THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

ABSOLUTE CHAMBER PRESSURE IN CENTER-FIRE RIFLES

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REPORT # 1 ABSOLUTE CHAMBER PRESSURE IN CENTER-FIRE RIFLES

DU PONT BALLISTIC GRANT STUDIES

THE UNIVERSITY OF MICHIGAN
ANN ARBOR, MICHIGAN

Table of Contents Page

Table of Contents (Cont.) Page

REPORT # 1 ABSOLUTE CHAMBER PRESSURES IN CENTER-FIRE RIFLES

DU PONT BALLISTIC GRANT STUDIES

THE UNIVERSITY OF MICHIGAN
ANN ARBOR, MICHIGAN

List of Tables Page

REPORT # 1 ABSOLUTE CHAMBER PRESSURE IN CENTER-FIRE RIFLES

DU PONT BALLISTIC GRANT STUDIES

THE UNIVERSITY OF MICHIGAN
ANN ARBOR, MICHIGAN

List of Figures Page

List of Figures (Cont.) Page

REPORT # 1 - ABSOLUTE CHAMBER PRESSURE IN CENTER FIRE RIFLES

DU PONT BALLISTIC GRANT STUDIES
THE UNIVERSITY OF MICHIGAN, ANN ARBOR, MICHIGAN

I. ESTABLISHMENT OF GRANT (L. E. Brownell)

The handloading of rifle ammunition has long been practiced by riflemen in the United States and is an important aspect in the use of rifles for sporting purposes. Until the mid thirties the Du Pont Company, Hercules Powder Co., as well as some others released data on pressure measurements for various powders and various cartridges using different powder charges and different bullet weights. This practice was discontinued in the middle thirties by all manufacturers of smokeless powder and ammunition. The hiatus continued until late 1962 when Du Pont for the first time in 25 years published once again pressure information for powders manufactured by the Du Pont Company.(1) Norma(2) and Hodgdon(3) and the National Rifle Association (NRA)(4) also published pressure data.

Although the release of information by Du Pont has been a significant contribution there is need for more data and a better understanding of internal ballistics if the sports of handloading, competition shooting, as well as hunting are to grow with improved performance, greater safety and the development of new markets and new products. There has been a need in particular for a procedure that permits the measurement of pressure in a rifle chamber without requiring the drilling of holes through the barrel for the use of crusher gages. Because the use of the crusher-gage technique for measuring chamber pressure requires the use of special barrels the accurate determination of chamber pressure in a rifle has been beyond the reach of most handloaders. Except for the powder manufacturers only the National Rifle Association has sponsored limited special tests using the crusher-gage technique to obtain and publish pressure data necessary for safe handloading.(4)

With the object in mind of improving the situation the strain gage method of accurate measurement of chamber pressures was investigated. This technique not only gives the maximum chamber pressure but the complete pressure versus time curve. Theoretical and experimental studies of internal ballistics at the University(5) have led to new techniques in experimental ballistic measurements which have been described briefly in the article "Ballistic-Breakthrough"(6) (see Appendix I).

The "break-through" consists of the development of a method for determination of time zero, t_o, which is the time when the bullet first begins to move from the cartridge case. In the initial studies a new ballistic laboratory technique was used in which a collimated beam of gamma radiation served to trigger a high-speed oscilloscope after the bullet moved 1/4". Similar beams of radiation located at various positions along the rifle barrel gave data on time versus distance of travel. The scope makes a single sweep in one millisecond (1/1000 sec.) and displays the voltage change in strain gages used to measure pressure. The sweep of the oscilloscope time scale has fifty subdivisions indicating that each subdivision measures the changes produced in 20 microseconds (20 millionths of a second). This new technique permits the precise determination of pressures versus time and bullet location versus time permitting cross-plotting of pressure versus bullet location for any type of powder, any type of gun, using any type of projectile without the need of special test barrels. A description of the early tests is given in the article "Ballistic-Breakthrough" published in Ordnance Magazine.[6] With this new technique and an active study program it is believed that a tremendous amount of ballistic information can be turned out rapidly. Such results are considered to be of value in improving the knowledge and state of the art in rifle handloading. For this reason a request was made to the Du Pont Company for assistance through a grant-in-aid to the University of Michigan for a program of research.

The Explosives Department of the E. I. Du Pont de Nemours & Company responded favorably and on March 31, 1964, a grant-in-aid identified as the Du Pont Ballistic Grant, Account No. 31626,was established at the University of Michigan to assist in continuation of these studies.

II. OBJECTIVES OF THE GRANT PROGRAM (L. E. Brownell)

One of the chief objectives of the research studies supported by the Du Pont grant is to develop and explore new means of investigation of the phenomena of internal ballistics in small arms, particularly internal ballistics for the center-fire, high powered rifle. The new techniques among other tests will involve the use of gamma radiation and ultrasonics for simultaneous determination of bullet location and chamber pressure versus time. New methods of correlation based on the use of dimensionless groups will be presented. The results of these studies will be reported at suitable intervals and copies of these reports with original experimental data will be made available to the Du Pont Company and the general public without cost via the editorial offices of various journals. The reports may be obtained by individuals for a small fee to cover the approximate cost of reproduction (estimated as $1.50 per copy)*. Students with an interest in research in the field of ballistics will be granted fellowships for thesis studies or employed on a part-time basis if a thesis is not involved. In this manner the grant will provide assistance to worthy students.

III. PERSONNEL (L. E. Brownell)

A. Research Fellows

Mr. Michael York is the first recepient for a fellowship from the Du Pont Grant for the academic year 1964-65. Mr. York received the M.S. degree in Nuclear Engineering from the University of Michigan in June 1963. Previously he graduated from U.S. Military Academy at West Point additional training in the Army Missile Schools. Mr. York has elected to do his additional graduate studies in the Department of Chemical Engineering at Michigan. The combustion of smokeless powder and the field of internal ballistics are recognized as suitable subjects for a thesis in the Department of Chemical Engineering but these subjects are not directly applicable to a thesis in the Department of Nuclear Engineering.

The Du Pont fellow during May and June 1964 was Mr. Roger Sinderman, B. Sc. in Science Engineering and graduate student in the field of Health Physics.

B. Research and Laboratory Assistants

Consideration of safety in the testing of high-pressure experimental loads in a high-power, center-fire rifle is important. Also, the use of curie quantities of gamma-emitting radioactive iridium-192 introduces an additional safety problem. It is believed that in the initial tests and for maximum safety all experimental firings involving the use of iridium-192 should be made with only two persons present. At least one of the research workers should be trained in the safety procedures for work with radioisotopes. In case of an accident there is a remote possibility that the iridium source containers could be overturned. Two persons working as a team can cope with an unexpected incident such as a spill of radioisotopes much better than one person alone. Furthermore, in working with high-pressure equipment there is always the possibility of an accident. The presence of a second person is desirable to offer assistance in case of such an accident.

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*Write to: Ulrich's Book Store, 549 E. University, Ann Arbor, Michigan or Ann Arbor Arms and Sporting Goods, 1340 N. Main St., Ann Arbor, Michigan. (Include 9 cents postage)

Mr. K. A. Jacob, B.S. in Chemistry and presently a student in the Department of Chemical Engineering at the University of Michigan, has been employed as a research assistant. He has had several years experience in industry where he became familiar with high-pressure equipment, fire and explosion hazards. He also has training in thermodynamics and chemical reaction kinetics which are applicable to the combustion of smokeless powder.

Neither Mr. Sinderman nor Mr. Jacob had past experience in the handloading of rifle ammunition. Therefore, Mr. Harold Robbins, Jr. was added as laboratory assistant. He is the 1964 and previously the 1963 junior champion for the State of Michigan for competition shooting in the 30 caliber rifle category. In both 1963 and 1964 he placed third in his category at the Camp Perry match competition. He is an experienced handloader and bench-rest shooter. He can consistently fire $1\frac{1}{2}$ inch groups at 200 yards bench-rest and is familiar with the various small factors that are important in obtaining maximum accuracy with center-fire rifles. Also, he has considerable experience in gunsmithing as part-time he works with his father, Mr. Harold Robbins, Sr., a professional gunsmith. Mr. Robbins originally was responsible for most of the handloading of the experimental cartridges and assisted in analyzing reasons for unexpected variations in the performance of test loads. A problem that University Faculty Supervisors of research programs must deal with is the constant turnover of personnel and the retraining of new research workers. Students working on research projects are usually available for one semester to a maximum of two to three years. We hope that if continued support is available that Harold Robbins can be kept on the project to provide continuity to the studies.

IV. USE OF STRAIN GAGES FOR MEASUREMENT OF CHAMBER PRESSURE (M. York)[5]

On first analysis it might seem rather simple to obtain chamber pressure measurements in a rifle chamber through the use of strain gages. However, when we consider that the projectile in a modern, high-power rifle traverses the entire length of the barrel in one-thousandth of a second and that the pressure peak lasts for less than one hundred-millionths of a second then we begin to realize the magnitude of the problem. The pressure in the chamber of a rifle will produce a stress in the surrounding rifle barrel and this stress can be detected through the use of a strain gage provided we have a means of amplifying and displaying the result of the change in resistance of the strain gage due to the stress in the rifle barrel.

Through the choice of the proper circuit associated with the strain gage and an amplifier and an oscilloscope, or just a good oscilloscope, it is possible to detect stresses on the order of those to be expected in a rifle barrel. However, the display on the oscilloscope will occur so fast that it cannot be interpreted by the human eye so we must take a picture of this display. Now we must consider some means of only displaying the pressure curve on the oscilloscope so that the picture we obtain is not clouded with the other voltage changes which are a result of the barrel vibrations induced by the firing of a cartridge. The strains induced by barrel vibrations are some one-hundred times as large as those associated with the pressure so we must separate these and only consider the voltage change which results from pressure. In order to separate these two strains we must trigger the display of the oscilloscope almost immediately after the projectile leaves the cartridge case or as the pressure begins to rise and then we must terminate this display as soon as the projectile has left the muzzle. Two methods were considered. Triggering could be accomplished by setting the trigger level of the oscilloscope to trigger internally on the initial voltage rise induced by the pressure, or an external trigger signal could be used to trigger the sweep of the oscilloscope. In the first tests by Mike York triggering was accomplished through an external triggering pulse. This external triggering pulse occurred when the projectile left the cartridge case and entered the rifling. A pulse was obtained through the use of a gamma beam and a detector. This detector was exposed to a certain intensity of radiation while the projectile was in the cartridge case and attenuating the gamma beam. Then as the projectile left the cartridge case and the gamma beam, the detector was exposed to a high intensity of gamma radiation. This increase in radiation provided a signal which could be fed into a circuit to provide a good external triggering signal for the oscilloscope. The problem of possible multiple display on the oscilloscope was taken care of by using an oscilloscope which incorporated a set trigger. A diagram of the original system used by York is illustrated in Figure 1.

A. The Resistance Strain Gage (M. York)[5]

The resistance strain gage operates on the principle that a change in strain produces a change in electrical resistance. Due to this property, the change in electrical resistance can be utilized to determine the strain produced in a wire etc. The strain produced in the wire then gives an indication of the stress in a structural member to which the wire strain gage is bonded.

The amount of resistance change due to a change in strain is defined as the strain sensitivity factor of the wire.

$$S_t = \frac{\Delta R/R}{\Delta L/L} \qquad (1)$$

where

S_t = Strain sensitivity factor of the wire

R = Resistance

ΔR = Differential change in resistance caused by change in cross sectional area of wire

L = Length

ΔL = Differential change in length of wire caused by elongation

Different materials exhibit different resistance changes as a result of strain. Some materials have a linear relationship between change in resistance and change in strain, whereas others exhibit a variable relationship. A linear relationship is generally desired in a strain gage. The simplest strain gage consists of just a wire that is mounted under tension between two supports. In this case any relative movement between the two supports can be detected through the change in strain that results from this movement. This simple wire strain gage could also be cemented directly on the material to be tested. A modification of this simple wire gage is the bonded wire strain gage. This gage consists of a wire that is bonded to some backing such as paper or plastic. This backing is then cemented to the part to be tested. The bonded strain gage is a vast improvement over the wire gage which is difficult to install. Another type of strain gage that is commonly used is the etched foil gage. In this type of gage excess foil is removed by etching to provide a thin strain sensitive element.

In general there are two types of materials used in wire strain gages. One type consists of Cupro-Nickel alloy and is designed for use under conditions in which there are temperature fluctuations. With this type of wire the temperature response is low which is a necessary requirement to obtain accurate results when the strain gage is subjected to temperature changes. The other type of material used in wire strain gages has a much greater response to temperature variations however, it has a better strain sensitivity than the Cupro-Nickel alloy. This second type of material consists of Ni, Cr, and Mo.

The conditions under which the strain measurement is to be obtained will dictate the choice of the strain gage material. In general the Cupro-Nickel alloy is preferred for static measurements over a comparatively long period of time where temperature variance might be encountered. The Ni, Cr and Mo material is preferred for dynamic testing in which the temperature variance, if it exists, occurs over a period of time which is long compared to the dynamic measuring time. The resistance change occurring is small in a strain gage under ordinary conditions. Therefore, a very sensitive and accurate means of detecting this change must be employed. The Wheatstone bridge provides this sensitivity and it is commonly employed for this purpose. Figure 2 is a diagram of a Wheatstone bridge circuit utilized for this purpose.

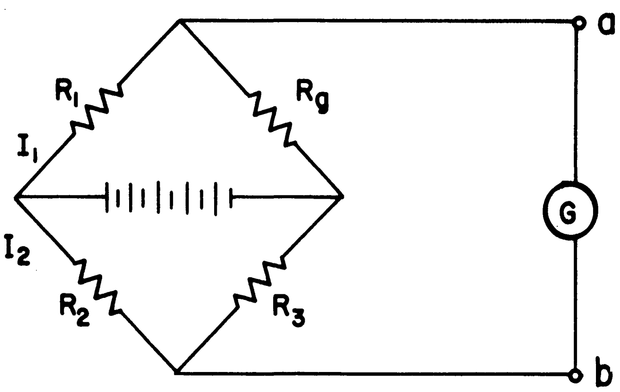


Figure 2. The Wheatstone Bridge Circuit (R_g represents the strain gage and R_1, R_2, R_3, represent resistors) (M. York)[5]

In Figure 2 leads a and b are connected to a galvanometer. The resistances are balanced so that the galvanometer reads zero. This means that the voltage drops across R_1 and R_2 are equal. Therefore,

$$I_1 R_1 = I_2 R_2 \quad (2)$$

Under balanced conditions, the currents I_1 and I_2 also flow through resistors R_g and R_3 respectively. If we consider the voltage drops across these resistors:

$$I_1 R_g = I_2 R_3 \tag{3}$$

Now we divide Equation (2) by Equation (3) to give

$$\frac{I_1 R_1}{I_1 R_g} = \frac{I_2 R_2}{I_2 R_3} \tag{4}$$

or

$$\frac{R_1}{R_g} = \frac{R_2}{R_3} \tag{5}$$

and

$$R_g = R_3 \left(\frac{R_1}{R_2} \right) \tag{6}$$

From this equation we see that when the bridge is balanced as indicated by the galvanometer, then R_g can be obtained by knowing R_3 and the ratio R_1/R_2.

Another circuit that is employed is the potentiometer circuit. This circuit is simpler than the Wheatstone bridge circuit, and is generally used for dynamic strain gage measurements. The potentiometer circuit is illustrated below. (See following page for diagram.)

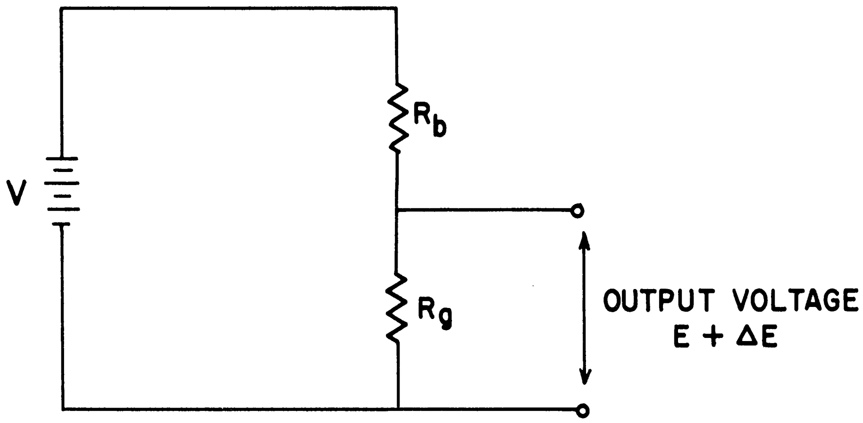


Figure 3. The Potentiometer Circuit (M. York)[5]

Analyzing the above circuit

$$V = I\,R_b + I\,R_g \tag{7}$$

$$V = I\,R_b + E \tag{8}$$

$$I = \frac{E}{R_g} \tag{9}$$

$$V = E\,\frac{R_b}{R_g} + E \qquad \text{or} \qquad E = \frac{V\,R_g}{R_g + R_b} \tag{10}$$

and therefore

$$\Delta E = V \left[\frac{R_g + \Delta R_g}{R_g + R_b + \Delta R_g + \Delta R_b} - \frac{R_g}{R_g + R_b} \right] \tag{11}$$

and letting $Z = \frac{R_b}{R_g}$

$$\Delta E = V \frac{Z}{(1 + Z)^2} \left[\frac{\Delta R_g}{R_g} - \frac{\Delta R_b}{R_b} \right] \left(1 - \frac{1}{1 + Z + \frac{1}{\frac{\Delta R_g}{R_g} + \frac{Z \Delta R_b}{R_b}}} \right) \tag{12}$$

considering a non-linear response

$$\Delta E = V \frac{Z}{(1 + Z)^2} \left[\frac{\Delta R_g}{R_g} - \frac{\Delta R_b}{R_b} \right] (1 - n) \qquad (13)$$

where

$$n = \frac{1}{1 + \dfrac{Z + 1}{\dfrac{\Delta R_g}{R_g} + \dfrac{Z \Delta R_b}{R_b}}} \qquad (14)$$

From this equation it can be seen that a large Z or $\frac{R_b}{R_g}$ reduces the dependence upon n which is desirable. Assuming $\Delta R_b = 0$ and a large Z then

$$\Delta E = \frac{VZ}{(1 + Z)^2} \left(\frac{\Delta R_g}{R_g} \right) \qquad (15)$$

It is also noted that a large V for a given Z results in the best ΔE and hence the best sensitivity for a given gage.

The choice of one of the two strain gage circuits just discussed is dependent upon the type of measurement to be performed. In general the Wheatstone bridge circuit is better suited for static measurements whereas the dynamic circuit is generally preferred for dynamic or time dependent measurements. The potentiometer circuit was used to obtain the measurements described in this report.

The type of strain gage used in the pressure measurements which were obtained is the Baldwin-Lima-Hamilton type C-1 strain gage. A sketch of this type of gage is shown in Figure 4. The gage consists of a thin isoelastic (Ni, Cr, Mo) wire which is cemented to a paper base. The sensitive element of the gage is covered by a rectangular piece of felt.

