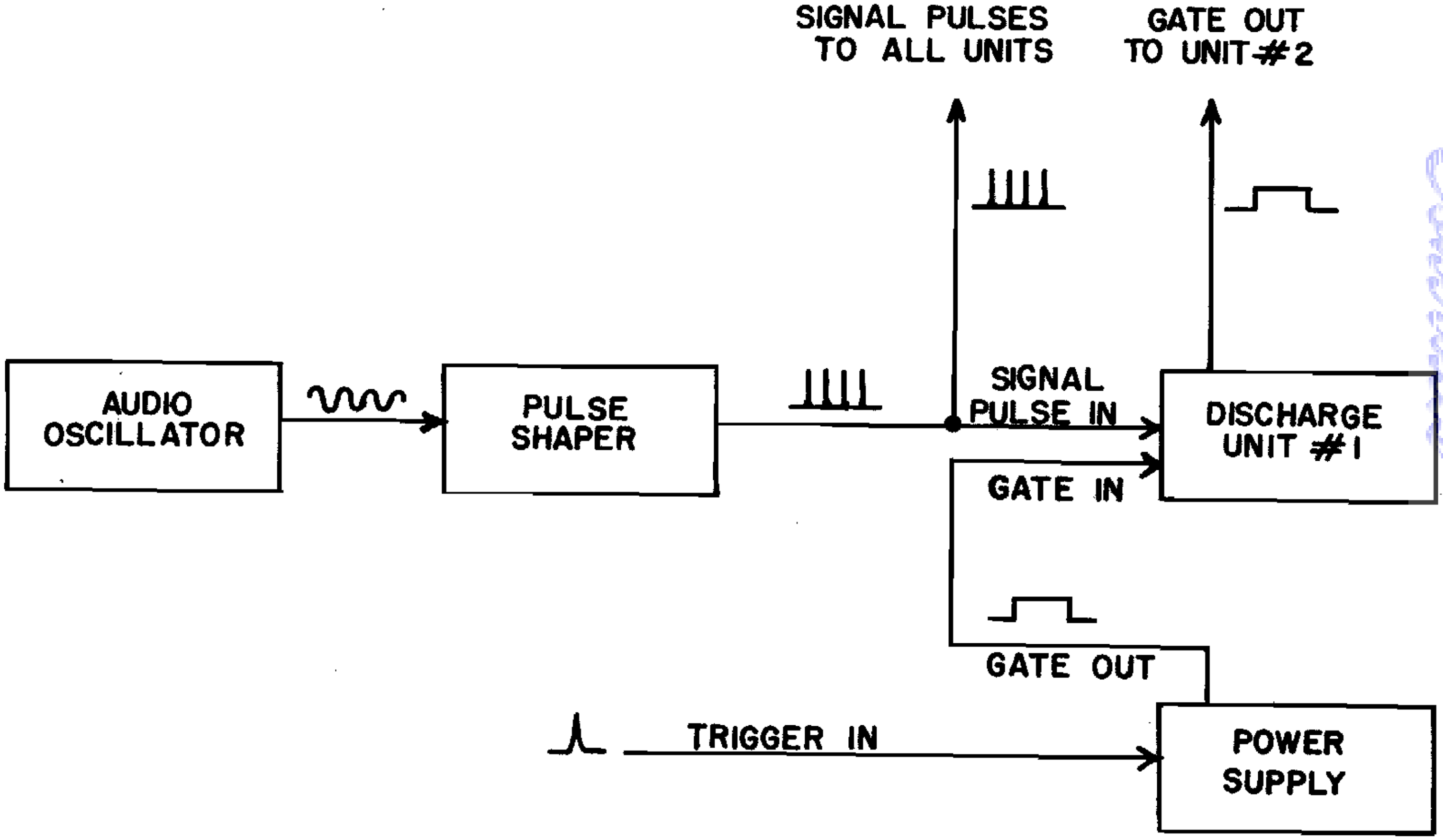

FIGURE 7. BLOCK DIAGRAM OF MULTI-MICROFLASH TRIGGERING CIRCUIT

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For preliminary studies, where observation without detailed measurement is desired, the new Polaroid 3000 Film can be successfully employed provided the Polaroid camera chosen has a relatively good lens system. (A Polaroid back was added to the 4 x 5 Linhof view camera normally used at Fabric Research Laboratories, Inc. in order to make some preliminary missile positioning and velocity checks).

IV. CALCULATIONS AND DATA ANALYSIS

As mentioned earlier, the uniqueness of the present impacting system is primarily in the use of photographic techniques for compilation of data. From the photograph of the specimen during impact it is possible to measure and calculate the following parameters:

a. Force to rupture the specimen
b. Specimen extension at rupture
c. Force-extension diagram
d. Force and/or extension time curve
e. Work to cause rupture

It is also possible to measure missile velocity before, during, and after impact as well as to measure the effective gauge length of the specimen involved in any given test. A detailed description of the various techniques employed to determine the aforementioned variables follows below.

4.1 Force to Rupture the Specimen

The most common way of measuring the tensile force imposed on a textile material loaded longitudinally on a tensile testing machine is with an electronic strain gauge system. Unfortunately, when a material is strained at a high rate the conventional strain gauge set-up is unable to respond, i.e., the rate of loading is so rapid that the specimen rupture load builds up more rapidly than can be detected by the gauge. Hence, the need for a more sensitive system.

In the current program the photographic technique was decided upon for several reasons. In the first place, as mentioned above, there is considerable danger in selecting a mechanical or electrical strain gauge system which may be only partly responsive. Electronic devices, such as accelerometers, could be used. However, the frequency response of such systems can cause trouble due to the large masses of the sample grips. Another reason for using the photographic method is that it supplies other useful information on the behavior of the specimen before, during, and after loading. The multiple-exposure film gives a permanent record of each test.

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The measurement of rupture force is accomplished by measuring the deceleration of the missile as it ruptures the specimen. It is known that:

$$F = m\,a$$

where

F = rupture force

m = mass of projectile

a = deceleration of projectile

The spacing between successive exposures of the missile as it impacts the specimen can be accurately measured on the enlarged photographic print. The time between light flashes is controlled by the multiflash unit. Knowing these distances and times it is possible to calculate the missile velocity at any given instant. The velocity change indicates deceleration. The mass of the projectile times the deceleration is the force supplied by the test sample acting on the projectile.

A means of checking the rupture force calculated above is through the displacement of the two pendulums. From conservation of momentum it is known that:

$$M_1 V_1 \text{ (Missile)} = M_2 V_2 \text{ (Pendulum)}$$

where

M_1 = missile mass

V_1 = missile velocity

M_2 = pendulum mass

V_2 = pendulum velocity

So that from the difference in momentum transferred to each pendulum it is possible to calculate the energy taken away from the missile or absorbed by the specimen knowing the energy absorbed and the rupture strain (next to be calculated). The rupture force can be calculated (assuming a linear stress-strain curve) from the expression:

$$E' = 1/2\, F \times \epsilon$$

where

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E' = energy to rupture

F = rupture force

ϵ = rupture extension

4.2 Rupture Extension

The rupture extension is measured directly from the photograph of the specimen during impact. Initially two gage marks are placed at a known interval on that leg of the sample which faces the camera. As the sample is strained during impact the distance between the gage marks increases on successive exposures by the Multiflash. The extension at rupture as well as at various times prior to rupture can thereby be measured.

4.3 Force-Extension Diagram

From the individual values of missile deceleration during impact and the corresponding strain readings it is possible to plot a force-extension diagram.

4.4 Force and/or Extension-Time Diagram

Since the time between successive exposures can be accurately determined from the Multiflash, the force and/or Extension-Time relationship can be readily determined.

4.5 Work to Cause Rupture on Impact

Having the impact stress-strain curve determined from 4.3 above, it is a relatively simple operation to determine the area under the curve which gives the work or the energy absorbed by the specimen during impact.