Prior to applying this gage, it is necessary to thoroughly clean the surface of the barrel to which the gage will be attached. This cleaning should be accomplished with acetone or some other suitable cleansing agent. After the surface of the barrel has been cleaned, the barrel should

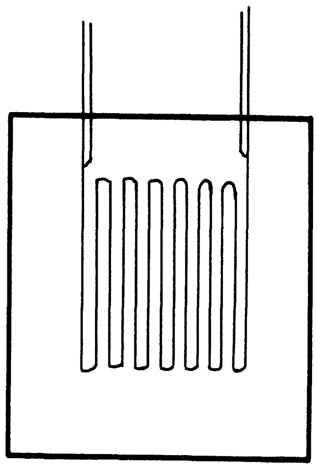


Figure 4. Paper Backed Wire Strain Gage (M. York)[5]

be coated with a fairly thick layer of Duco cement. Then the gage or gages are applied to the surface of the barrel. Next a clamp or a wide rubber band is placed over the gage so that pressure is applied to the felt that is covering the gage. Enough pressure should be applied so that the cement oozes out around the edges of the paper base and that all air pockets under the paper base are eliminated. This pressure should be maintained until the cement is dry (usually about 20-30 minutes). The clamp or rubber band can then be removed. However, the cement should be allowed to set for some 36 hours prior to using the gage. This setting time can be cut down to some 12 hours if Baldwin-Lima-Hamilton SR-4 cement is used in place of Duco cement.

The location of the gages on the Springfield model 1903 A3 barrel is illustrated below.

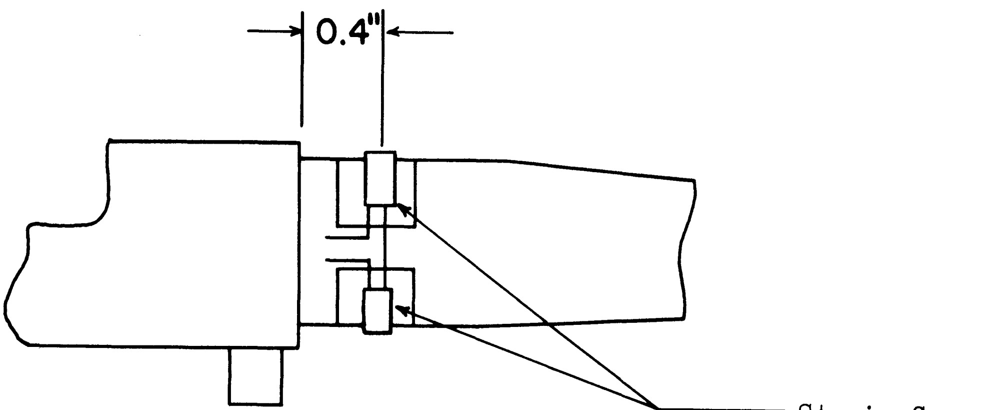


Figure 5. Location of Strain Gages on Springfield Rifle Barrel (M. York)[5]

The gages are located so that the center of the sensitive portion of the gages are directly opposite to each other. Care must be taken to insure that nothing touches the strain gages or the leads while strain measurements are being taken.

B. York's Method of Triggering the Oscilloscope (M. York)[5]

In the first tests the triggering of the oscilloscope was accomplished through the use of a collimated beam of gamma radiation and a sodium iodide crystal which is sensitive to gamma radiation and photomultiplier tube and associated electronic circuits.

A diagram of the general arrangement of the triggering procedure is shown in Figure 6.

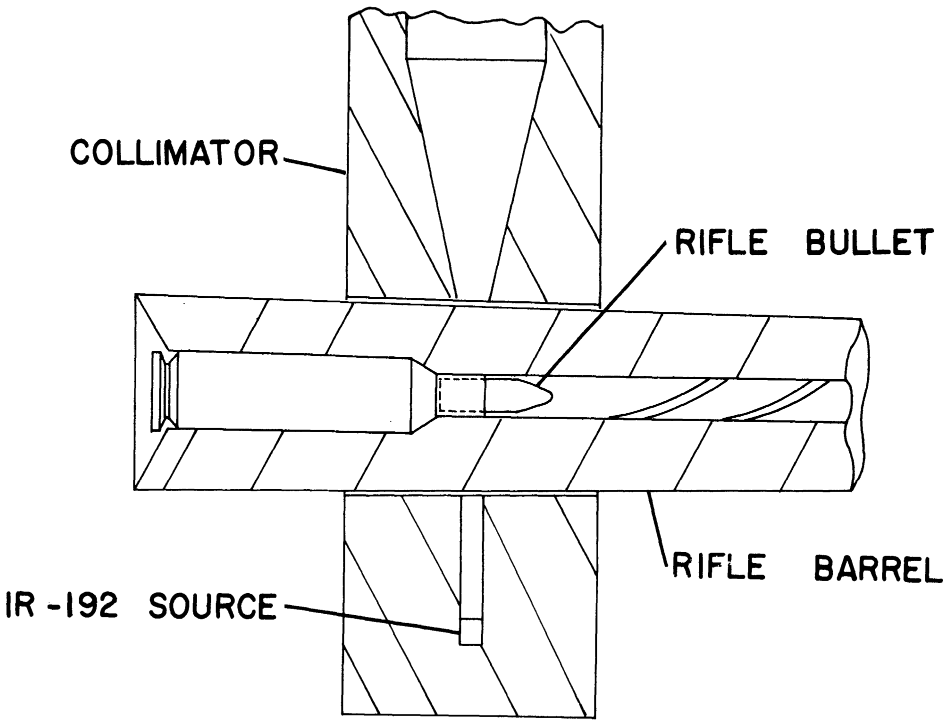


Figure 6. Gamma-Beam Trigger (M. York)[5]

From the diagram we see that as the bullet leaves the mouth of the cartridge case the sodium iodide crystal is exposed to a higher intensity of radiation due to the fact that the projectile is no longer attenuating the gamma beam. This increase in radiation results in an increase in the amplified pulses out of the photomultiplier tube. These pulses then go through the preamplifier to a frequency selection circuit which tends to eliminate background pulses. Then these pulses are fed into a circuit which produces a DC signal from these AC pulses. It is the resulting DC signal which triggers the oscilloscope. A diagram of the actual triggering signal obtained and the ideal signal is shown in Figure 7.

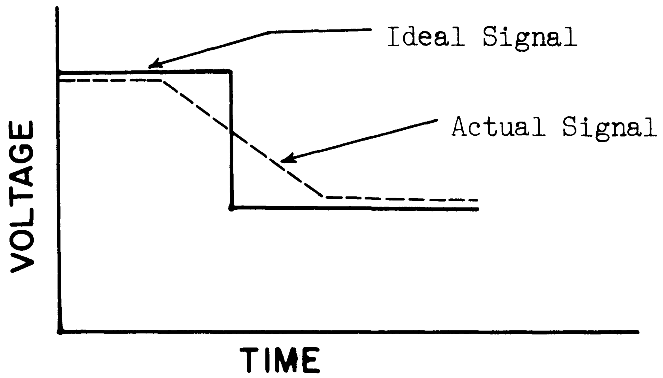


Figure 7. Trigger Signal (M. York)[5]

The fact that there is not an abrupt voltage change in the triggering signal is due to the finite amount of time it takes for the projectile to leave the gamma beam. Therefore, the resulting signal has a slope to it. If fast trigger is desired, which is usually the case since the pressure peaks after the projectile has traveled only a short distance, then the triggering level on the oscilloscope must be set so that actual triggering occurs when the signal starts its initial drop. If this is not done part of the pressure curve will not be displayed on the oscilloscope.

C. <u>The Original (Model 545) Oscilloscope (M. York)</u>[5]

The oscilloscope used in York's measurements was a Tektronix type 545 oscilloscope with a type B plug-in unit. This plug-in unit has a fast rise time of .015 μ seconds. The type 545 oscilloscope also has a set trigger capability which means that when this trigger is used only one sweep of the oscilloscope is displayed as a result of the triggering of the oscilloscope.

D. The Original Rifle Mount (M. York)[5]

The rifle mount used in obtaining the pressure data is shown diagramatically in Figure 1. The mount was constructed from cold rolled steel. The rifle mount consists mainly of a base of two flat pieces of steel, four supporting legs and a receiver adapter. The base serves as a rest for the collimator and radiation detector of the triggering system. The collimator can be moved and positioned so that triggering can be accomplished when the bullet is located at any position in the rifle barrel. The receiver adapter holds the rifle securely to the base and the force exerted by the recoil upon firing is taken up by the recoil lug on the receiver of the rifle. In firing, the rifle and the rifle mount are secured so that neither the rifle or the mount can move due to recoil.

E. The Original Test Rifle (M. York)[5]

The rifle used in these tests was a Springfield Model 1903 A3, Serial number 3518042 that was manufactured by Remington Arms Company. The rifle has a two groove barrel with a bore diameter of 0.3000 inches and a groove diameter of 0.3075 inches. For these tests the barrel and action were removed from the stock and secured to the rifle mount. The barrel and receiver of this rifle were not modified in any manner in obtaining the pressure data.

V. FIRST EXPERIMENTAL FIRINGS IN 1964 (L. E. Brownell)

Before additional experimental firings were made the method of triggering the oscilloscope originally used by York was modified. In York's procedure the oscilloscope was triggered by a signal from the radiation detector placed directly above the rear $\frac{1}{4}$" of the bullet. In this procedure a bullet travel of 1/8" to 1/4" (depending upon setting of sensitivity level of oscilloscope) exposed the radiation detector to a collimated beam of gamma radiation from an iridium-192 source. Although the 1/8" to 1/4" range in bullet travel required to trigger the oscilloscope does not appear large on the distance scale for a rifle with a 24" barrel it corresponds to a significant variation on the time scale because of the low velocity of the bullet when it first starts to move.

In the revised method, triggering the oscilloscope is performed internally by the voltage rise from the strain-gage signal. The instrument can be triggered at pressures of about 2000 psi. Electronic noise prevents reliable triggering at lower pressures. To accomplish the internal triggering it was necessary to remove the 4 sweep plug-in unit and replace it with a more sensitive single sweep unit. Perhaps the 4-sweep unit can be used again if a preamplifier is added.

The first experimental firings with support of the Du Pont grant were made in the third week of May using Remington cases, 220 grain Core-Lokt bullets, IMR 3031 powder and the new method of triggering. Figure 9 shows firing H-41 used as a "calibration" load for the 220 grain Remington Core-Lokt bullets with a charge of 41.0 grains of HV #2 powder loaded into new Winchester cases with Winchester primers. This is a load reported by NRA in their Handloading Handbook(4) to give a pressure of 48,100 psi maximum pressure. This load was used in May 1964 for the 220 grain Remington bullet to determine a preliminary calibration of the experimental equipment using the strain gage and oscilloscope.

Figures 8 and 9 show the negatives of the original polaroid pictures taken from the oscilloscope display. Points of particular interest have been indicated at "a", "b", "c", "d". The inflection in the pressure rise curve at "a" is observed on most firings in which the pressure in terms of crusher value is 50,000 psi or more. The signal is observed more often with rapid burning powders than with slow burning powders. Mr. G. F. Dunn of Carney's Point Du Pont Development Laboratory has stated that the same inflection is observed in piēzo gage measurements of pressure versus time. He explains that this inflection is believed to be caused by escape of powder gas upon plastic deformation of the neck of the cartridge case. At the pressure indicated by point "a" the neck of the case is believed to be forced open by the gas pressure until it is restrained by the chamber throat. This allows a portion of the gas to leak past the bullet and this leakage results in a reduction in slope of the pressure rise curve. At this point the bullet may be considered to be in suspension on a ring of escaping gas and free of any restraint from the neck of the case. Therefore, point "a" may also be considered to be time zero or the time that the base of the bullet starts to move forward from its original position. After the bullet base is upset or the bullet moves forward a short distance it seals the barrel preventing further escape of gas. The slope of the pressure rise curve then turns upward again and for the next 200 microseconds or so the pressure rises almost linearly with respect to time.

The next point of interest is at point "b" where the bullet ingress ultrasonic signal is produced. At present we believe engraving of the bullet by the rifling of the barrel can produce a rapid rise in circumferential stress of the barrel. This increase in barrel stress

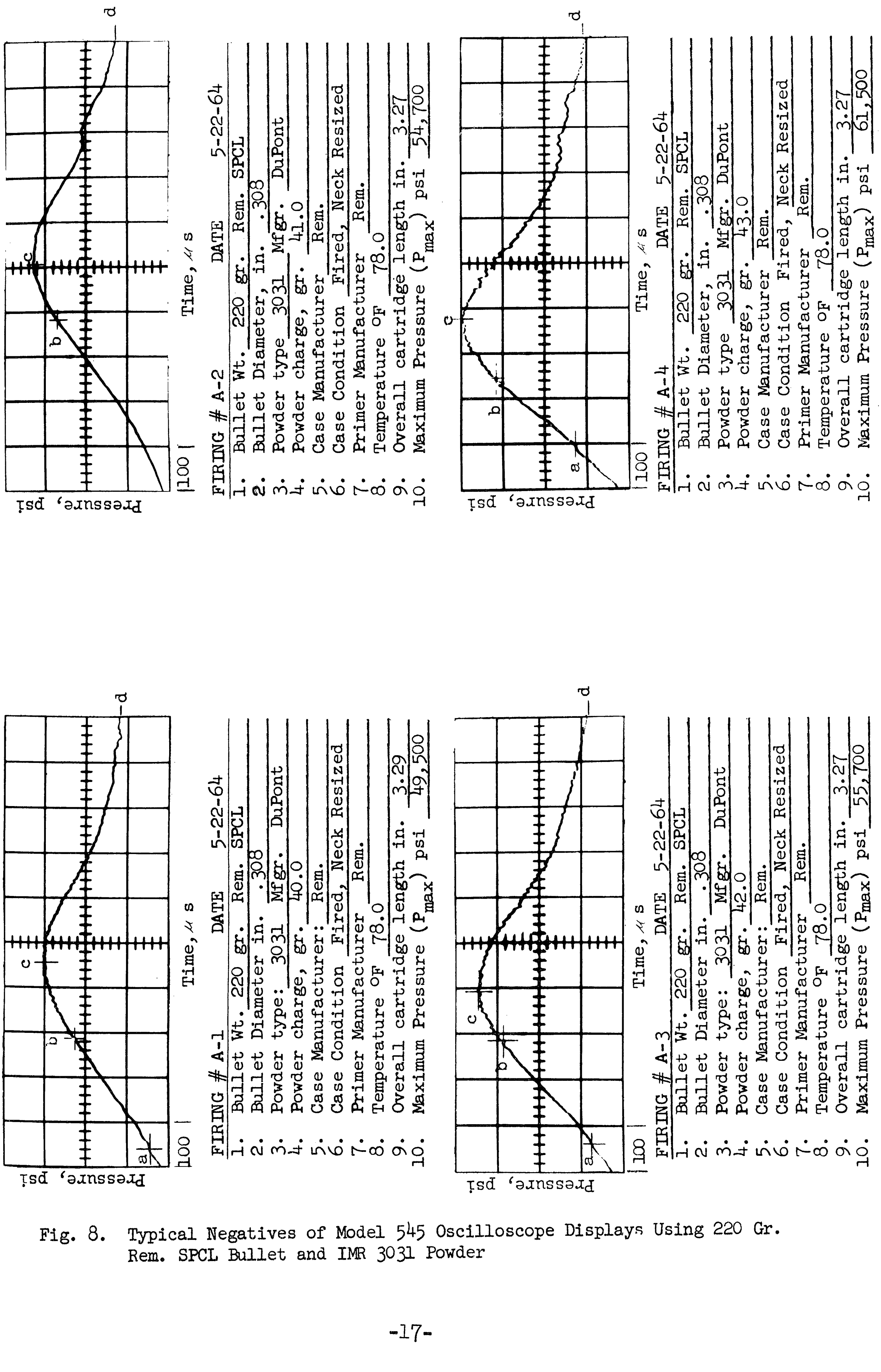


Fig. 8. Typical Negatives of Model 545 Oscilloscope Displays Using 220 Gr. Rem. SPCL Bullet and IMR 3031 Powder

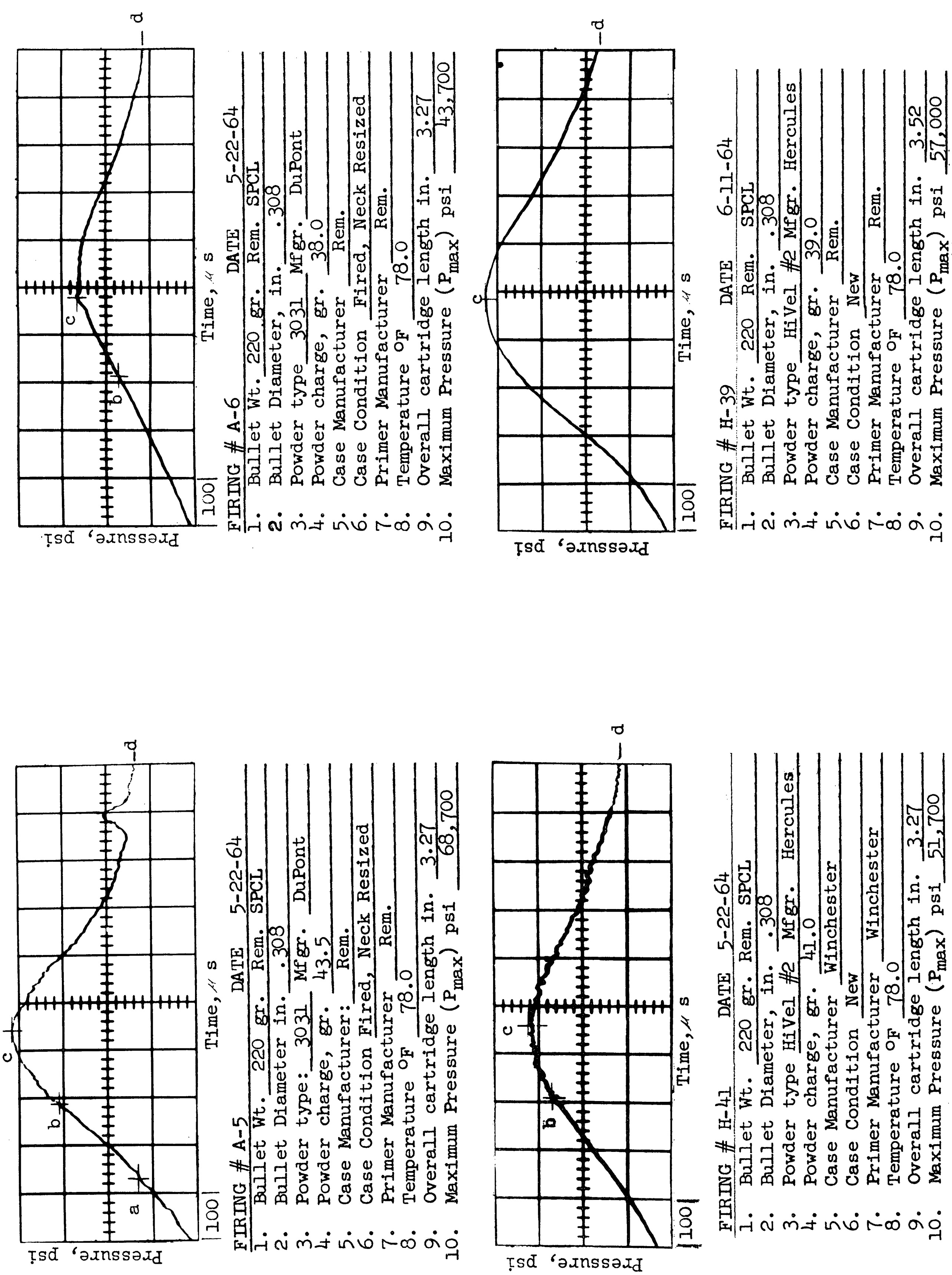


Fig. 9. Typical Negatives of Model 545 Oscilloscope Displays Using 220 gr. Rem. SPCL Bullet and IMR 3031 Powder

produces a harmonic vibration in the stress signal which is picked up by the strain gage. In the case of high pressures (above 55,000 psi crusher values) the bullet base is upset during initial travel as a result of the opposing forces of the inertia of the bullet mass and the gas pressure on the bullet base. These opposing forces produce enlargement of the bullet base which can cause a pronounced ultrasonic signal upon ingress of the bullet into the barrel proper. (For further discussion see section on "Discovery of Ultrasonic Signal".)