4.6 Sample Calculations of Webbing Breaks

A typical calculation of an impact test is included as an example of the data which can be obtained. The test is number 141. A photograph of the impact is shown in figure 8. The test conditions are as follows:

Sample: MIL-T-5608, Class E, Type II Tape
Gas and Pressure: Nitrogen at 70 psi
Multiflash Frequency: 2000 cycles per second

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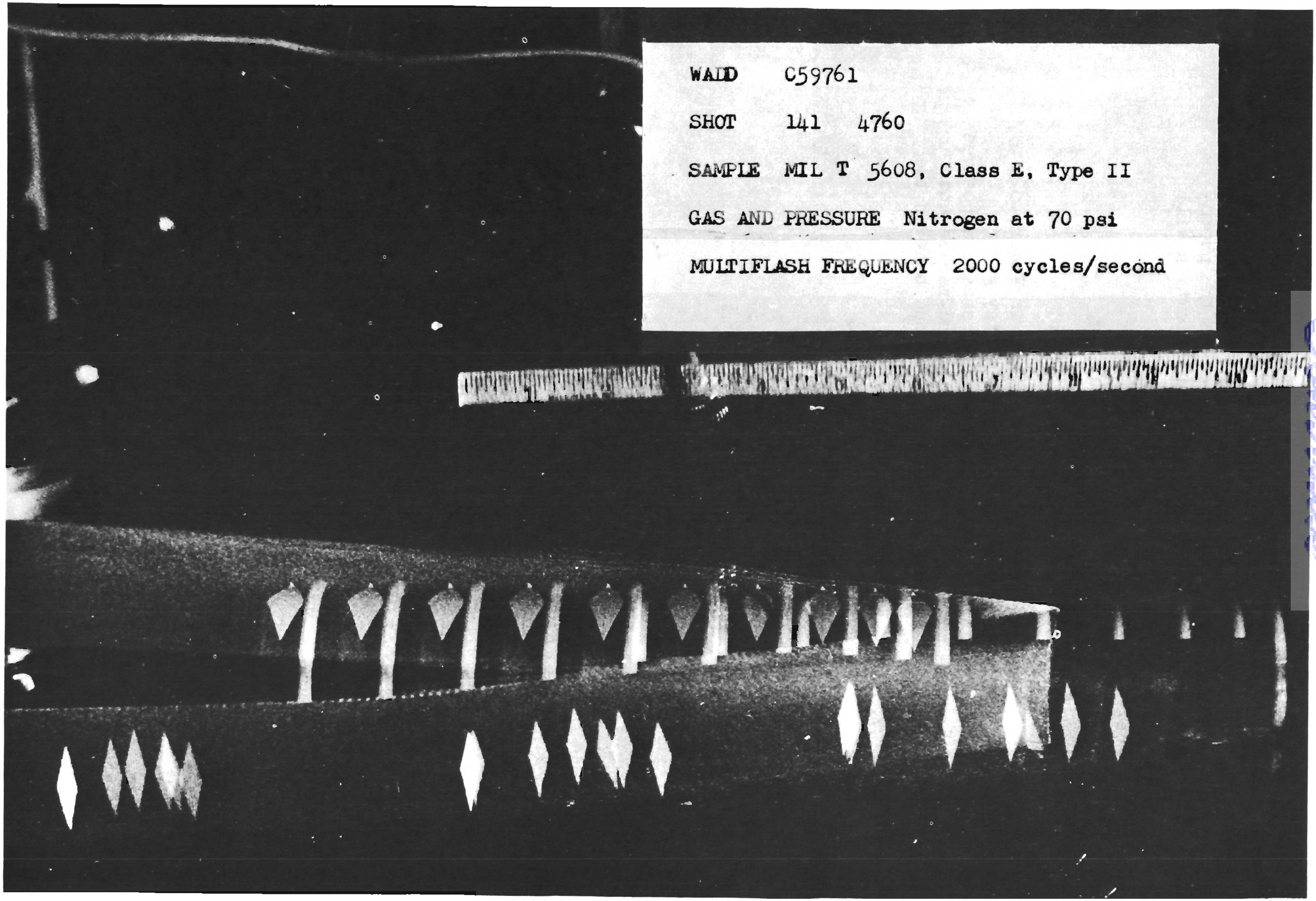

WADD C59761

SHOT 141 4760

SAMPLE MIL T 5608, Class E, Type II

GAS AND PRESSURE Nitrogen at 70 psi

MULTIFLASH FREQUENCY 2000 cycles/second

FIGURE 8. PHOTOGRAPH OF SHOT NO. 141

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4.6.1 Magnification Factor

In order to convert measurements made on the photograph to true distance, it is necessary to first calculate a "magnification factor". This is done by measuring a known distance on the photograph, e.g., 10 inches on the ruler shown. The magnification will be:

$$M.F. = L/10 = 5.54/10 = 0.554$$

4.6.2 Missile Velocity

A schematic representation of the photograph in Figure 8 is shown in Figure 9. The velocity of the missile at any given time is obtained by measuring the distance between successive exposures of a designated part of the missile, namely, the diamond-marked end (X_{1-2}, X_{2-3}, X^{3-4} etc.). The velocity in feet per second between the first and second exposures is given by

$$V = \frac{X_{1-2}}{12} \times \frac{\text{multiflash frequency}}{\text{magnification factor}}$$

$$V = \frac{0.58}{12} \times \frac{2000}{0.554} = 174 \text{ ft/sec.}$$

4.6.3 Missile Deceleration

The missile deceleration, a, is defined as the change in velocity between successive exposures:

$$a = (V_{1-2}) - (V_{2-3}) \text{ in feet per second per cycle}$$

Example:

$$a_{4-6} = (V_{4-5}) - (V_{5-6}) = 174 - 168 = 6 \text{ ft/sec/cycle}$$

4.6.4 Rupture Force

The rupture force as calculated from the missile deceleration between exposures 9 and 10, is (See Table 1).

$$F = 1/32.2 \times 36 \times 2000 = 2236 \text{ lbs.}$$

This value is twice the actual force since two legs of the specimen are being tensioned. The true rupture force is, therefore, 1118 pounds at a striking velocity of 174 feet/second. A listing of all data obtained from this test is included in Table 1.

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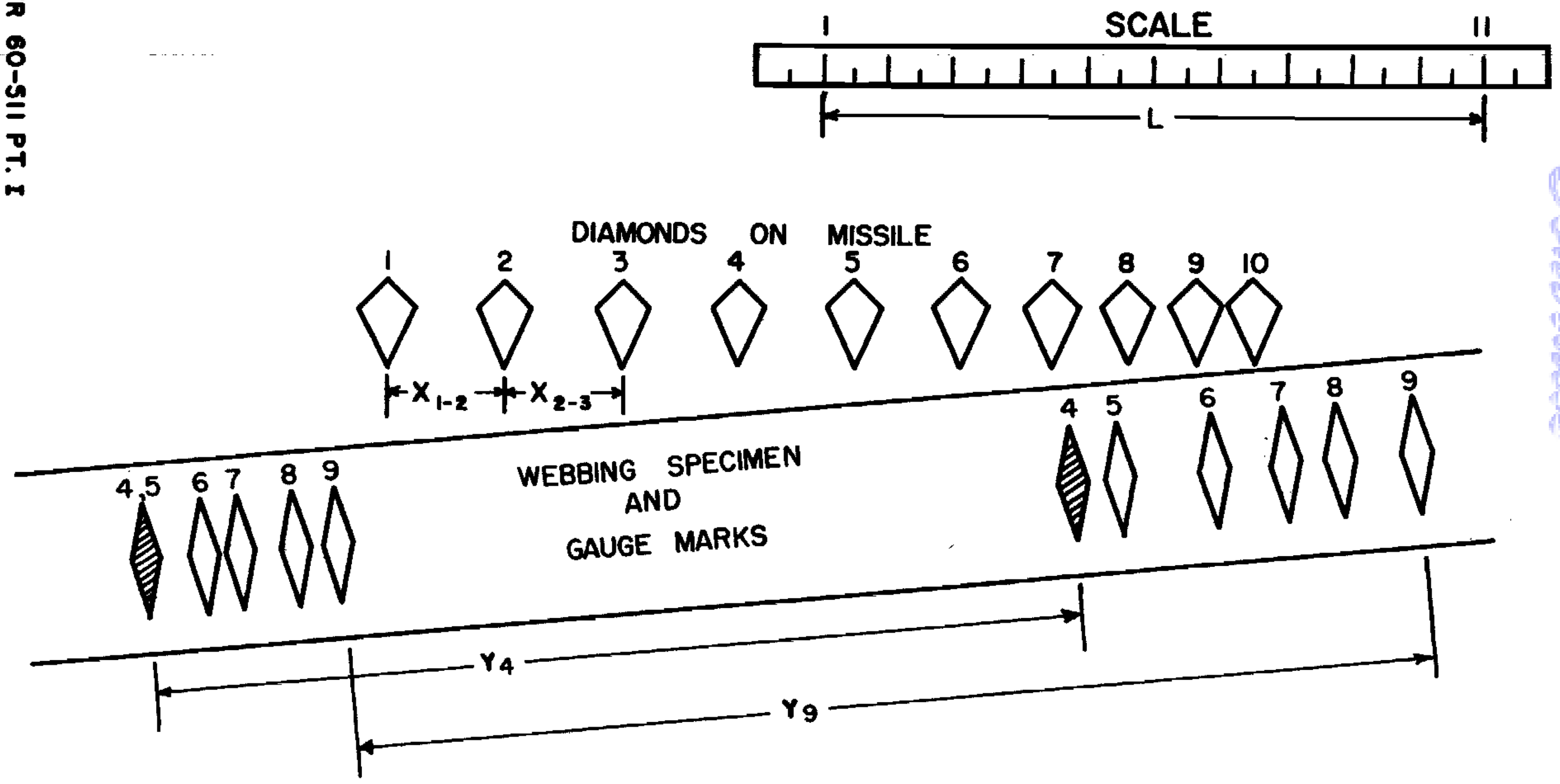