The next point of interest is "c" which is the maximum pressure at the peak of the curve where the curve has zero slope. This point is the pressure that corresponds to the maximum value reported in crusher gage tests.

The last point "d" is the pressure at the end of the sweep and has the order of magnitude in most firings of the pressure in the chamber at bullet egress. This value is of importance only if the bullet location at time "d" also is known.

VI. DISCOVERY OF THE "ULTRASONIC" SIGNALS (L. E. Brownell)

A. Bullet Ingress (First) Ultrasonic Signal

With normal bullet seating the oscilloscope displays show a harmonic oscillation which starts at about 60-70 percent of the maximum pressure and which is believed to be caused by the impact of the bullet on the rifling. A sharp signal is obtained on the scope trace as shown in Figure 8, firing A-3 at the(time)instant the bullet strikes the rifling. This point can be determined within about 10-15 microseconds which is much faster than with the radiation detector. For this reason and because in these firings a single trace sweep was used the iridium-192 detectors were not used.

The "discovery" of the "ultrasonic signal" necessitated a fast letter to the editor of Ordnance Magazine and an insertion regarding the phenomenon before the first article went to press for the July-August issue of Ordnance.(6) The insert should read as follows. (See Appendix I)

"Numerous additional firings similar to that shown in Figure 5* have been made since the preparation of the first draft of this manuscript. In most observations the oscilloscope sweep showing pressure rise is a smooth curve until a pressure similar to the discontinuity at 25,000 psi of Figure 5* is reached. Then the sweep oscillates and the

From Ballistic Breakthrough, courtesy of Ordnance Magazine.

data show that a definite period of oscillation occurs of the order of 10 to 20 microseconds. This corresponds to the order of magnitude for the time period required for sonic vibration in steel to travel from the bore of the rifle throat to the strain gage. It is believed that this signal is produced by the impact of the bullet on the rifling of the barrel and that at time, T_0, as shown in Figure 5 the bullet has traveled about 1/4 inch from its initial position to contact the rifling. This is consistent with the observation that a bullet travel of about 1/4 inch also is required to trigger the detector placed over the end of the bullet as shown in Figure 6 to produce an oscilloscope sweep as shown in Figure 4 in the Appendix.*

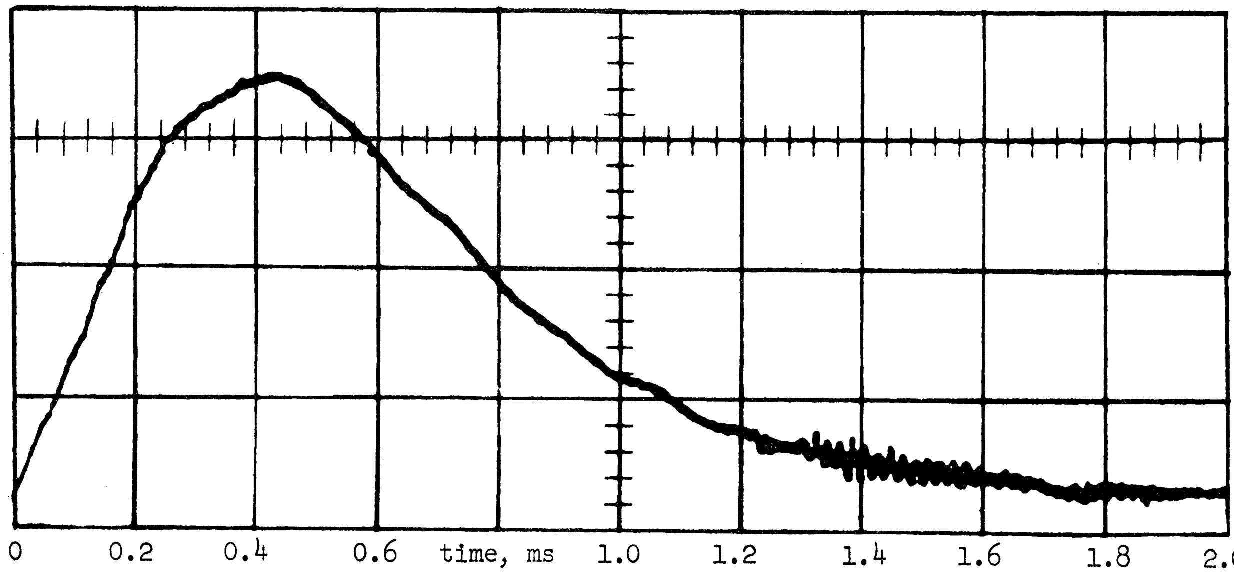
Although the distance of 1/4 inch of bullet travel would seem to be a small factor it actually corresponds to about 100 microseconds of time because of low initial bullet velocity. If this correction is made to the distance vs pressure curve for this load the bullet begins to move when the pressure is about 6,000 psi and travels 1/4 inch to the rifling while the pressure rises to about 25,000 psi. Obviously much is to be learned by further study".(6) (See Appendix I.)

To investigate the "ultrasonic signal" various bullet seating depths were tested. In this series of tests the signal was not observed when the bullet was seated all the way out so as to engage rifling with no free bullet travel (compare Figure H-41 with Figure H-39 in Figure 9). As additional firings were made during the summer months the intensity of the "ultrasonic signal" gradually decreased. By the end of September, 1964, the signal was no longer observed except in very high pressure firings and the amplitude of the signal was decreased as compared to those obtained from firings in May, 1964. Inspection of the bore showed erosion of most of the rifling for the first 1-2 inches of barrel travel. This was not unexpected as about 3000 rounds had been fired through the barrel between May and September. The barrel was removed and replaced with a new 4 groove Remington 03A3 (1943) barrel. The original barrel was cut in half lengthwise and the errosion of the rifling was clearly visible.

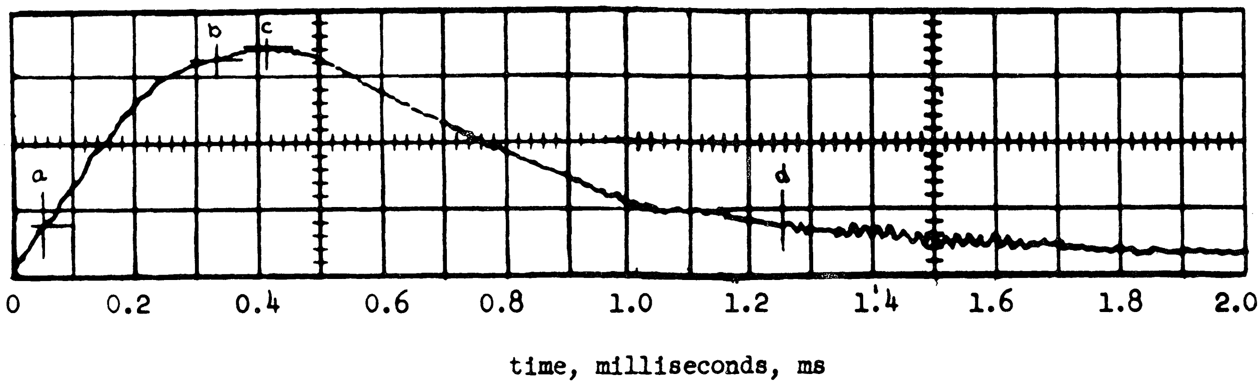
B. Bullet Egress (Second) Ultrasonic Signal

If the oscilloscope is set to give a sweep covering 2 ms instead of 1 ms the last portion of the display will show the strain gage signal after the bullet has left the barrel. Figures 10 and 11 show two such displays for 30-06 RN military cartridges loaded in 1958. These military loads were intended for use in "cleaning" barrels to "normal" conditions after firing low-pressure loads which may leave unburned powder in the

*From Ballistic Breakthrough, courtesy of Ordnance Magazine.



a Negative of 2 ms Display from Model #564 Oscilloscope



b Composite Negative of Two 1 ms Displays from Model #545 Oscilloscope

Fig. 10 "Second" Ultrasonic Signals Produced by Bullet Egress (FN-1958 Military Cartridges) barrel. These cartridges are apparently loaded with some type of "ball" powder which has different characteristics than the IMR powders. Lake City Arsenal military loads with IMR powder are now used for "cleaning" the 30-06 barrel after low-pressure firings.

Some of the FN cartridges were fired late in the summer of 1964 and show very slight or no ultrasonic signal on initial bullet travel partly because of the worn condition of the barrel and partly because of the burning characteristics of the ball powder. Firing some 1957 FN cartridges loaded with an European powder (apparently double base) gave a good impact signal even though the barrel was worn. Obviously the effect of burning characteristics on the signal needs further investigation.

The important observations with the 1958 FN cartridge are the "second" ultrasonic signal observed after egress, that is, the bullet leaves the barrel. A military load for a 150 gr. bullet in the 30-06 cartridge requires almost exactly 0.001 sec (1 ms) for the bullet to reach the muzzle of a 1903 A3 Springfield after it first starts to move from the cartridge case. Figure 10a shows a display from a single firing of a 1958 FN cartridge. Note that at about 1.2 ms a sharp harmonious signal is obtained which is believed to be caused by the drop in bore pressure as the bullet leaves the barrel. The drop in pressure occurs first at the muzzle and results in a contraction of the barrel at the muzzle. Consider the muzzle to be 22 inches from the strain gages and the sonic velocity in powder gas to be about 2000 ft/sec (at powder gas temperature) and in barrel steel about 16,000 ft/sec. The times for the signal to travel 22 inches are:

$$t_{gas} = \frac{22 \text{ in. } (1)}{12 \text{ in/ft. } 2000 \text{ ft/sec}} \quad 0.00092 \text{ sec or about } 0.92 \text{ ms}$$

$$t_{steel} = \frac{22 \text{ in. } (1)}{12 \text{ in/ft } (16{,}000)} \quad 0.000114 \text{ sec or about } 0.11 \text{ ms}$$

Since the time for the pressure wave to travel at sonic velocity through the powder gases is almost 1 ms we would expect little or no signal in an oscilloscope with a 2 ms sweep as about 1 ms would be required for bullet acceleration and almost as much (0.9 ms) for the sonic wave to travel back to the breech and the strain gages. Thus the velocity of the signal must be "ultrasonic" with respect to sonic velocities in gases. Pressure waves in steel travel with a velocity about 8 and 20 times as great as through hot powder gases and normal air respectively. The approximate 0.11 ms required for the signal to travel through the barrel steel plus the approximate 1.0 ms required for the bullet to reach the barrel agrees well with the 1.25 ms shown in Figure 10a. Figure 10b is a composite of two replicate firings of the 1958 FN cartridges. The right half was produced accidently by a 1 ms time delay in the #545 Tektronix oscilloscope. Combining this picture with a conventional 1 ms FN 1958 firing gives better definition and shows that the frequency of the oscillation is about 20 microseconds. This is about the same as obtained with the "first" or "impact" signal. The reason for this similitude in frequency needs more study to be understood.

C. Hypothesis for Ultrasonic Signals

Consider the condition of bullet egress. At the instant the bullet leaves the muzzle of the barrel the gas pressure suddenly drops at the muzzle causing a rapid contraction of the barrel radially inward. However, the gas pressure behind the muzzle remains high and decreases only as the powder gas is forced out of the muzzle. For this reason there is no sudden drop in pressure in the chamber as there is at the muzzle.

The radial contraction at the muzzle produces a harmonic oscillation resulting in an alternate tensile and compressive circumferential stress. This harmonic oscillation travels with the speed of sound in the steel of the barrel (about 16,000 ft/sec) from the muzzle to the breech. A barrel two feet long would require 1/8000 secs or about 0.13 ms (130 μs). The period of the harmonic is that of the alternate radial contraction and expansion of the steel cylinder constituting the barrel.

This hypothesis helps to explain the impact or "first" ultrasonic signal. When the bullet engages the rifling the rifling must reduce the bullet diameter from 0.308 inches to the bore diameter of 0.300 inches (for the 30-06 Springfield). This deformation of 0.008 inches of the rifling into the jacketed bullet produces a sudden and large tensile circumferential stress in the barrel. Again, as in the case of the muzzle a harmonic oscillation is set up in the circumferential stress of the barrel in this case at point of ingress rather than egress. This harmonic travels at ultrasonic speed (as compared to speed of sound in air) to the strain gage. In this case the gage is only about 1.2 inches from the source of the signal. Therefore the signal will travel from the rifling to the strain gage in about 0.013 ms (13 μs).

The sweep of the oscilloscope is usually set at 1 ms. For this case the time lag is 1.3 per cent of the total time scale and is half this value (or 0.65 per cent) for a 2 ms sweep. Thus, the ultrasonic signal provides a very precise means of locating the bullet with respect to time with a time lag of only a few millionths of a second.

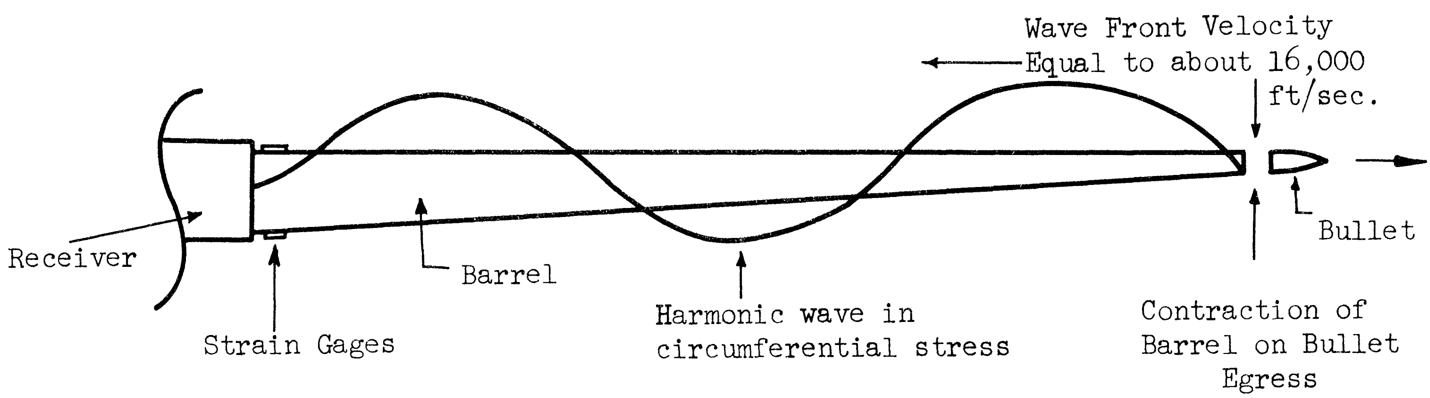


Figure 11. Diagram Illustrating Hypothesis of Ultrasonic Egress Signal

D. Ingress Signal in Smooth-Bore Rifles

In the previous discussion of the impact signal and the hypothesis explaining these signals mention has been made of impact of the bullet on the rifling. However, the theory requires extension to explain the very definite impact signals obtained in a worn barrel with high pressure firings such as shown later in Figure 23. At present it is believed that bullet upset can result in an increase in the diameter of the rear portion of the bullet while the bullet is still in the throat of the chamber. Naramore[8] has discussed this phenomenon to a considerable extent in his Chapter 25 "Reloading vs. Ballistics". He points out that if a rifle barrel is cut off just ahead of the throat so that the point of the bullet will protrude out of the muzzle of the very short barrel, upsetting of the bullet can be demonstrated. When cartridges are fired the high gas pressure behind the bullet expands a flat base bullet as indicated in Figure 12.

(a) Flat Base Bullet Before Firing

(b) Flat Base Bullet After Firing in Short Barrel

Figure 12. Upsetting of Flat Base Bullets by Gas Pressure in Short-Barreled Gun (According to Naramore)[8]

Naramore states that upon initial movement of the bullet forward into the barrel "The base is moved first, and expands, and this degree of expansion is very considerable, even with flat-base bullets having stiff jackets. The actual degree of expansion is limited only by the space available within the limits of the barrel and chamber. But finally the point of the bullet also begins to move and the bullet goes forward into the throat of the rifling, whereupon the escape of gas past the bullet is to all intents and purposes checked. The effort of the base to move faster than the point of the bullet may continue while the bullet is traveling as much as two or three inches or more along the barrel, by which time the entire mass will have attained the same velocity. This expansion of bullet bases is easily proved by sawing off the barrel just ahead of the chamber, firing a cartridge in it and recovering the bullet. The degree of expansion will naturally depend upon the hardness of the bullet and the force that is applied to it."

Thus, a high-pressure loading such as 53 grains of 4064, with the 150 grain bullet (see Figure 24) will upset the base of the bullet, expanding it beyond the original diameter of 0.308 inches. Even though the rifling has been completely worn away and the smooth bore erroded to a diameter of 0.309 inches the upset base of the bullet can produce a high tensile circumferential stress on bullet ingress as the expanded base of the bullet is forced into the barrel. In conclusion we can state that a sharp change in circumferential stress of the barrel is possible at both bullet ingress and bullet egress producing ultrasonic signals that can be detected by the strain gage and recorded on the oscilloscope display.

These hypotheses require verification by additional tests. If correct, another very useful procedure has been discovered to locate bullet position with respect to time. This technique gives excellent precision in the early stages of bullet travel whereas the gamma beam technique gives best precision after the bullet has attained a sufficient velocity to give a sharp cut-off of the gamma beam. A combination of the two techniques give improved precision over the entire range of bullet travel through the bore.

VII. MODIFICATIONS OF TEST APPARATUS
(R. Sinderman, H. Robbins, Jr., and L. E. Brownell)

Figure 13 is a diagram of the test apparatus as modified by August, 1964. At the right side of Figure 13 two sand barrels are indicated and are used as a bullet trap and as a shield for the personnel working on the project. Left of the sand barrels is the Chrondek chronograph. This instrument differs from the conventional chronograph in that only a one foot spacing is used between tapes. Its crystal oscillates at approximately one megacycle (1 million times a second). The frequency was measured and found to be 1.03 megacycles, which results in a slight error in velocity computed on charts for 1.0 megacycles. When the bullet strikes the first tape it breaks the electrical circuit which triggers the chronograph electronic recording of the crystal oscillations. As the bullet cuts the second tape, a second circuit is broken which stops the instrumental recording of the oscillations and the elapsed time in microseconds is displayed by illuminated bulbs on a binary type counter. Tables supplied with the instrument permit the total count to be converted directly to muzzle velocity in feet per second. Some difficulty was experienced in reproducing results with this chronograph. Because of this and the high cost of printed tapes for this instrument it has not been used in most firings.