FIGURE 9. SCHEMATIC DIAGRAM OF SHOT NO. 141

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TABLE 1

IMPACT DATA OF MIL-T-5608 CLASS E TYPE II Tape

Exposure Number	Missile Travel, "X", in.	Missile Velocity (v", f.p.s.)	Deceleration (v_{1-2} v_{2-3}), f.p.s./cycle	Force lbs.	Time After Initial Impact (millisecs.)	Sample Gage Length "y", in.	Extension (y_2- y_1) in.	Elongation (%)
1	0.58	174	---	---	0	5.60	0	0
2	0.58	174	0	0	0	5.60	0	0
3	0.58	174	0	0	0	5.60	0	0
4	0.58	174	0	0	0	5.60	0	0
5	0.58	174	6	373	0.5	5.76	0.16	2.9
6	0.56	168	9	559	1.0	5.96	0.36	6.4
7	0.53	159	18	1118	1.5	6.22	0.62	11.1
8	0.47	141	24	1491	2.0	6.42	0.82	14.6
9	0.39	117	36	2236	2.5	6.58	0.98	17.5
10	0.27	81	--	----	---	----	----	----

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4.6.5 Rupture Extension

The rupture extension of this tape. as measured from the difference in gauge marks at rupture (Exposure 9) and the initial mark spacing on the photograph of the tape prior to impact is:

$$E_{rupture} = \frac{6.58 - 5.60}{5.60} \times 100 = 17.5\%$$

4.6.6 Force-Extension Diagram

Plotting the individual force and extension values calculated from successive multiflash exposures gives the curve shown in Figure 10. Also included in this figure is a typical load-extension curve for this material tested statically at 0.5 inches per minute on an Instron Tensile Tester.

4.6.7 Force and/or Extension Time Diagram

The buildup of force or extension with time can be plotted, knowing the time between multiflash exposures. This time is accurately controlled by the built-in oscillator and can be pre-set to any given value between 10 milliseconds and 10 microseconds. In the particular example being cited the time between flashes was 0.5 milliseconds so that each particular load or extension measurement was made .5 milliseconds after the previous one. The diagrams are shown in Figures 11 and 12.

4.6.8 Work to Cause Rupture

The work to cause rupture (energy absorbed by the specimen) may be determined either by planimetering the area under the impact stress-strain curve or from the velocity lost by the missile. In this second case, solving the expression:

$$E = 1/2\, m\, (V_1^{\,2} - V_2^{\,2})$$

gives energy absorbed.

Example:

$$E = 1/2\ 1/32.2\ (174^2 - 81^2) = 23750/64.4 = 369 \text{ foot pounds}$$

$$E = 369 \times 12 = 4420 \text{ inch pounds}$$

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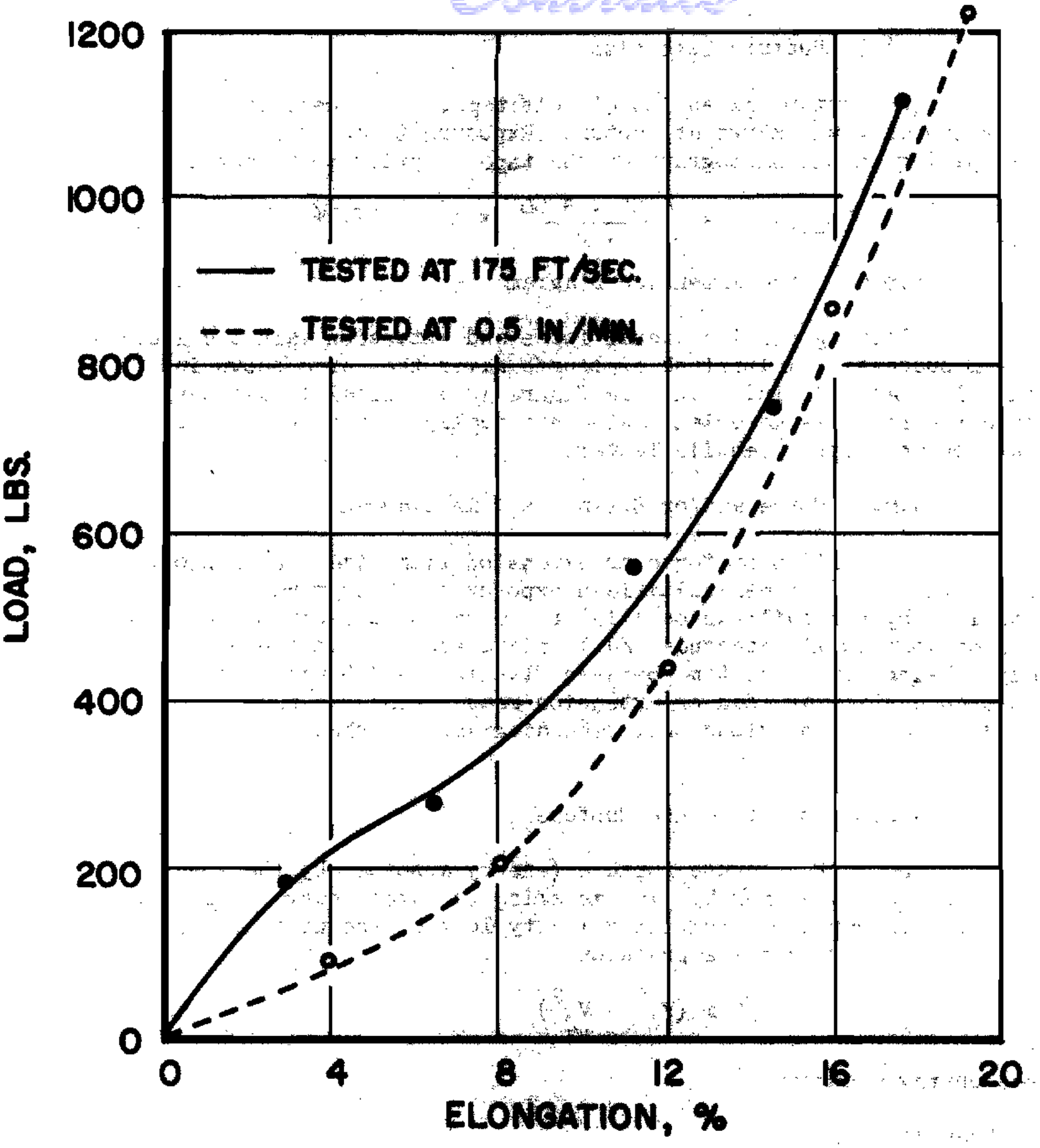