The muffler indicated in Figure 13 to the left of the chronograph is used to deaden the sound created by the muzzle blast. The apparatus of the project is located at present in the Michigan Memorial Phoenix Research Laboratory where loud noises are undesirable. The muzzle blast should be reduced to a fraction of its original intensity. Difficulties involving sound control and personnel in the same general area have interferred with firings to some extent and have brought about the requirements for the use of the muffler and the shielding devices shown. Considerable time and effort was required to provide shielding and a muffler partially satisfactory to other personnel involved in research near the project. A Maxim-type silencer attached directly to the barrel

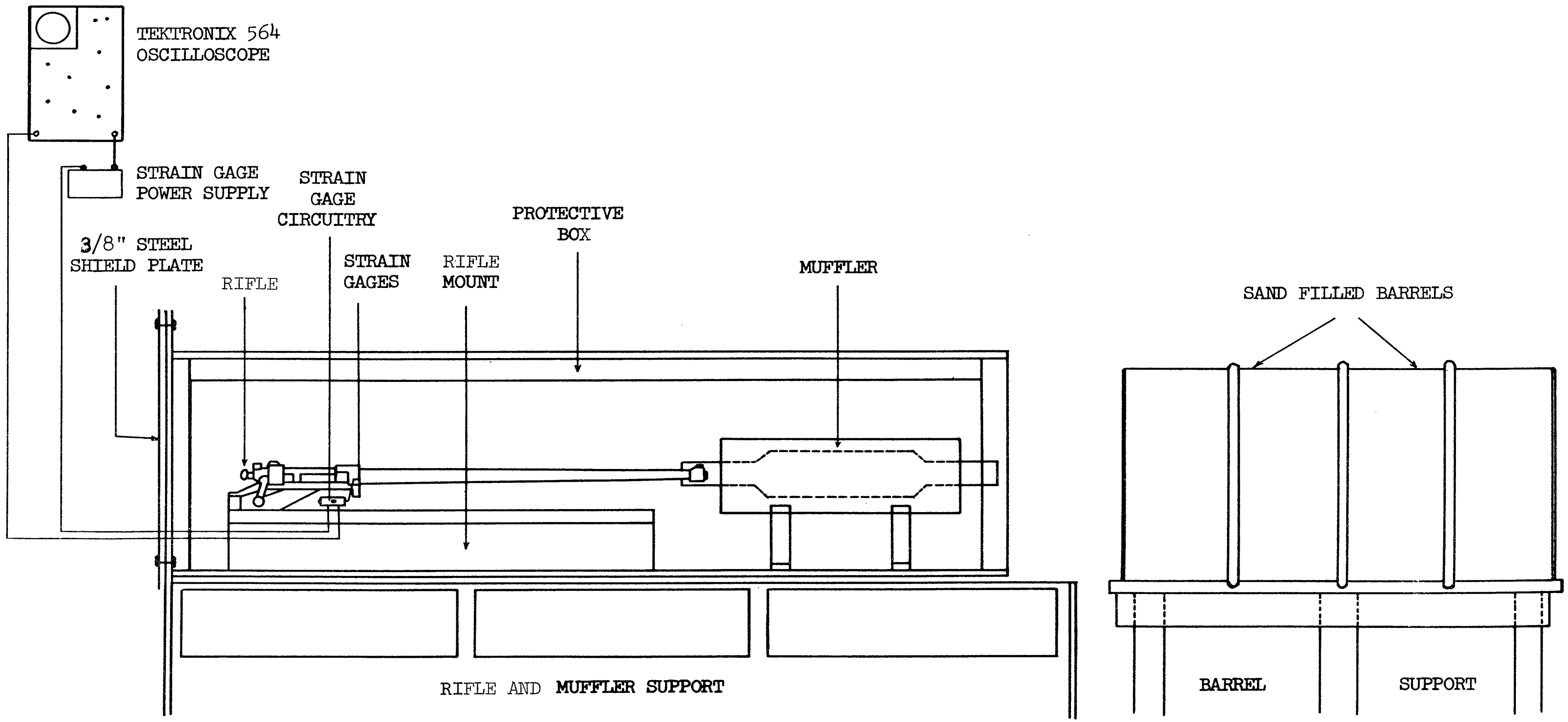


Figure 13. Sketch of 1964 Revisions in Ballistic Test Apparatus. (Sinderman)

and inside the muffler should improve the control of sound. We are presently attempting to obtain such a silencer at low cost. The plywood box surrounding the rifle and muffler provides some sound shielding and also provides a personnel shield against minor fragments of bullets, etc., while the 3/8" steel plate directly behind the bolt provides the main shield for the immediate working personnel for protection against a ruptured gun or ricochetting bullets. Consideration is being given to a better location, preferably underground for future firing. Such a new location should be of sufficient length to permit some external ballistic measurements to be made.

The test gun used during the summer of 1964 is the same as used by York in his first tests and is an 03-A3 Springfield 30-06 rifle. The mount for the rifle receives the full recoil via the recoil lug and serves as a free floating stock in which no pressure is exerted on the barrel. For simplicity and to avoid electronic noise the gun is triggered mechanically by a pull cord through the shield. The use of a solenoid has been considered. However, low levels of voltage change are used in measuring pressure. Consequently, any source of electronic noise with an amplitude greater than about 1 millivolt is picked up by the strain-gage circuit and may cause premature or faulty triggering of the oscilloscope.

The oscilloscope now being used is a Tektronix Model 564 storage scope. The scope originally used was a Tektronix 545 scope. The new instrument gives a better trigger-level adjustment and has a greater sensitivity in the lower-voltage regions. Also, the Model 564 has the advantage of storing any trace so that data can be recorded or discarded without the wasting of Polaroid camera film. The method of triggering the Model 564 scope has been changed from York's procedure. The scope is triggered internally using a much lower voltage signal. This was accomplished by transferring the trigger circuit directly to the strain gage circuit. Satisfactory internal triggering has been obtained using a signal of about 0.2-0.5 millivolts. This allows the scope to begin its sweep on the primer pressure alone. This is quite an improvement over the original method and allows measurements to be made on initial bullet movement and pressures before the bullet encounters the rifling.

The same simple strain gage circuitry is used and involves two electrical resistances in series with a constant voltage potential applied across them as previously described by York. After detonation of the primer the pressure in the chamber begins to rise and the strain gage voltage changes. A small voltage change triggers the scope and its trace displays the pressure in the chamber as a function of time.

VIII. CRUSHER GAGE VALUES VERSUS ABSOLUTE CHAMBER PRESSURE (L. E. Brownell)

A. Discussion of Crusher Gages

The crusher gage has a long history. It was developed and first used back in the black powder days to provide a means of indicating the magnitude of the maximum chamber pressure in firearms. For handloading purposes the pressures indicated by the crusher gage procedure are sufficiently accurate to provide information on the combinations of loading components that give safe loads. This is essentially the basis for the loading information in the NRA Handloading Handbook.[4] However, data based on the crusher gage technique are not considered to be sufficiently accurate for use in ballistic correlations.

The crusher gage and its use is well described in Norma's publication, "Gunbug's Guide".[2] The limitations of crusher measurements are mentioned briefly. The copper crusher is a rather crude device, which is used to determine plastic deformation above the elastic limit of the copper used and therefore is a measure of the work expended during plastic deformation. Copper crushers are not absolutely uniform in their physical properties and some error is introduced by variations in yield point and cold working characteristics beyond the yield point. Physical properties such as yield point and modulus of elasticity also are temperature dependent. For this reason measurement and control of temperature during firing is important in tests made with copper crushers. As the copper cylinder is compressed the copper becomes cold worked and the cross sectional area is increased. Thus, the measured deformation by compression is not directly proportional to the force applied by the chamber pressure. Frictional resistance of the steel piston used to transfer the force of the gas to the crusher absorbs energy. Probably one of the greatest errors in the "American" crusher technique is that introduced by the force required to shear the cartridge case before the piston is activated. This force varies with both the thickness and yield point of the brass in individual cases.

Each lot of crushers should be calibrated against a known load in the range of pressures being studied. The crusher is also sensitive to the duration of loading which introduces another source of error. Thus, although crusher measurements are useful and serve to indicate the magnitude of the maximum pressure they do not give the true absolute chamber pressure.

Two other techniques: (1) the strain gage, and (2) the piëzometric pressure gage have been used to measure chamber pressures with greater accuracy than possible with the crusher gage. We have been informed that most of the ballistic laboratories of the various powder manufacturers now are using "piëzo" gages to obtain better pressure data. The use of strain gages appears to be less extensive. Dr. E. L. Eichhorn, ballistician,[9] states that strain gages are used by: (1) RWS-Genschow, (2) Svenska P.F.-Stockholm, (3) Norma-Amotfors, (4) Hembrug-Ijmuiden, (5) CCl-Lewiston and we know that they are used by (6) Detroit Testing Laboratory-Detroit.

B. Linear Relation Between Barrel Strain and Chamber Pressure (M. York and L. Brownell)[5,10]

Both the strain gage and the piëzo gage can be used in conjunction with an oscilloscope to give a pressure versus time curve for a selected time, usually 1.0 or 2.0 milliseconds. Using the correct instrumentation both systems can be made to produce a response that is linear with respect to pressure.

The strain produced in a rifle barrel as a result of the sudden applied pressures due to the burning propellant is difficult to calculate rigorously if the barrel does not have the shape of a simple cylinder. However, the relationship between strain and chamber pressure can be calculated through the use of the Lamé Theory. This theory is applicable to long thick-walled cylinders which are subjected to internal pressure. With a rifle we do not have a long thick-walled cylinder and the barrel is subjected to dynamic rather than static pressures. Therefore, some error is bound to result from this analysis. However, this error should be relatively small and for convenience the Lamé Theory will be used.

Consider a thick-walled cylinder such as the chamber portion of a rifle barrel subjected to an internal and external pressure of p_i and p_o respectively. Denote the inside diameter as d_i and the outside diameter as d_o. Stresses are induced in the wall of the cylinder to oppose the pressures p_i and p_o. These stresses may be resolved into three components. These are:

f_a the axial stress

f_r the radial stress

f_t the circumferential hoop or tangential stress.

These are pictured below.

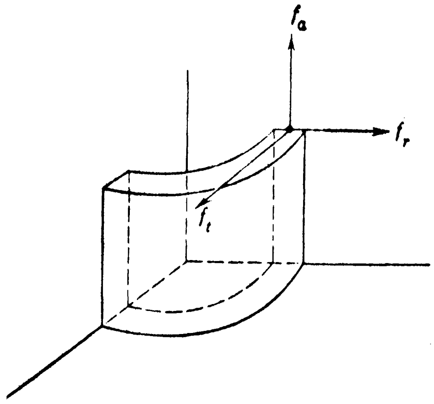


Figure 14. Orientation of Stresses in the Shell of a Thick-Walled Cylinder(10)

The force exerted in the axial direction is $\frac{p_i \pi d_i^2}{4}$. This is opposed by the outside pressure and by the axial stress in the wall. Considering half of the cylinder, the sum of the upward forces must equal the downward forces where the upward force is $\frac{p_i \pi d_i^2}{4}$ and the downward force is:

$$\frac{p_o \pi d_o^2}{4} + f_a \left(\frac{\pi}{4}\right) (d_o^2 - d_i^2) \tag{16}$$

So,

$$\frac{p_i \pi d_i^2}{4} = \frac{p_o \pi d_o^2}{4} + f_a \frac{\pi}{4} (d_o^2 - d_i^2) \tag{17}$$

and

$$f_a = \frac{p_i d_i^2 - p_o d_o^2}{d_o^2 - d_i^2} \tag{18}$$

Figure 15 indicates the axial, tangential and radial stresses and an element of dr thickness in a thick-walled cylinder.

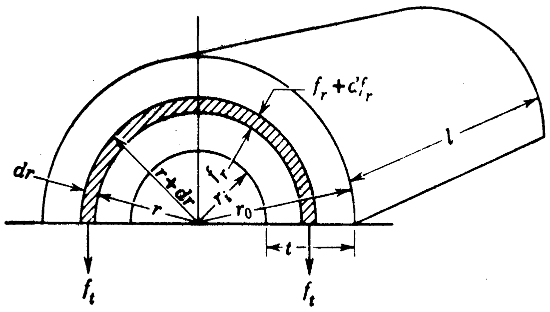


Figure 15. Stresses and an Elemental Shell in a Thick-Walled Cylinder

Considering the radial stresses in the differential element of the cylinder illustrated above we have:

$$f_r(2r\ell) - (f_r + df_r)\ 2(r + dr)\ell = 2f_t dr\,\ell \qquad (19)$$

or

$$- f_r dr - r\,df_r - d_r\,df_r = f_t dr \qquad (20)$$

We divide Equation (20) by dr and assume that df_r is small

$$f_t = - f_r - r\frac{df_r}{dr} \qquad (21)$$

Then

$$f_t = - f_r - r\frac{df_r}{dr} = - \frac{d}{dr}(f_r r) \qquad (22)$$

For one directional strain in axial direction with the stress below the yield point

$$\epsilon_a = \frac{f_a}{E} \tag{23}$$

where:

ϵ_a = unit strain in the axial direction, in inches per inch

f_a = stress in axial direction, pounds per square inch

E = modulus of elasticity, pounds per square inch.

For three dimensional strain

$$\epsilon_{a3} = \frac{1}{E}\left[f_a - \mu\,(f_t - f_r)\right] \tag{24}$$

where μ = Poisson's ratio, a constant for a given material or rearranging

$$f_t - f_r = \left(\frac{f_a - E\epsilon_{a3}}{\mu}\right) = 2a \tag{25}$$

where a is a constant. By substitution in Equation (25) for f_t by Equation (22) gives:

$$-2f_r - r\frac{df_r}{dr} = 2a \tag{26}$$

or

$$\frac{df_r}{f_r + a} = -\frac{2dr}{r} \tag{27}$$

By integration

$$\ln\,(f_r + a) = -\ln r^2 + C_1 \tag{28}$$

by taking the antilogarithms

$$f_r + a = \frac{b}{r^2} \tag{29}$$

(where antilogarithm $C_1 = b$) or

$$f_r = \frac{b}{r^2} - a \qquad (30)$$

The convention that positive values are used for tensile and negative values for compressive stresses gives:

$$f_r = a - \frac{b}{r^2} \qquad (31)$$

and from the previous expression for f_t and the above expression

$$f_t = \frac{b}{r^2} + a \qquad (32)$$

Now applying the boundary conditions

$$\text{at } r = r_o \qquad p = p_o = f_{r_o}$$

$$\text{at } r = r_i \qquad p = p_i = f_{r_i}$$

and substituting these values into Equation (30)

$$-(f_r)_{r = r_o} = -(a - \frac{b}{r_o^2}) = p_o \qquad (33)$$

$$-(f\ )_{r = r_i} = -(a - \frac{b}{r_i^2}) = p_i$$

Then subtracting the first equation from the second

$$p_i - p_o = \frac{b}{r_i^2} - \frac{b}{r_o^2} \qquad (34)$$

and

$$b = \frac{r_o^2 \, r_i^2 \, (p_i - p_o)}{r_o^2 - r_i^2} \tag{35}$$

for our case $p_o = 0$.

Therefore,

$$b = \frac{d_o^2 \, d_i^2 \, p_i}{4(d_o^2 - d_i^2)} \tag{36}$$

Then substituting Equation (35) into Equation (33)

$$a = \frac{r_i^2 \, (p_i - p_o)}{r_o^2 - r_i^2} - p_o \tag{37}$$

$$= \frac{p_i \, r_i^2 - p_o \, r_o^2}{r_o^2 - r_i^2} = \frac{p_i \, d_i^2 - p_o \, d_o^2}{d_o^2 - d_i^2} = f_a$$

Again for the case when $p_o = 0$.

Therefore,

$$f_a = \frac{p_i \, d_i^2}{d_o^2 - d_i^2} = a \tag{38}$$

and using these constants a and b

$$f_t = a + \frac{b}{r^2} \tag{39}$$

$$= \frac{p_i \, d_i^2}{d_o^2 - d_i^2} + \frac{d_o^2 \, d_i^2 \, p_i}{4(d_o^2 - d_i^2)r^2}$$

at $r = \frac{d_o}{2}$,

$$f_t = \frac{2p_i\, d_i^2}{d_o^2 - d_i^2} \qquad (39a)$$

and

$$f_r = a - \frac{b}{r^2} \qquad (40)$$

$$= \frac{p_i\, d_i^2}{d_o^2 - d_i^2} - \frac{d_o^2\, d_i^2\, p_i}{4(d_o^2 - d_i^2)r^2}$$

$$= \frac{p_i\, d_i^2}{d_o^2 - d_i^2} - \frac{d_i^2\, p_i}{d_o^2 - d_i^2} = 0$$

Equations (38) and (39) and the equations listed below provide a means of determining the unit strain on the barrel surface above the chamber section of a rifle barrel. The radial stress is zero on the barrel surface therefore Equation (24) reduces to

$$\text{Axial unit strain on barrel surface} = \epsilon_a = \frac{1}{E}\left[f_a - \mu\, f_t\right] \qquad (41)$$

The tangential (circumferential) stress is twice the axial stress in a thin-walled cylinder and therefore the tangential unit strain, ϵ_t, will be greater than the axial unit strain, ϵ_a , for a given internal pressure.

$$\text{Tangential (circumferential) unit strain on surface of barrel} = \epsilon_t = \frac{1}{E}\left[f_t - \mu\, f_a\right] \qquad (42)$$

or by substitution Equations (39a) and (38) for f_t and f_a respectively gives:

$$\epsilon_t = \frac{1}{E}\left[\frac{2\, p_i\, d_i^2}{d_o^2 - d_i^2} - \mu\, \frac{p_i\, d_i^2}{d_o^2 - d_i^2}\right] \qquad (43)$$

$$\epsilon_t = \frac{p_i}{E} \quad \frac{d_i^2 (2 - \mu)}{d_o^2 - d_i^2} \tag{44}$$

or for a given chamber diameter, d_i external barrel diameter, d_o and for a given steel, μ and E are known therefore:

$$\epsilon_t = p\ k \tag{45}$$

where

$$k = \frac{d_i^2 (2 - \mu)}{E\ (d_o^2 - d_i^2)}$$

p = chamber pressure, psi.

Thus by Equation (45) the chamber pressure p_i is directly proportional to the unit strain in the circumferential (tangential) direction and inversely proportional to a barrel constant, k which has a constant value for a barrel of fixed dimension and material. Because the unit strain ϵ is directly proportional to pressure, p , the strain gage signal will be directly proportional to unit strain and the oscilloscope display will be linear with respect to pressure if strain gages with a linear relation are used. We should point out that the modulus of elasticity, E , (sometimes called Young's modulus) is constant for a given material at a given temperature. Hooke's law states that stress is directly proportional to unit strain and definitely is applicable if the stress in the barrel does not exceed the elastic limit. If the elastic limit is exceeded, we will have a plastically permanently deformed (bulged) barrel. Such conditions of plastic deformation exist only in destructive testing and are not applicable to the studies in the present tests.

At chamber pressures between 20,000 and 40,000 psi fair agreement is possible using the crusher technique and either the piëzo or strain gage. The magnitude of this difference is not known by most handloaders and gunsmiths. Powder companies have been somewhat reluctant to bring these facts to the attention of the average handloader. A handloader may be firing a cartridge with a charge of 42.0 gr. of IMR-4895 powder and a 180 gr. bullet in a 308 W cartridge. This load gives a pressure of 49,700 psi as determined by crusher measurement. The true pressure for the identical load measured by piëzo gages is 60,580 psi.[7,9] Some reloading handbooks list higher charges than the 42.0 grains for this powder and cartridge.

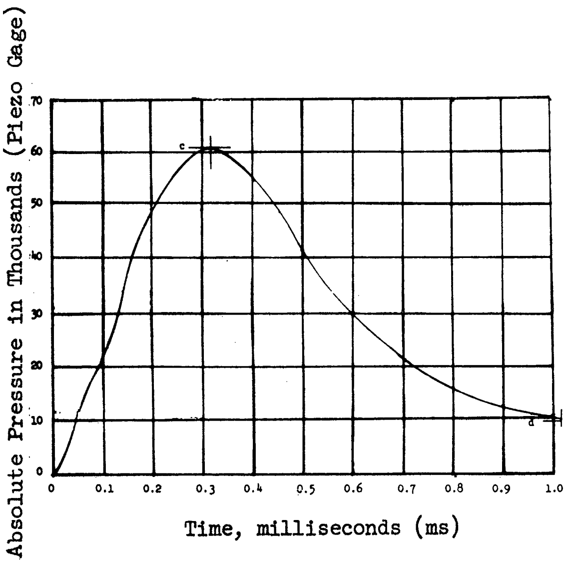
Sufficient laboratories are using strain and piëzo gages to speak in terms of the true absolute pressure. The deception that absolute pressures over 55,000 psi are unsafe should be dismissed. Commercial rimless cartridges for modern rifles are consistently loaded with charges that produce actual absolute chamber pressures in excess of 70,000 psi. However, it is M O S T important that the absolute chamber pressure and the values from crusher tests N O T be confused. The possibility that crusher values might be confused with real pressures may have been one reason for continuation of the use of crusher values by the powder companies.

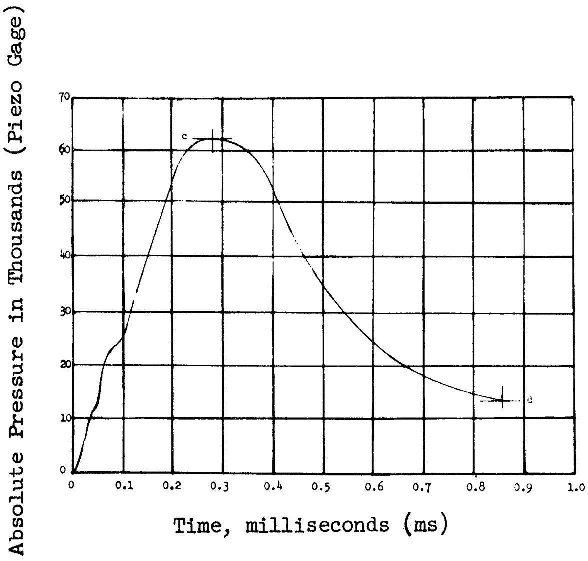
In this research the intent is to work with fundamentals and facts. Hereafter references to pressure will be specifically to the true absolute pressure rather than the crusher values when the term pressure is used.

C. Piezoelectric Gage Data Compared to Strain Gage Data

Special permission has been obtained from Dr. W. F. Jackson, Ass't. Director Research and Development Division, Explosives Department, E. I. Du Pont de Nemours & Co., Inc.(9) to reproduce the piëzo-gage data shown in Figure 16a, b, c, and d. Figures 11a and 11b show data for the .308 cartridge loaded with IMR 4895 powder and fired in a rifle with a 22 inch barrel. Note the similarity between the pressure curve in Figure 16a based on the piëzo gage and some of the strain gage pressure curves such as firing A-3 in Figure 8. An inflection in the pressure rise curve occurs at "a" in firing A-3 of Figure 8. This is believed to be the point at which the pressure expands the neck of the case permitting powder gas to escape and thereby decrease the rate of pressure rise until the bullet moves or is upset at the base to seal the barrel from further loss of powder gas. In Figure 16a, b, c and d point "c" is the maximum chamber pressure and point "d" is bullet egress. No ultrasonic signal is detected with the piëzo gage as shown in Figure 8 at point "b".

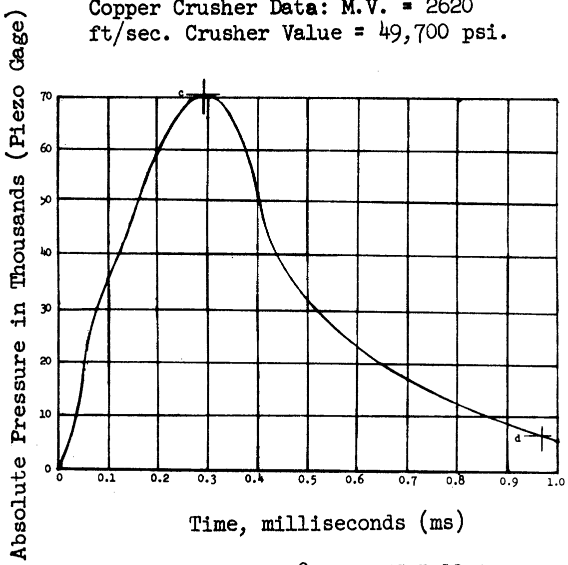
The second inflection in pressure rise curve shown in firing A-5 of Figure 9 may be caused by bullet upset produced by the very rapid rise in pressure. A similar second inflection in the pressure rise curve can be detected in the strain gage pressure curves shown in Figure 24b. This load also has a rapid rise in pressure. Figures 16c and d show piëzo gage data for the same rifle using a faster burning powder IMR 4198. Note that with the faster burning IMR 4198 powder the pressure peaks more sharply than for IMR 4895 and the curve falls off more rapidly after the maximum chamber pressure is reached.

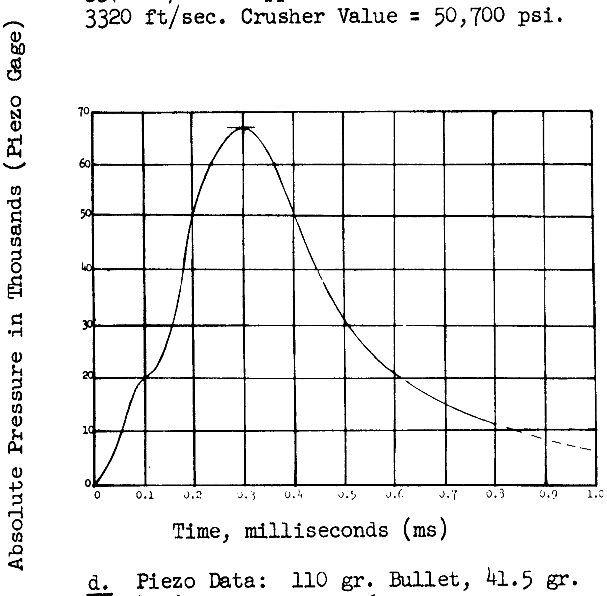




a. Piezo Data: 180 gr. B.T. Bullet, 42.0 gr. IMR 4895 Powder, P_{max} = 60,500 psi. M.V. = 2680 ft/sec. Copper Crusher Data: M.V. = 2620 ft/sec. Crusher Value = 49,700 psi.

b. Piezo Data: 110 gr. Bullet, 51.0 gr. IMR 4895 Powder, P_{max} 63,000 psi, M.V. = 3370 ft/sec. Copper Crusher Data: M.V. = 3320 ft/sec. Crusher Value = 50,700 psi.





c. Piezo Data: 180 gr. MC Bullet, 35.0 gr. IMR 4198 Powder. P_{max} = 70,500 psi, M.V. = 2620 ft/sec. Copper Crusher Data: M.V. = 2540 ft/sec., Crusher Value = 60,800 psi.

d. Piezo Data: 110 gr. Bullet, 41.5 gr. IMR 4198 Powder, P_{max} = 67,000 psi, M.V. = 3310 ft/sec. Copper Crusher Data: M.V. = 330 ft/sec. Crusher Value = 57,100 psi.

Fig. 16a,b,c,d. Piezoelectric Measurements of Absolute Pressure vs Time for .308 Cartridge and 22 Inch Rifle Barrel. (Reproduced by Special Permission of DuPont Co.)

D. Maximum Pressure Tests

To obtain data in the region of 90,000 to 100,000 psi for a calibration curve of crusher values versus absolute pressure two experimental loads were especially prepared and tested with copper crushers at Carney's Point Research and Development Laboratory, E. I. Du Pont and Co., Inc. The maximum pressure was selected to simulate the proof loads used to test U. S. Government rifles. In these tests a proof load giving a crusher value of 67,000 psi has been used for years. Because of the very high pressure, pre-deformed crushers are used in the government test. However, since we did not wish to introduce the additional factor of cold working of the crushers, simple copper crushers were used in all the Du Pont measurements. The results reported by Du Pont were a crusher value of 67,400 psi using 49.0 grains of IMR 3031 powder (Lot #1224) a 220 grain Remington SPCL bullet, and Remington cases and primers. The second load consisted of 48.0 grains of the same powder and gave a crusher value of 61,900 psi. (WARNING: These are proof loads and should never be fired by an individual holding the gun. A proof-testing rack with suitable protection for the operators should always be used with tests of proof loads.) Du Pont did not measure pressures with piëzo apparatus because the upper limit for this equipment is about 70,000 psi absolute pressure. There is no such limit for strain gages.

The results of the strain gage measurements using these loads at the University of Michigan are shown in Figure 17. The data are listed in Table I and are plotted in Figure 18. The four lowest traces are of four calibration firings using 44.0 grains of IMR 3031, Lot # 1224 and the 220 grain SPCL bullet load. This load was found by Du Pont to produce a crusher value of 52,700 psi and a piëzo-gage value of 63,600 psi absolute pressure. The lowest of the four curves for this loading was fired first in a comparatively cold rifle and produced an oscilloscope peak of only 13.0 vertical units. Then three loads of 48.0 grains of IMR 3031, Lot # 1224, were fired to produce three nearly replicate curves with peaks of 20, 20-1/2 and 21 oscilloscope units above the zero-voltage reference line. The head spacing was checked during firings and was found to be beyond the "No-Go" but less than the "Field" gage limit and the tests were continued. The three maximum loads of 49.0 grains of IMR 3031, Lot # 1224, were fired to give three similar curves peaking at 21-1/2, 22 and 22-1/2 oscilloscope units respectively. Next three additional calibration loads were fired and these firings were 1, 1-1/4 and 1-3/4 units higher than the original firings. A value of 14 units was taken as the average for the calibration firings.

TABLE I

Calibration Data for Crusher Readings versus Absolute Chamber Pressure

No.	Cartridge	Powder	Charge (gr 1)	Bullet	Crusher Reading psi	Source of Crusher Data	Pressure by Strain Gage, psi	Source of Strain Gage Data	Muzzle Vel. ft/sec	Pressure by Piezo Gage, psi	Source of Piezo Gage Data
1	308W	4895	42.0	180gr boat tail	49,700	E.I. DuPont*	-------	-------	2650	60,580 ⊡	E.I. DuPont*(Fig. 16)
2	308W	4198	35.0	180gr boat tail	60,800	E.I. DuPont*	-------	-------	2580	70,000 ■	E.I. DuPont*(Fig. 16)
3	308W	4895	51.0	110gr spitzer	50,700	E.I. DuPont*	-------	-------	3345	63,400 ◪	E.I. DuPont*(Fig. 16)
4	308W	4198	41.5	110gr spitzer	57,100	E.I. DuPont*	-------	-------	3305	66,860 ◩	E.I. DuPont*(Fig. 16)
5	30-06	3031 Lot 1224	44.0	220gr SPCL	52,700	E.I. DuPont**	62,000 ⊖	U. of M.	2352	63,600 ⊡	Du Pont
6	30-06	3031 Lot 1224	37.0	220gr SPCL	40,700	E.I. DuPont**	40,000 ⌀	U. of M.	2078	48,000 ⊘	Du Pont
7	30-06	3031 Lot 1224	29.0	220gr SPCL	30,400	E.I. DuPont**	33,000 ⦸	U. of M.	1681	28,000 ⧅	Du Pont
8	30-06	3031 Lot 1224	48.0	220gr SPCL	61,900	E.I. DuPont**	90,800 ⊙ 93,100 ⊙ 95,300 ⊙			90,800	E.I. DuPont E.I. DuPont E.I. DuPont
9	30-06	3031 Lot 1224	49.0	220gr SPCL	67,400	E.I. DuPont**	97,700 ● 100,000 ● 102,300 ●				E.I. DuPont E.I. DuPont E.I. DuPont
10	30-06	3031 Lot 1230	44.0	220gr SPCL	(52,700)	taken as for Lot 1224	64,000 ⊕	U. of M.	----	(63,600)	------------
11	30-06	3031 Lot 1230	37.0	220gr SPCL	(40,700)	taken as for Lot 1224	40,000 ◐	U. of M.	----	------	------------
12	30-06	3031 Lot 1230	29.0	220gr SPCL	(30,700)	taken as for Lot 1224	29,000 ◑	U. of M.	----	(28,000)	------------
13	30-06	3031 Lot 194	37.0	220gr SPCL	(40,700)	taken as for Lot 1224	46,300 Φ	U. of M.	----	(48,000)	------------
14	30-06	3031 Lot 194	29.0	220gr SPCL	(30,700)	taken as for Lot 1224	30,000 -●-	U. of M.	----	------	------------
15	30-06	HiVel #2	23.0 (cor.primer)	220gr	20,000	P.Sharpe***	19,600 ▲	U. of M.	1400	------	------------
16	30-06	HiVel #2	38.0	220gr	36,000	P.Sharpe***	39,000 △	U. of M.	2140	------	------------
17	30-06	HiVel #2	43.6	220gr	51,000	P.Sharpe***	61,500 ◭	U. of M.	2315	------	------------
18	30-06	HiVel #2	37.0	180gr Sierra	34,150	N.R.A.+	42,600 ▼	U. of M.	2297	------	------------
19	30-06	HiVel #2	41.0	220gr SPCL	48,100	N.R.A.+	51,700 ▽	U. of M.	2357	------	------------

*Reproduced by special permission. (Data first brought to attention by Dr. Edgar L. Eichhorn, Ballistician)[9]

**Personal communication.

***Reproduced by special permission courtesy of Funk and Wagnalls Co., New York, N.Y.[11]

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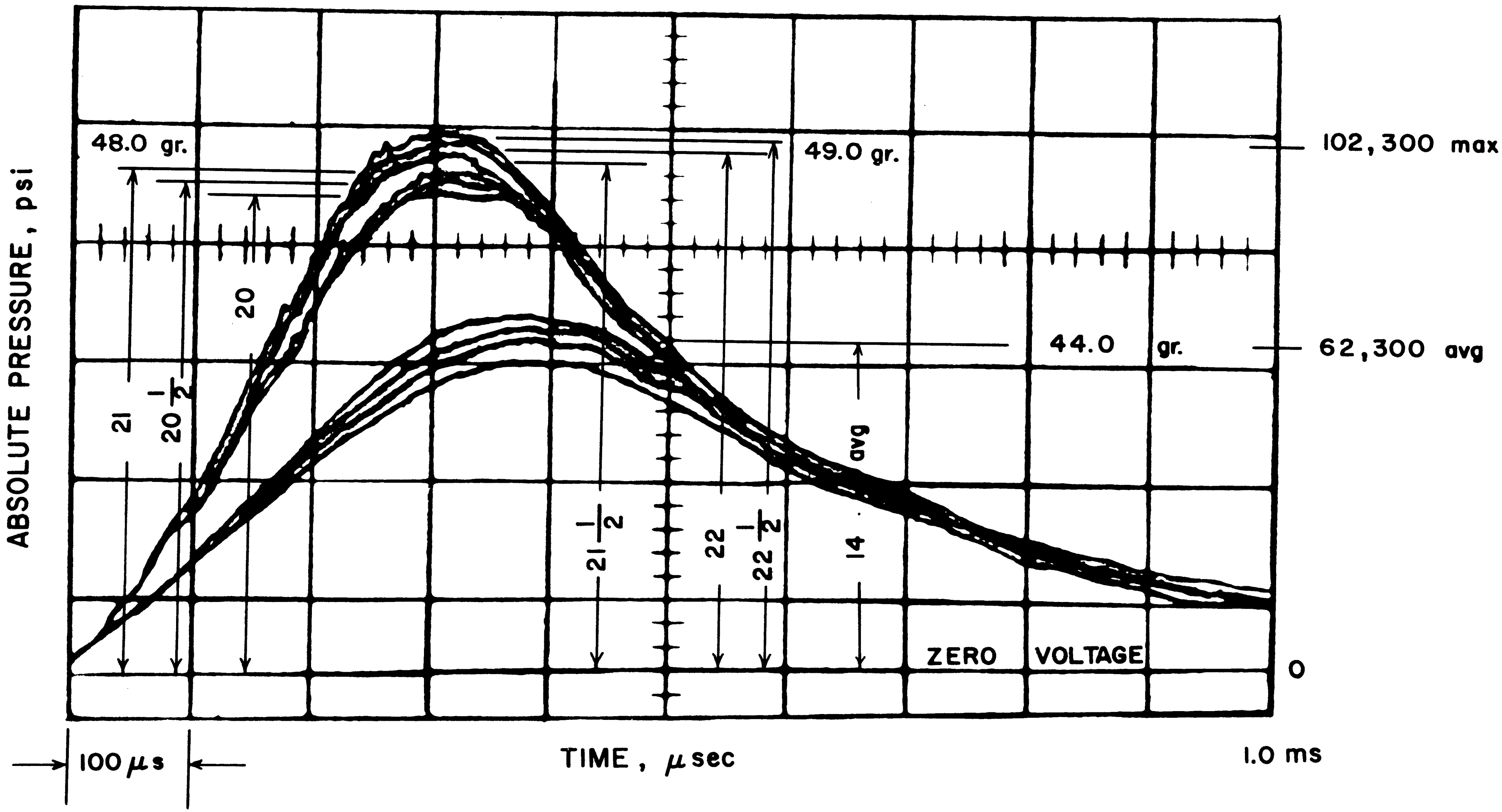

Fig. 17. High Pressure (100,000 psi) Calibration Curves for IMR 3031 Powder

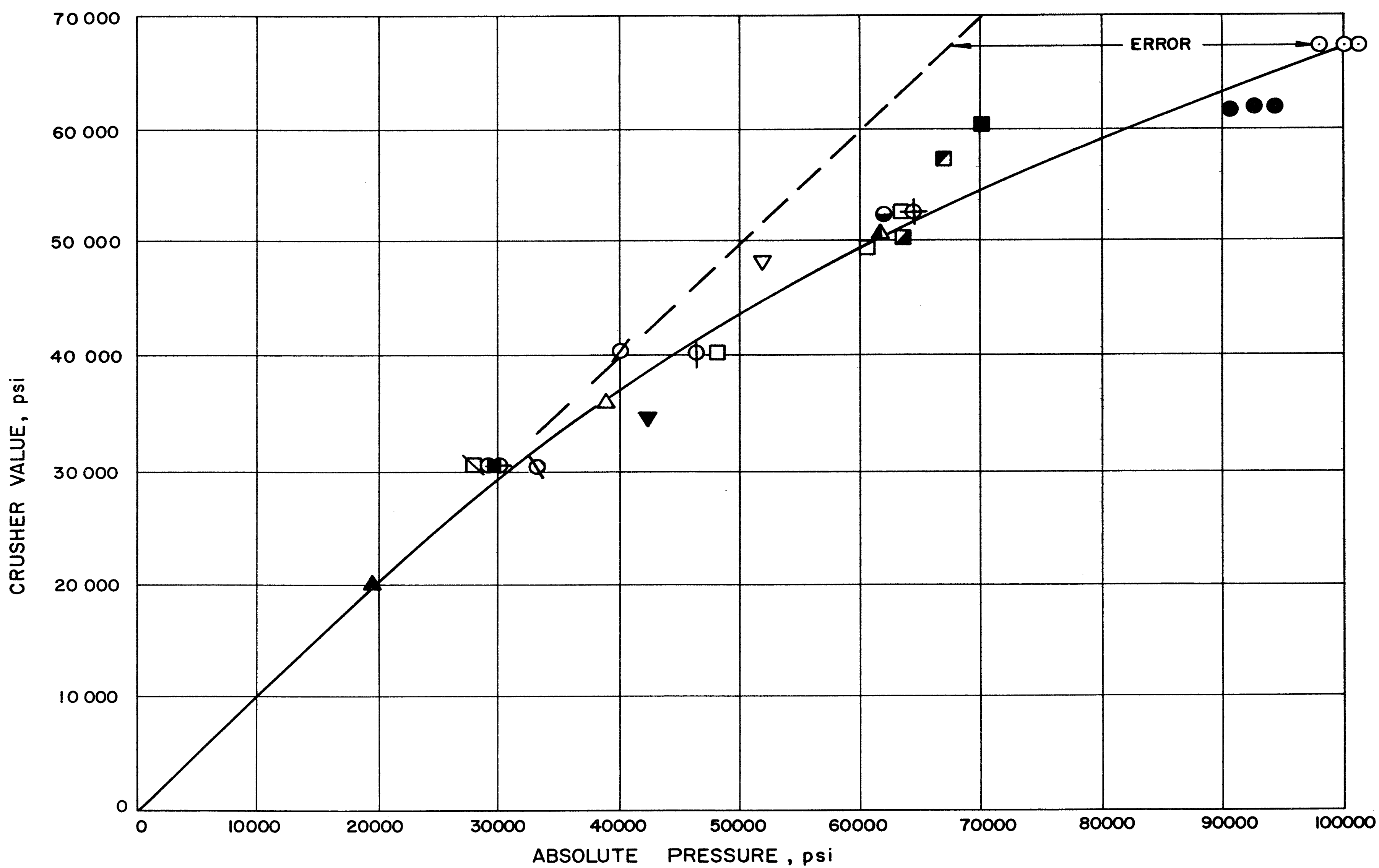

Fig. 18. Calibration Curve for Ballistic Crusher Values vs Absolute Chamber Pressure

Perhaps examples of the procedure for calculation of pressures would be appropriate here. If we divide 63,600 psi by 14 units we obtain 4,540 psi absolute pressure per vertical unit on the oscilloscope sweep. For the 20, 20-1/2 and 21 vertical units for the 48.0 grains IMR 3031 loading we obtain absolute pressures of 90,800, 93,100, 95,300 respectively by multiplying the scaling factor of 4,540 psi per unit by the value of the vertical units at peak pressure. Similarly for the load of 49.0 grains we obtain 97,700, 100,000 and 102,300 psi absolute pressure respectively. It is important to note that at the highest pressure of 102,300 psi absolute the crusher value is only 67,400 psi which gives a difference of 34,900 psi. This corresponds to a difference of over 50 per cent with respect to the crusher value. After these high-pressure tests both the receiver* and bolt of the rifle were replaced.