FIGURE 10. LOAD-ELONGATION CURVES OF MIL-T-5608 CLASS E TYPE II TAPE

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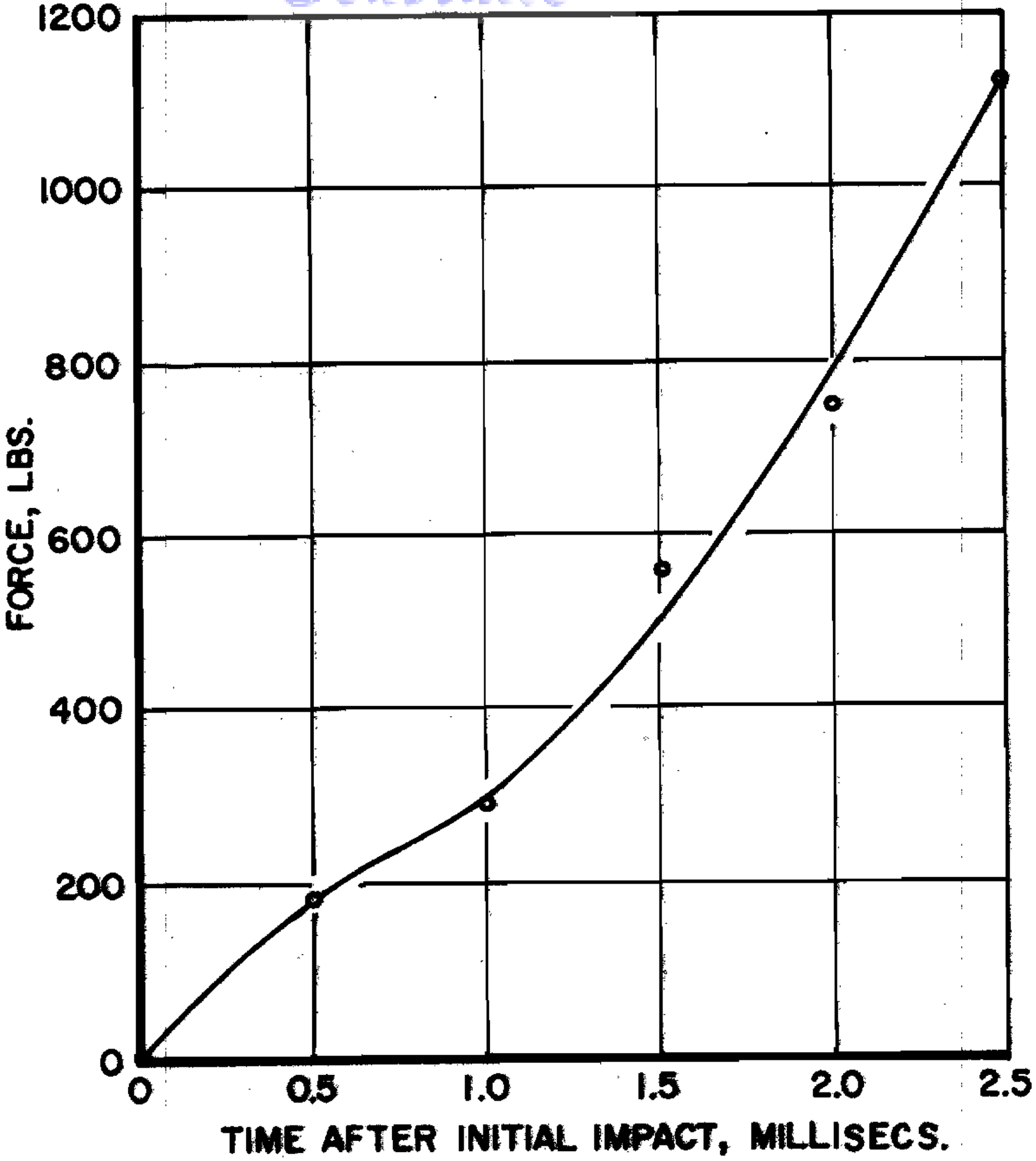

FIGURE 11. FORCE-TIME DIAGRAM FOR MIL-T-5608 CLASS E TYPE II TAPE IMPACTED AT 174 FT/SEC.