E. Plot of Relation Between Crusher Value and Absolute Pressure

Table I lists data from various sources used to prepare a general relationship between absolute pressure and crusher values. The data in Table I are plotted in Figure 18. Different designs of crusher gage apparatus give crusher values that vary somewhat for the same loads. Also, instruments for measurement of absolute pressure including piëzo and strain gages require calibration. Differences in calibration procedures will result in inconsistancies in evaluation of the same pressure. Thus, the curve shown in Figure 18 has limited application and may not correlate data from some measurements. The calibration is based on the ratio of piëzo gage pressures and crusher values determined in the Carney's Point Development Laboratory of the Explosives Division of E. I. Du Pont de Nemours and Co., Inc.,[7] and firings of the same loads at the University of Michigan. Additional calibration data are planned to establish these relationships more precisely.

IX. PRELIMINARY OBSERVATIONS ON THE EFFECT OF SEATING DEPTH ON MAXIMUM CHAMBER PRESSURE IN THE .30-06 CARTRIDGE

(R. Sinderman, K. Jacob and L. E. Brownell)

A. Reasons for Tests

There was no intent to investigate the effect of seating depth in these preliminary studies. However, the investigation of reported crusher gage values versus pressures determined by strain gage measurements for various loads for the .30-06 cartridge inadvertently introduced the problem of seating depth. One experimental loading involved a charge of 53 grains of IMR 4064 powder used with the 150 gr. Remington SPCL

*Receiver No. 614677, U.S. Springfield Armory was used in high-pressure tests.

bullet seated to an overall case length of 3.27 inches to give a reported[4] crusher value of 44,360 psi.* The 220 gr. Remington SPCL bullets used as a standard of reference were round-nosed and for this reason the first firings of the 150 gr. Remington SPCL bullets also used a round-nosed (30-30 type) bullet. The seating depth required to give an overall cartridge length of 3.27 inches gave only about 1/8 of an inch of bullet seat within the case. Firing these rounds produced unexpectedly high pressures in excess of 70,000 psi absolute pressure.

An attempt was made to investigate the unusually high pressures obtained. Remington produces three different 150 gr. SPCL bullets designed for three different seating depths and we first thought that the wrong bullet was being used. The pointed version of the SPCL bullet gives a more reasonable depth of bullet seat in the case for an overall length of 3.27 inches listed by NRA.* Therefore firings loaded with IMR 4064 powder with various seating depths were made with the 150 gr. SPCL (RN) Remington bullet. However, high pressures were still observed over a range of seating depths as shown in Table II and Figure 19. Substituting the pointed SPCL bullet for the round-nosed bullet failed to give a crusher value less than 54,000 psi at any seating depth.

The Du Pont handloading tables for center-fire rifle[1] report that 52.0 gr. of 4064 powder give a crusher value of 49,700 psi. An additional charge of 1.0 grains would be expected to raise the pressure possibly 3,000 to 5,000 psi. Other loading sources such as The Speer Handbook[12] and P. O. Ackley[13] indicate that 53 grains of 4064 powder and a 150 gr. bullet is approximately maximum for the 30-06 cartridge. The pressure reported by NRA for this load appears to be low.

To compare the observations on seating depth with data obtained on IMR 3031 powder and the 220 gr. Remington SPCL bullet a second series of preliminary tests were made as described in Table III and shown in Figure 20.

B. Discussion

Two opposing factors influencing the chamber pressure are believed to be involved if bullets are seated at various depths with a given charge of powder. One effect is that of change in the volume of

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TABLE II

Preliminary Data on Seating Depth for 150 Gr. Rem. SPCL Bullet in 30-06
Cartridge and 53 Gr. IMR 4064 (RN Bullet)

Total Cartridge Length (In)	Seating Depth from Cannelure (In)	Absolute Pressure P_{max}, (psi.)	Deviation from Median (%)	Total Cartridge Length (In)	Seating Depth from Cannelure (In)	Absolute Pressure P_{max}, (psi.)	Deviation from Median (%)
3.27	5/16" out	77,500	-0.3	3.02	1/16" out	71,400	+0.0
	(5/32" in case)	78,000	0.0		(13/32" in case)	71,000	0.0
		78,700	+0.3			68,500	-1.5
3.21	4/16" out	76,000	0.0	2.96	At Cannelure	70,000	+0.2
	(7/32" in case)	78,500	+1.2		(15/32" in case)	69,500	0.0
		76,100	-0.0			69,500	-0.0
3.14	3/16" out	73,000	-0.3	2.90	1/16" in	74,500	+2.2
	(9/32 in case)	73,500	0.0		(17/32" in case)	71,000	0.0
		75,500	+1.8			71,000	-0.0
3.08	2/16" out	73,500	0.0	2.84	1/8" in	75,300	+1.4
	(11/32 in case)	72,500	-0.7		(19/32" in case)	73,300	0.0
		73,500	+0.0			71,200	-1.4

TABLE III

Preliminary Data for Seating Depth Firings Using 30-06 Cartridge Loaded
with 38 Gr. 3031, 220 Gr. Rem. SPCL Bullets and Rem. Cases

Total Cartridge Length (In)	Seating Depth from Cannelure (In)	Absolute Pressure P_{max}, (psi.)	Deviation from Median (%)	Total Cartridge Length (In)	Seating Depth from Cannelure (In)	Absolute Pressure P_{max}, (Psi.)	Deviation from Median (%)
2.47	13/16" in	56,200	+0.4	3.01	4/16" in	49,000	+1.3
	(22/16 in case)	55,500	0.0		(13/16" in case)	48,100	0.0
		55,100	-0.4			47,200	-1.3
2.59	11/16" in	53,300	-0.6	3.14	2/16" in	48,400	0.0
	(20/16" in case)	54,000	0.0		(11/16" in case)	48,400	0.0
		54,600	+0.6			54,400	7.2
2.65	10/16" in	53,800	+0.0	3.26	At Cannelure 0" in	50,400	-2.1
	(19/16" in case)	53,800	0.0		(9/16" in case)	52,400	0.0
		53,800	-0.0			54,400	+2.1
2.71	9/16" in	52,200	-2.1	3.38	1/8" out	58,100	-3.5
	(18/16" in case)	53,300	0.0		(7/16" in case)	62,200	0.0
		54,400	+2.1			62,200	0.0
2.77	8/16" in	49,000	0.0	3.50	1/4" out	59,500	0.0
	(17/16" in case)	49,000	0.0		(5/16" in case)	61,600	0.0
		54,400	5.3			58,400	0.8
2.89	6/16" in	50,400	-3.7				
	(15/16" in case)	54,400	+2.0				
		54,000	0.0				

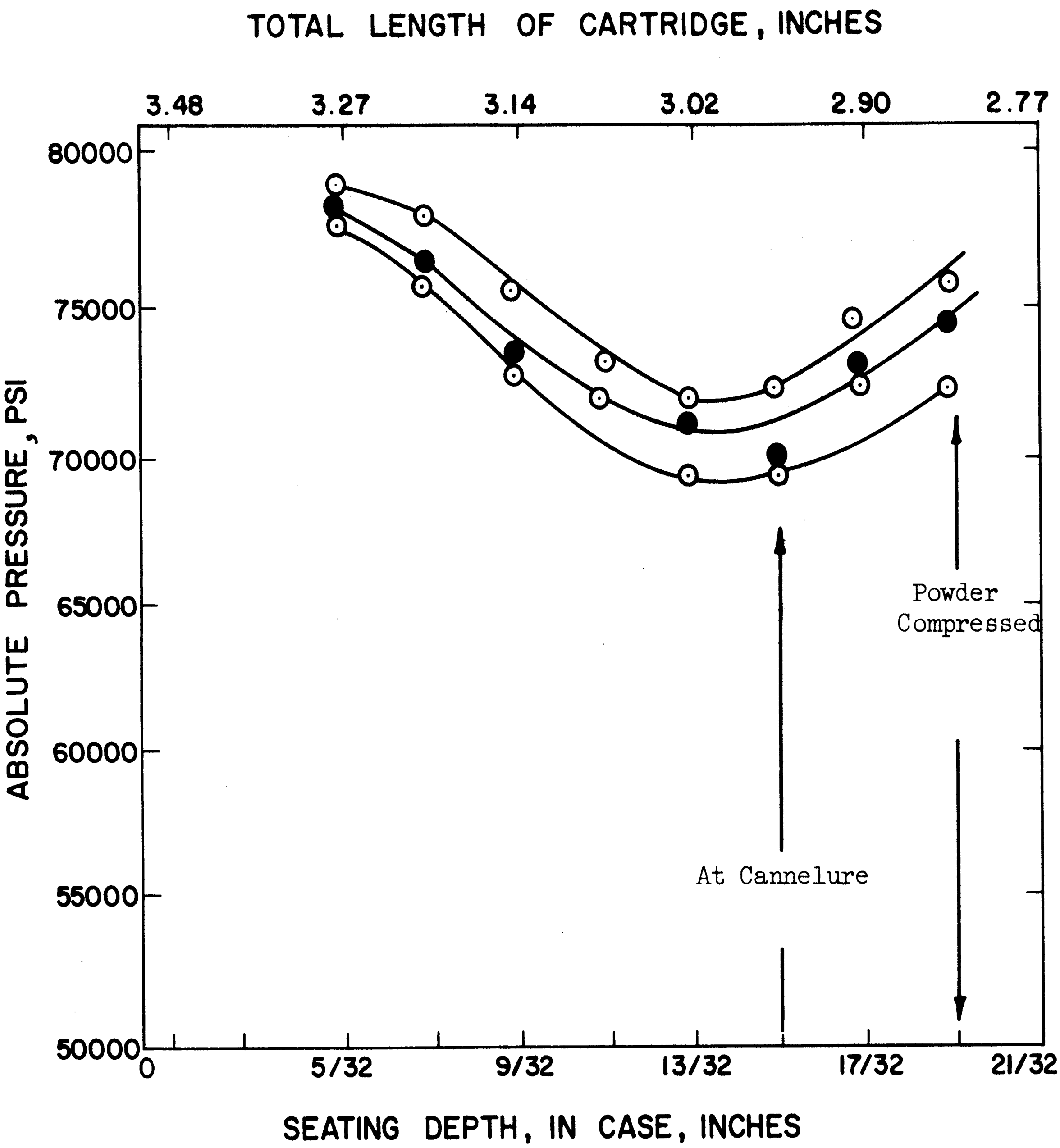


Fig. 19. Effect of Seating Depth on Maximum Chamber Pressure for 150 gr. Rem.SPCL (RN) Bullet and 53.0 gr. IMR 4064 Powder.

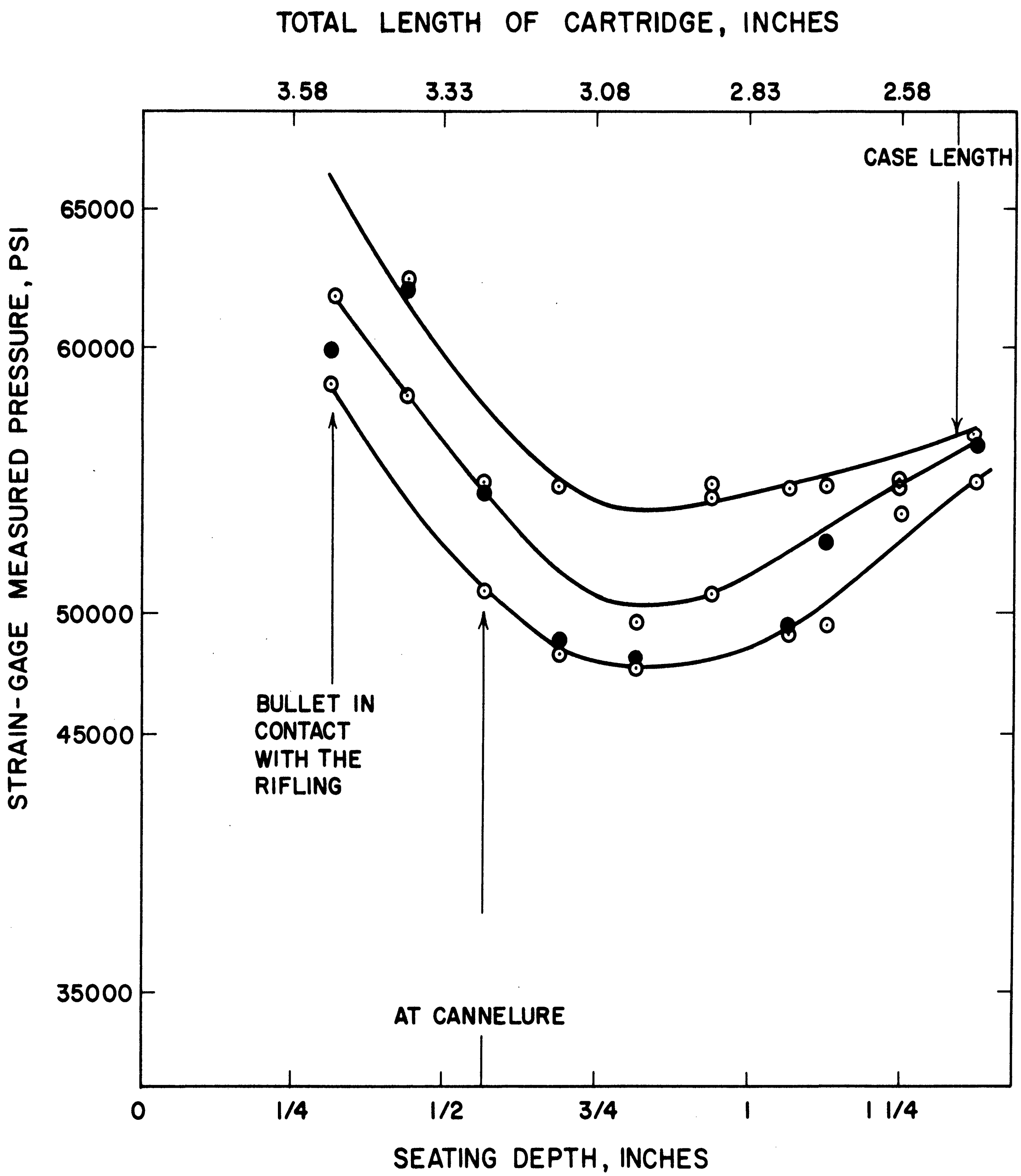


Fig. 20. Effect of Bullet Seating Depth on Maximum Chamber Pressure for 220 gr. Rem. SPCL Bullet and 38 gr. IMR 3031.

the case to the bullet base. Boyle's Law for gases states that if the temperature is not varied the pressure of a confined gas times its volume remains a constant. Or, stated as an equation:

$$P \times V = C$$

where

P = gas pressure, psi,

V = volume of confined gas, cu. in. and

C = is a constant which depends on the mass of the gas, (grains), the temperature of the gas, and the average molecular weight of the gases produced by burning of the powder.

For a given type of powder, the temperature of the powder gas versus fraction of powder charge burned and the average molecular weight of the gases may be considered to be fairly constant. Therefore, the mass of the gas will be determined mainly by the weight of powder burned. If a given per cent of the charge is burned the larger charge will produce a greater pressure; i.e., if a charge of 40 grs. of a certain powder is used, one would expect to get a larger number for the constant than if 30 grs. of the same powder were used. Also, if one were to increase the temperature of the confined gas, the product of the pressure and volume would increase (according to Charles' Law) thereby increasing the constant, C .

The second effect is termed gas leakage. In most rifles the bullet is allowed to travel some distance before engaging the rifling of the barrel. This distance is termed "free-travel distance". Some gas will leak past the bullet after the rise in chamber pressure expands the neck of the cartridge case but before the bullet starts to move. In other words, some of the gases produced by the burning powder actually enter the barrel before the bullet during the period of the "free-travel" of the bullet and before it is forced tightly into the rifling. High-speed photography has been used to record this phenomenon and show that a small portion of the powder gases actually come out of the muzzle before the bullet. The egress of initial volume of gas is followed by the bullet and then by the major volume of powder gas.

The data on the series of firings for the 150 gr. Remington SPCL bullets loaded with a charge of 53 gr. of IMR 4064 powder are shown in Table II. Because of the larger volume of this larger charge it was impossible to seat the bullet more than 3/16 inch into the case from the cannelure. Also, because of the shorter length of the bullet it was impossible to seat the bullet out far enough to engage the rifling. However, the two opposing effects were still observed as shown in Figure 19. The chamber pressure reached a minimum value when the bullet was seated out 1/16 inch from the cannelure; but if the bullet was seated 5/16 inch out or 3/16 inch in from the cannelure a higher maximum pressure was produced. This indicates that the minimum value for maximum chamber pressure can be expected to be different for different powder charges and bullet weights.

A difference of about 6,250 psi was observed between the minimum and maximum values of absolute maximum chamber pressure.

In the second series of tests a 220 gr. Remington SPCL bullet was used with a charge of 38 grs. of IMR 3031 powder. The charge of 38 grs. of IMR 3031 produces a moderate pressure when the bullet is seated at the cannelure. The effects on pressure of the extremes of seating the bullet: (1) out to the rifling, and (2) in to the point of powder compression were not known, therefore, a reduced load seemed advisable. The reduced charge of 38 grains also permitted seating the bullet completely into the case without causing the powder grains to be excessively compressed or to be partially broken.