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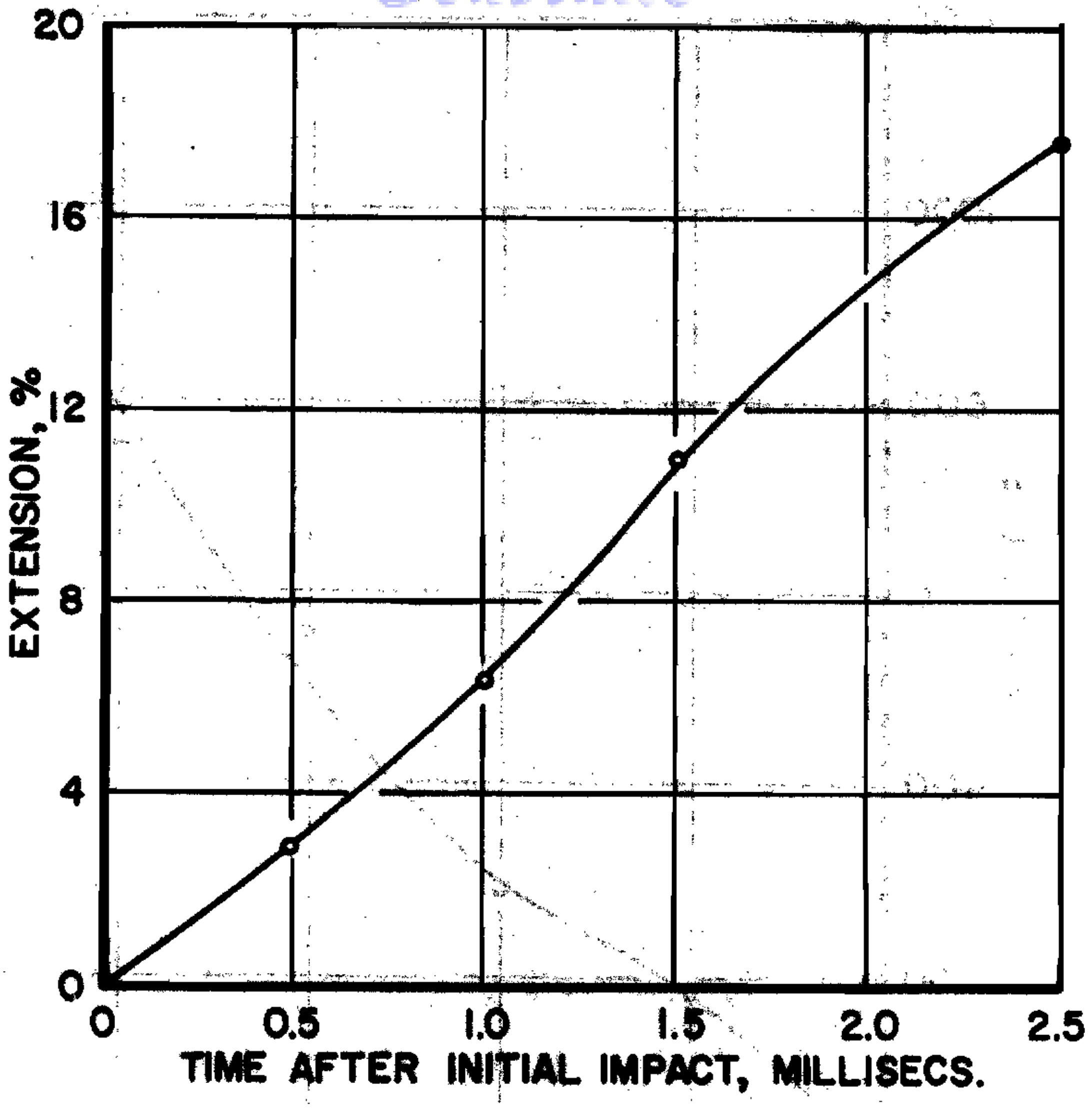

FIGURE 12. EXTENSION - TIME DIAGRAM FOR MIL-T-5608 CLASS E TYPE II TAPE IMPACTED AT 174 FT/SEC.

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This is readily verified by planimetering the area under the solid curve in Figure 10. This area is 11.5 square inches. Each square inch represents 360 inch-pounds of energy (based on an effective gauge length of 45 inches for this test). Thus the energy absorbed by the specimen is:

$$E = 11.5 \times 360 = 4140 \text{ inch pounds}$$

The 6% discrepancy between the energy values of 4420 and 4140 inch pounds is by no means large and it is readily reconcilable by the fact that the last exposure in the photograph of Figure 8 may not have been taken at the exact moment of rupture. If, indeed, the specimen continued to extend for an additional 0.5% beyond the last exposure before rupturing, the energy would have increased by approximately 260 inch pounds which brings the total energy absorbed to 4400 inch pounds.

V. CONCLUSIONS

It has been shown that the impact test machine has fulfilled all the design requirements, namely:

(a) Attainment of impact velocities of from 200 to 750 feet per second.

(b) Capacity to rupture specimens of up to 10,000 pounds.

(c) Instrumentation and calculations capable of determining the rupture force, elongation and energy to cause rupture.

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