Bullets were seated over a range from 1/4 inch out from the cannelure to 13/16 inch from the cannelure. Seating the bullets out 1/4 inch actually engaged the 220 gr. Remington SPCL bullets with the rifling when the bolt was closed. This seals the barrel so as to produce a minimum of gas leakage past the bullet. Consequently, essentially all of the gases produced by the burning of the powder contributed to increase of the pressure in the chamber. This tends to produce a higher maximum chamber pressure in spite of the slightly larger case volume produced by seating 1/4 inch out from the cannelure.

At the other extreme of seating the bullets were pushed into the case 13/16 inch past the cannelure. The bullet at this seating must travel about 1-1/16 inches of "free-travel" before engaging the rifling. An increase in pressure again was noted. This is a result of Boyle's Law effect. When the bullet is seated into such an extreme the case volume is reduced to such an extent that the pressure increases in spite of the greater leakage of gas.

Intermediate seating depths produced intermediate pressures as shown in Figures 19 and 20. Figure 20 for IMR 3031 powder and 220 Remington SPCL bullets indicate that the pressure reaches a maximum at the smallest seating depth of 1/4 inch with the bullet in contact with the rifling. As the seating depth of the bullet is increased pressure decreases due to the gas leakage past the bullet into the rifle barrel. Boyle's Law would predict that the pressure would rise because of the decrease in volume, but apparently this is overshadowed by the gas leakage past the bullet. The chamber pressure appears to reach a minimum value at a seating depth of about 1/4 inch in from the cannelure. This corresponds to a total bullet seating depth of 13/16 inch. At greater seating depths the pressure rises again. This rise in maximum chamber pressure, as stated previously, is believed to be due to the predominence of Boyle's Law effect. Though considerable gas is leaking past the bullet, gas leakage is now overshadowed by the large decrease in the case volume to the base of the bullet. This decrease in case volume increases the maximum pressure rapidly as shown by Figure 20. The maximum pressure is over 5,000 psi greater than the minimum value produced with the bullet seated 1/4 inch in from the cannelure. On the other hand the maximum pressure increases about 10,000 psi above this minimum when the bullet is seated out so that it engages the rifling. Thus, some danger of excessive pressure is involved if seating depths are used which differ appreciably from those used in loadings known to be safe.

X. THE PRESSURE "HORN"

A. Reproducibility of Replicate Firings

Measurements made with the strain gage and oscilloscope equipment indicate a good reproducibility of the absolute maximum chamber pressures if the powder charge is sufficient to produce a crusher value of about 50,000 psi or more. This is indicated by the data for P_{max} in Tables II and III. In Table II the absolute pressure for each selected seating depth seldom varied more than 400 psi. However, the absolute pressures ranged from 68,500 to 78,700 depending upon the seating depth. The variation for each seating depth corresponds to a pressure deviation of about 1 per cent in most cases. All but 2 of 22 firings have pressure variations less than 1.8 per cent and the maximum observed was 2.2 per cent.

As the maximum pressure is decreased the spread in value of P_{max} for replicate firings begins to increase as is indicated by Table III where the absolute pressure values range from 47,200 psi to 62,200 psi.

However, the deviation is not great usually being less than 3.7 per cent except for two firings. The absolute pressure reported in Table III are safe pressures for any modern bolt-action rifle with proper head spacing and designed to handle the 30-06 cartridge. The pressures in Table II are excessive and definitely are unsafe for use in hand loads. When this series of firings was completed the head spacing of the test rifle had been increased to the "field gage" limit and it was necessary to replace the bolt to bring the head spacing back to a value between Go and No-Go gages. Repeated firings of cartridge loads with absolute pressures in the range of 70,000 to 80,000 psi will produce excessive loads which will result in plastic deformation of tough nickel-steel bolt lugs and might produce brittle fracture failure in bolts with high hardness.

Figures 21 and 22 show the spread in P_{max} for the 180 gr. and the 220 gr. SPCL Remington bullet respectively using charges of Du Pont IMR 3031 powder ranging from 9.0 gr. to 49.0 gr. As larger charges of powder are used higher values of P_{max} are obtained and minimum deviation in pressure for replicate firings is observed. However, in both figures a pressure "Horn" exists at powder charges of about 20 grains. There is obviously a "Pressure Excursion" with some firing loads in this range in which the maximum pressure for replicate firings may differ by factors of more than 2 to 1. The data for Figures 21 and 22 are listed in Tables IV and V.

B. <u>The "Pressure Excursion"</u>

The "Pressure Excursion" occurs in the region of the pressure "Horn". It is clearly demonstrated in Figure 23a which shows four successive firings using 180 gr. Remington SPCL bullets (cut from 220 gr. bullets). Remington components and a charge of 20.0 gr. of IMR 3031 powder weighed to $\pm$ 0.1 grains were used for each firing. Figure 23 shows a P_{max} with a variation from 7.2 to 17.5 vertical units on the oscilloscope grids. This corresponds to a pressure ratio of 2.44 or 244 per cent increase in pressure from minimum to maximum values. Figure 24a is included for comparison and shows five successive firings with near maximum charges of Hi-Vel # 2 powder. The five vertical scale readings all are between 18.0 and 19.0 or less than 6 per cent variation.

The phenomenon of the "Pressure Excursion" indicated by the "Horn" in both Figures 21 and 22 and the erratic replications in Figure 23 indicate the difficulty in obtaining good reproducibility of pressure using reduced charges of powder. The authors believe that the explanation of the cause of this "Horn" is directly related to excessive pressures

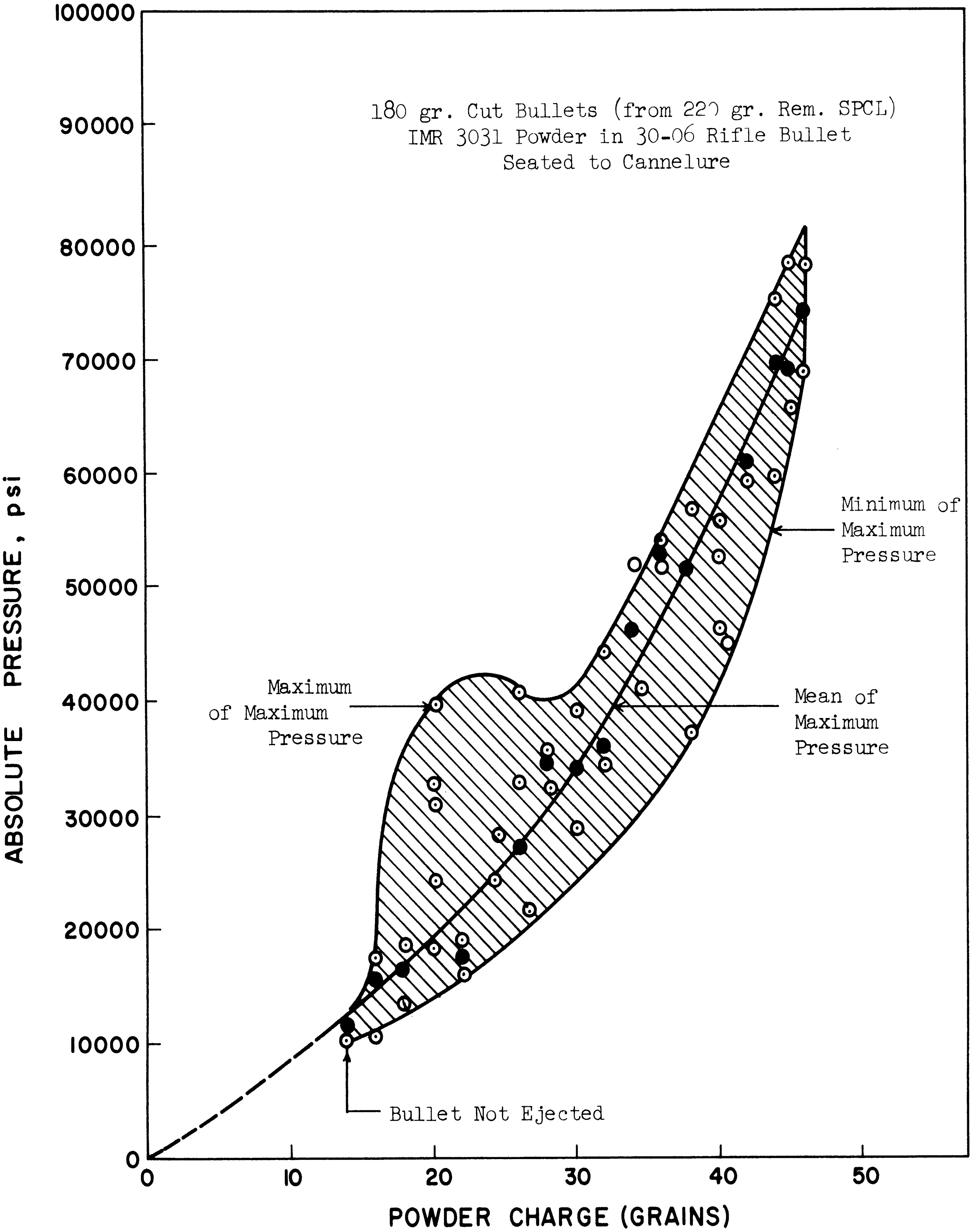


Fig. 21. Maximum Chamber Pressure, (P_{max}) versus Charge of IMR 3031 Powder

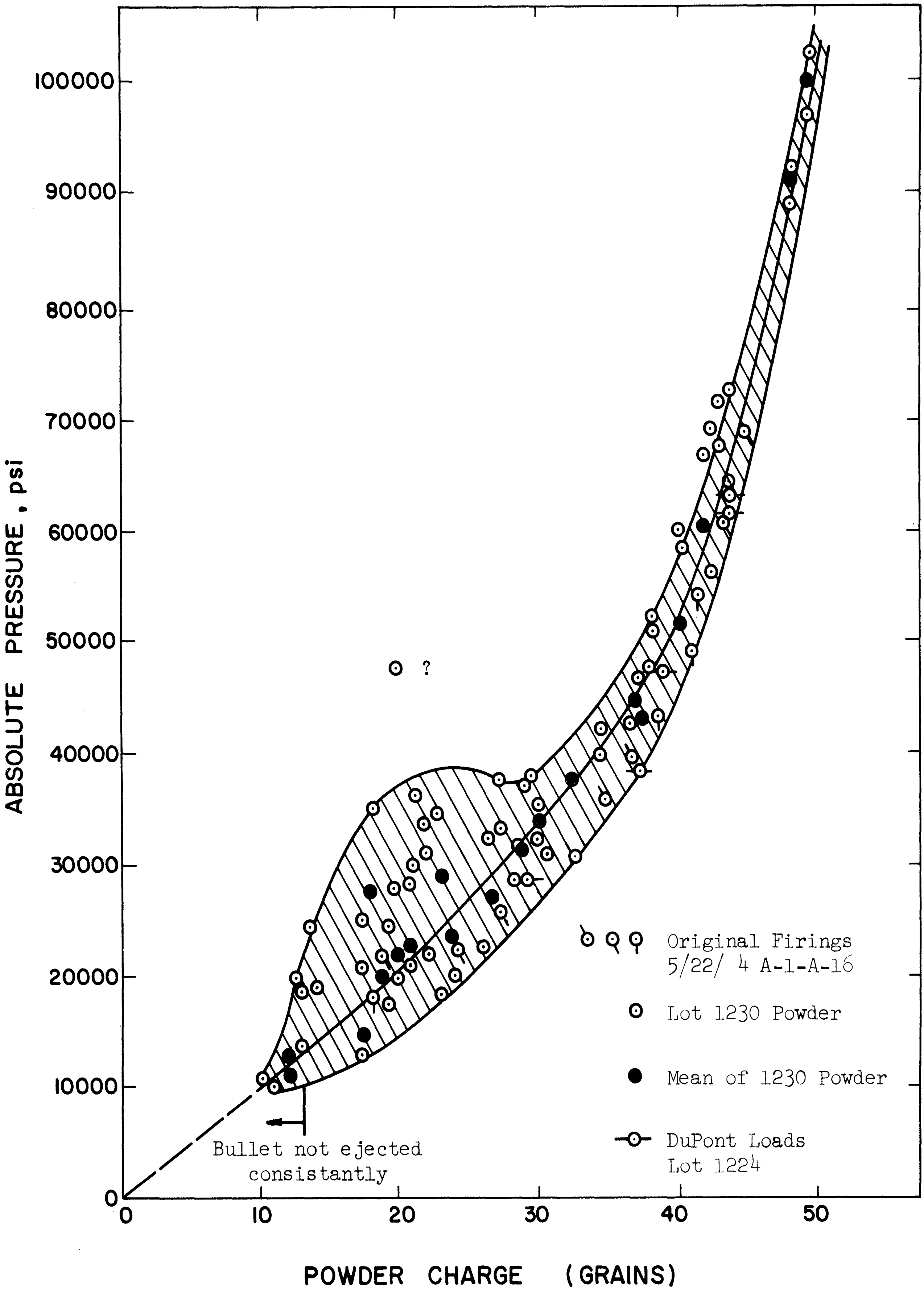


Fig. 22. Maximum Chamber Pressure (P_{max}) versus Charge of IMR 3031 Powder for 220 gr. Bullets (Rem. SPCL)

TABLE IV

Preliminary Data on P_{max} Pressures Produced by Various Charges of IMR 3031 Powder Using 180 Gr. Bullets (cut from 220 gr. Rem. SPCL) and Remington Components

3031 Powder Charge gr.	Absolute Pressure P_{max}, (psi.)	3031 Powder Charge gr.	Absolute Pressure P_{max}, (psi.)
14.0	11,200	32.0	32,400
	10,000		41,500
16.0	17,000	34.0	36,200
	14,500		43,400
	10,000		51,000
18.0	12,500	36.0	50,500
	16,300		48,800
	14,800		49,000
20.0	17,000	38.0	34,400
	19,200		40,000
	30,800		38,000
	31.200		53,000
	28,400	40.0	44,300
	37,000		43,200
22.0	14,300		46,700
	15,700		51,000
24.0	24,200	42.0	55,700
	18,400		56,500
26.0	19,500		57,500
	30,400	44.0	55,600
	30,400		56,500
28.0	30,000		65,000
	32,600		64,000
	33,200		70,000
30.0	27,400	45.0	61,500
	28,000		64,000
	31,800		64,600
	32,500		65,000
	33,600		73,500
		46.0	64,000
			69,000
			73,000

TABLE V

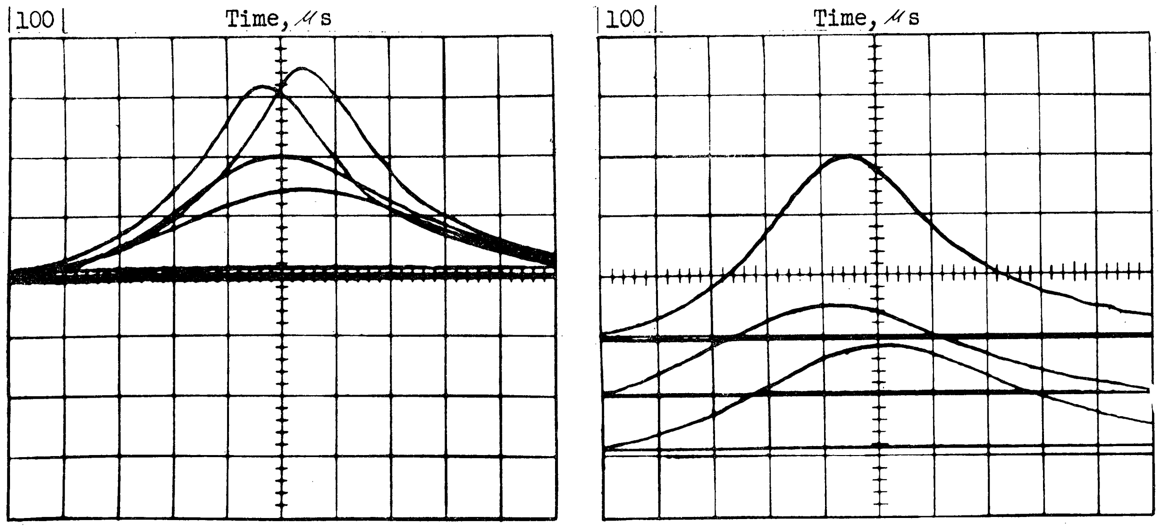
Preliminary Data on P_{max} Pressures Produced by Various Charges of IMR 3031 Powder Using 220 Gr. Bullets and Remington Components

3031 Powder Charge (gr.)	Absolute Pressure P_{max}, (psi.)
10.0	10,000
11.0	10,000
12.0	11,000
	12,500
	(15,600)*
	19,000
	20,000
13.0	14,000
	19,000+
	25,000
16.0	25,500
17.0	13,500
	15,000
	16,000
	(16,400)*
	21,000
18.0	18,000
	22,500
	28,000+
	32,000
	35,400
19.0	17,400
	19,000
	(20,900)*
	22,500
	25,000
20.0	20,000
	25,000
	28,400+
	35,000
	48,000
21.0	21,300
	22,500
	(24,600)
	30,000

3031 Powder Charge (gr.)	Absolute Pressure P_{max}, (psi.)
22.0	22,400
	31,000+
	33,800
23.0	18,600
	22,400
	(25,600)*
	29,000
	32,400
24.0	20,400
	23,800
	(24,300)*
	25,000
	28,000
26.0	24,500
	26,400
	27,000
	(27,500)*
	32,000
28.0	29,200
	33,800+
	37,600
29.0	29,000
	33,000+
	37,000
30.0	31,200
	33,000
	(33,500)*
	34,200
	35,600
32.0	31,600
	35,000
	38,300
34.0	36,000
	40,000+
	41,400
26.0	43,300
	44,500+
	46,400

3031 Powder Charge (gr.)	Absolute Pressure P_{max}, (psi.)
37.0	39,000
	43,000+
	47,000
38.0	43,700
	51,400+
	51,800
40.0	49,500
	51,500
	(55,500)*
	59,400
	60,000
41.0	54,700
42.0	55,700
	60,000+
	66,100
43.0	61,500
	67,500+
	68,600
43.5	68,700
44.0	62,000
	64,000
	65,000+
	67,500
	71,000
44.5	71,500
48.0	92,000
	90,700+
	88,500
49.0	97,500
	100,000
	102,500

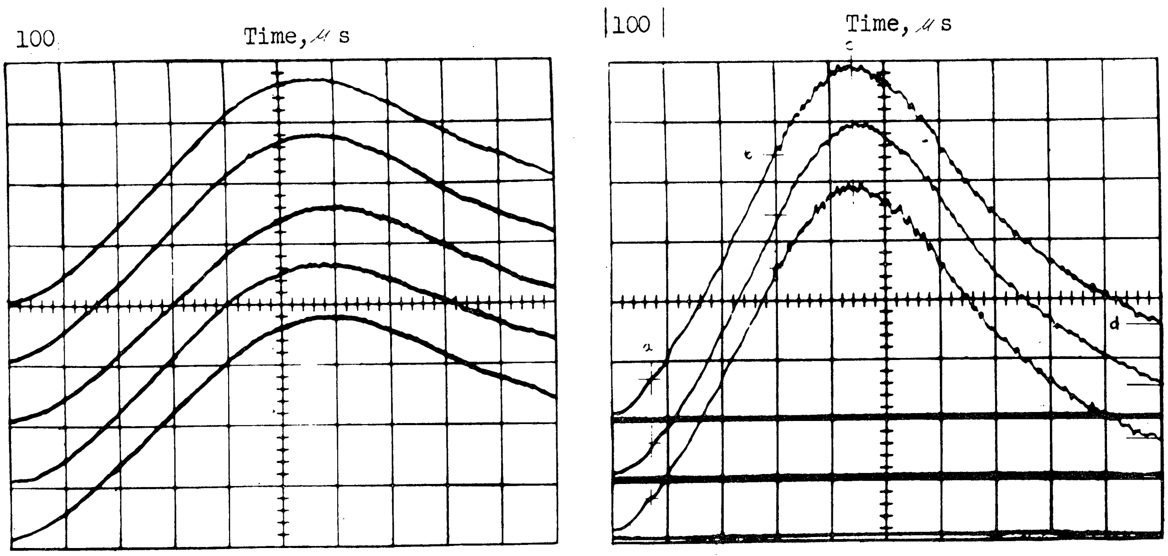
* Average value
\+ Median



a. Four replicate firings of 20.0 gr. IMR 3031 powder, 180 gr. Rem. SPCL Bullet (cut from 220 gr.) with new Rem. 30-06 cases and Rem. primers.

b. Three replicate firings of 21.0 gr. IMR 3031 powder, 220 gr. Rem. SPCL Bullet with new Rem. 30-06 cases and Rem. primers.

Fig. 23. Negatives of Displays on Model 564 Oscilloscope Showing Pressure Excursions of Replicate Firings of Reduced Charges



a. Five replicate firings of 43.0 Hi-Vel #2 powder, 180 gr. Sierra Bullet with new Rem. 30-06 cases and Rem. primers.

b. Three replicate firings of 53.0 gr. IMR 4064 powder, 150 gr. Rem. SPCL bullet with new Rem. cases and Rem. primers.

Fig. 24. Negatives of Displays on Model 564 Oscilloscope Showing Excellent Duplication of Replicate Firings of Maximum Charges

that have been reported for reduced charges of slow burning powder. In the case of 3031 powder the peak of the pressure "Horn" is less than 40,000 psi, absolute pressure and therefore this phenomenon may not have been observed by hand loaders particularly those who depend upon such signs as plastic deformation of cases and primers as an indication of pressure. In the case of IMR 3031 the pressures produced by the "Pressure Excursion" is both normal and safe. We believe that much may be learned about improvement in the uniformity of reduced loads and about what precautions should be taken to prevent large "Pressure Excursions" that have been reported by P. O. Ackley, Jack O'Connor, Speer Bros., Inc., and other authors[9] on the subject of handloading. If the present ballistic studies are continued we hope to have the opportunity to explore the phenomenon of the "Pressure Excursion" with slow burning powders such as IMR 4350, 4831, and Spherical H-870.

REFERENCES

1. "Du Pont Handloading Information for Center-Fire Rifle, Pistol and Revolver Ammunition," Chemical Products Sales Division, Explosives Department, E. I. du Pont de Nemours & Co. (Inc.), Wilmington 98, Delaware, (1962).

   Hutton, R., "On the Technical Side - New Loading Data," Guns & Ammo, 5, No. 12, p. 56, December 1962, Robert Peterson Publishing Co., Los Angeles, California, 1962.

2. "Gunbugs Guide," A. B. Norma Projsktilfabrik, Amotfors, Sweden, Norma Precision, South Lansing, N. Y., 1962.

3. "Hodgdon's Loading Data No. 16," B. E. Hodgdon, Inc., Shawnee Mission, Kansas.

4. NRA Illustrated "Reloading Handbook," National Rifle Association, Washington, D. C., 1960.

   Waite, M. D., "Loads for the 30-06," The American Rifleman, 104, No. 10, 36, 1956.

5. York, M. W., "The Non-Destructive Measurement of Rifle Chamber Pressure Through the Use of Strain Gages," Thesis for C. M. 690, Department of Chem. and Met. Eng., The University of Michigan, Ann Arbor, Michigan, May, 1963.

6. York, M. W., Gyorey, G. L., and Brownell, L. E., "Ballistic Breakthrough," Ordnance, J. Amer. Ord. Assoc., Washington, D. C., 49, No. 265, 1964.

7. Dunn, G. F., "Personal Communication," Du Pont Development Laboratory, Carney's point, N. J., 1964.

8. Naramore, E., "Principles and Practice of Loading Ammunition," Small Arms Technical Publishing Co., Georgetown, S. Carolina, 1954.

9. Eichhorn, E. L., "Personal Communication," Manager, Professional Services, Burroughs Corp., Equipment and Systems Marketing Div., Pasadena, Calif., 1964.

10. Brownell, L. E. and Young E. H., "Process Equipment Design - Vessel Design," John Wiley and Sons, Inc., New York, N. Y., 1959.

11. Sharpe, P. B., "Sharpe's Complete Guide to Handloading," Funk and Wagnalls Co., New York, N. Y., 3rd Edition, 1953.

12. Speer Manual for Reloading Ammunition, No. 6, Speer Inc., Lewiston, Idaho, 1964.

13. Ackley, P. O., "Handbook for Shooters and Reloaders," P. O. Ackley, Salt Lake City, Utah, 1962.

Appendix A*

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Ballistic Breakthrough

A new method has been developed for taking very accurate internal measurements of projectile velocity, acceleration, and relative pressure from the same test firing by the use of nuclear radiation

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A NEW method for obtaining internal ballistic measurements by the use of nuclear radiation has been developed. This method makes it possible to obtain internal ballistic measurements that are difficult or impossible to obtain by conventional means. Through the use of gamma radiation, our knowledge of internal ballistics can be improved, and this improvement can result in increased efficiency and reliability of weapons and ammunition.

Internal ballistic measurements such as the determination of the velocity or acceleration of the projectile and the chamber pressure in a weapon as a function of projectile travel down the bore are important to designers of weapons and ammunition. Such measurements allow the designer of a weapon system to obtain the maximum efficiency and accuracy from the system.

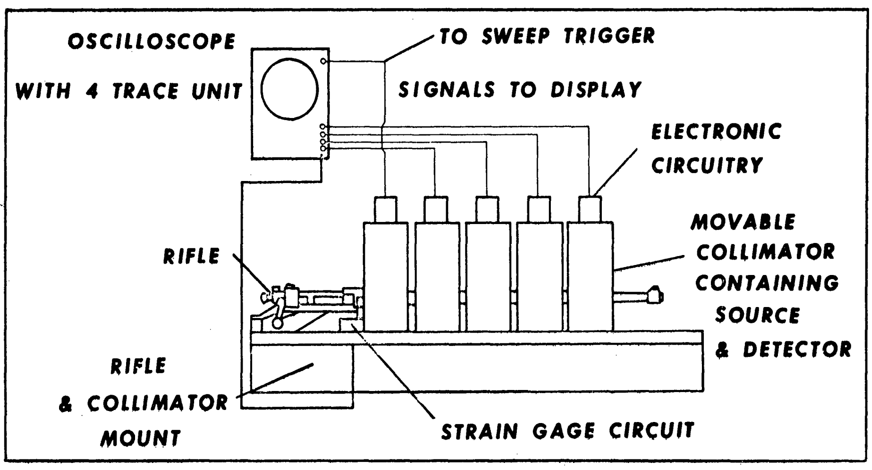
Internal ballistic measurements are difficult to obtain because of the short time interval in which a projectile is accelerated within a rifle or cannon barrel. The magnitude of this problem is readily evident when one considers that in a modern high-velocity small arm the projectile is accelerated from zero velocity to a velocity of about 3,000 feet a second within a time interval of only one-thousandth of a second.

In spite of the inherent difficulties in obtaining internal ballistic data, methods have been developed for acquiring some of these measurements. Chamber pressures have been measured in the past by the use of a copper "crusher" cylinder which is compressed by the pressure in the chamber of the weapon. This method gives approximate values of maximum chamber pressure, and for most reliable measurements is restricted to use in a special test-gun barrel that has been prepared for such a device.

Some other methods, such as the use of a piezoelectric gage, have been used to obtain pressure information, but these suffer from some of the disadvantages of the crusher-cylinder technique.

Procedures for the measurement of the acceleration and/or velocity of projectiles within gun bores have also been developed. Some methods have involved the use of wires, etc., that were inserted into the gun bore to detect the passage of the projectile. Ultrasonic or electromagnetic waves can be reflected from the projectile out the muzzle to give information on bullet travel versus time.

Fig. 1. Apparatus used in experimental tests is shown in diagram below.



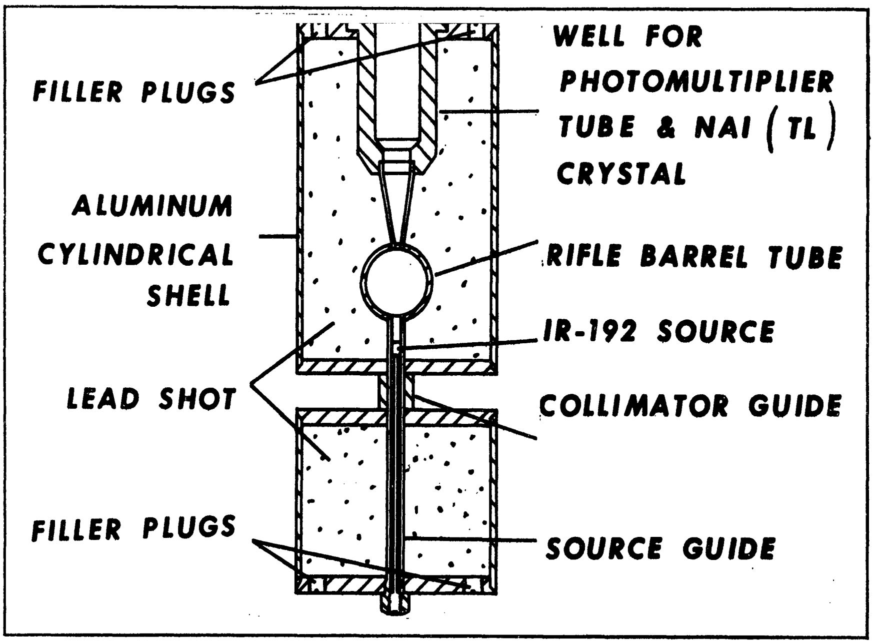


Fig. 2. Diagram shows cross section of aluminum collimating cylinder.

These methods may require modification of the barrel that is being tested. The main disadvantage is that none of the methods described give data simultaneously on both the chamber pressure and bullet position as a function of time.

THE new nuclear radiation method does not have the disadvantages and limitations that are inherent in previous techniques. Furthermore, the new method provides information that cannot be obtained with the methods in current use, and therefore the method is considered to be an experimental "breakthrough."

Using nuclear radiation it is possible to obtain accurate projectile velocity and acceleration information based on the distance the projectile has traveled down the gun bore. During the same firing, pressure information related to the travel of the projectile down the gun bore also can be obtained through the use of strain gages combined with nuclear radiation.

Through the proper selection of a radiation source, this nuclear method can be utilized to obtain internal ballistic measurements from guns of almost any caliber. The tests that were conducted to develop and verify the feasibility of this method were made with a model 1903/A3, .30/'06 Springfield rifle. These tests were sufficient to show that nuclear radiation can be applied to internal ballistic measurements on larger guns.

The radiation technique developed with the .30/'06 Springfield rifle utilized nuclear radiation from the radioisotope iridium 192 and suitable radiation detectors. Iridium 192 emits gamma rays that are capable of penetrating matter in the same manner as the more familiar X-rays.

This radioisotope has been used in radiographic work and it is readily available from commercial suppliers as well as from the U. S. Atomic Energy Commission at a relatively moderate cost.

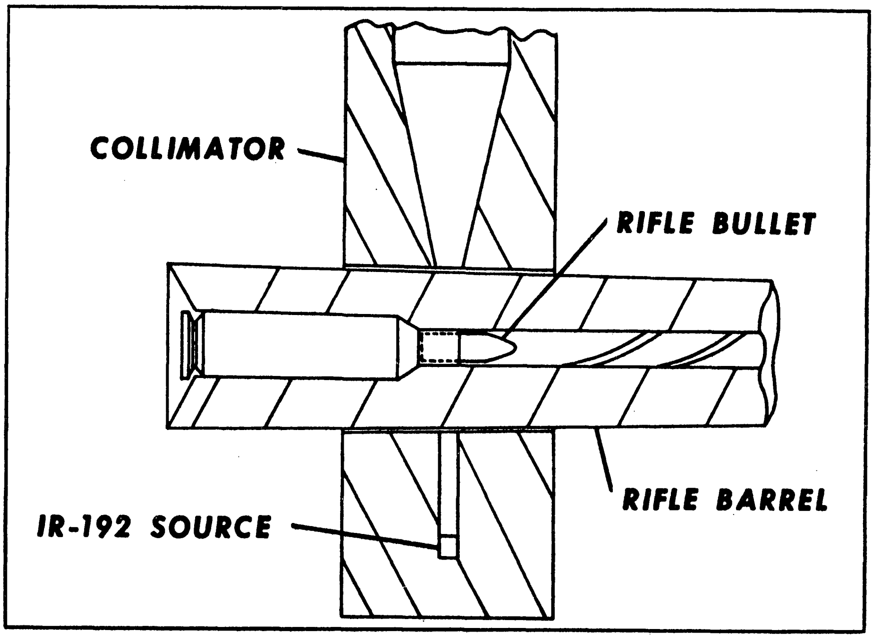
A diagram of the apparatus used in the experimental tests is shown in Figure 1. The equipment consists of a rifle, five radiation collimating cylinders, a mount for the rifle and the collimators, five iridium 192 gamma radiation sources, five radiation detectors and the associated electronic circuitry, two strain gages, a strain-gage circuit, an oscilloscope, and a camera.

The rifle and collimator mount serves two basic functions: it secures the rifle, preventing motion from recoil, and it provides a base and guide for the collimating cylinders which can be moved to any desired positions along the rifle barrel.

The collimating cylinders are aluminum casings filled with lead shot. They each contain an iridium 192 radiation source and a radiation detector. A diagram of the cross section of a collimator is shown in Figure 2. The collimator casing is cylindrical, and the iridium 192 gamma source is located in a source guide at the bottom of the collimating cylinder. A large hole through each collimator at right angles to the axis of the cylinder permits the rifle barrel to be slipped through the collimator. The collimating cylinder contains a funnel-shaped insert so that virtually all the gamma radiation intersecting the bore is incident upon the radiation detector.

The radiation detector consists of a scintillation crystal and a photomultiplier. The nuclear radiation signal is detected by the crystal, and the signal is passed to the photomultiplier tube. The photomultiplier tube is attached

Fig. 3. Sectional diagram shows relationship of first collimator to rifle bullet.



to a preamplifier mounted on top of the collimating cylinder. The output of the photomultiplier tube and preamplifier is fed to an integrating circuit.

AFTER passing to the integrating circuit, the output of the photomultiplier tube located closest to the breech of the rifle also is fed to the external trigger input on an oscilloscope. The oscilloscope is capable of simultaneously displaying four voltage traces.

The output of each of the other photomultiplier tubes is fed first to an integrating circuit and then to one of the four inputs on the oscilloscope. A camera is used to record the display on the oscilloscope.

The two strain gages used to obtain pressure measurements are attached around the chamber section of the rifle barrel and are connected to an electronic circuit whose output is displayed as one of the traces on the oscilloscope.

The first collimator is located so that when a cartridge is seated in the chamber of the rifle, the lead core of the projectile intersects and attenuates the beam of gamma radiation from the iridium 192 radiation source. Figure 3 shows a cross section of the rifle chamber and the first collimator, indicating the relationship of the bullet and the gamma beam.

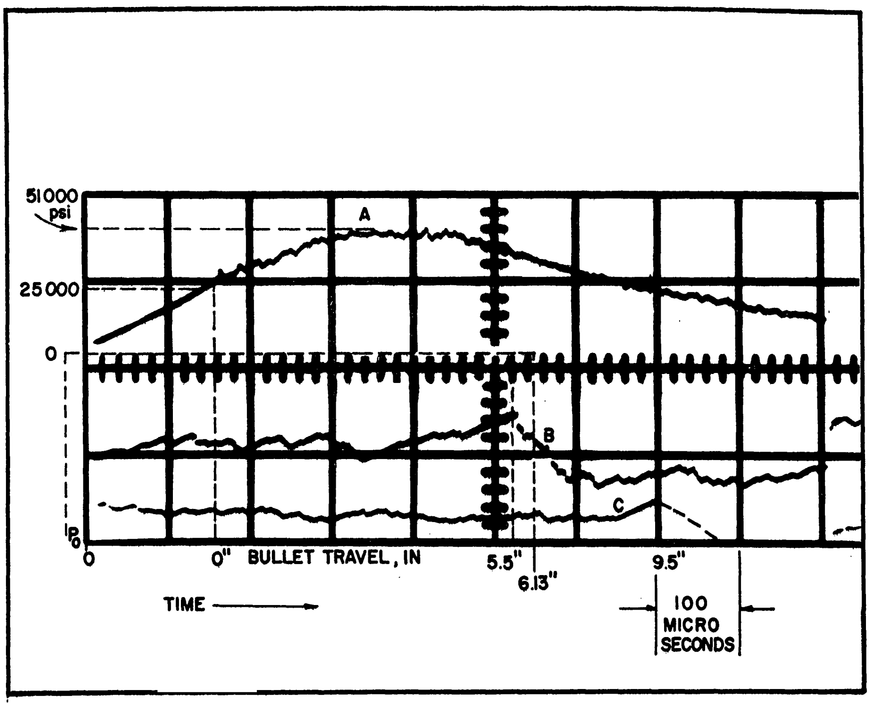
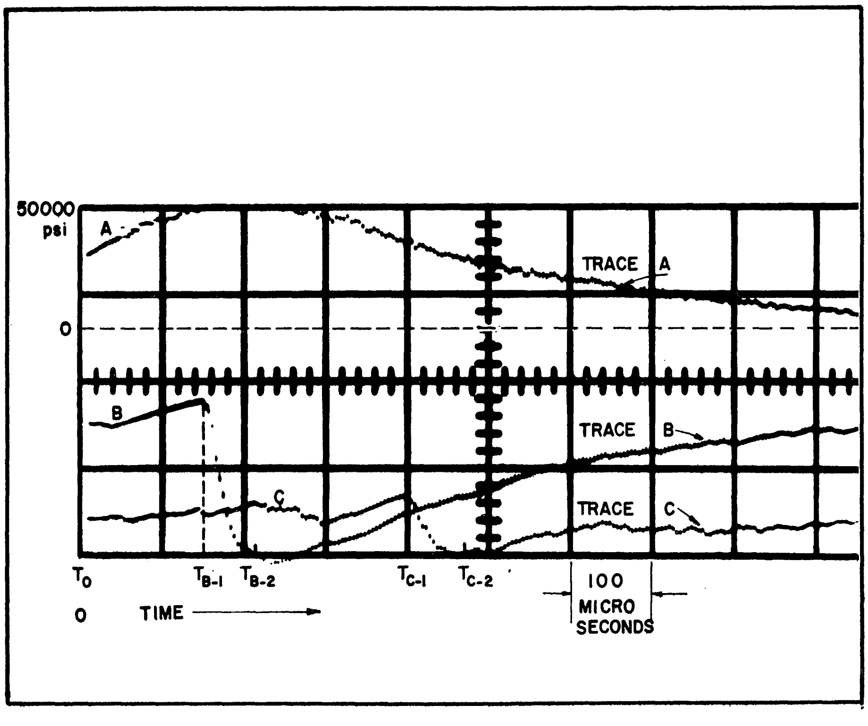


Fig. 5. Chamber pressure and bullet position after primer firing and ⅛-inch of initial bullet movement (at T_0) with detectors at 0, 5.5 and 9.5 inches shown above.

When the rifle is fired, pressure builds up behind the projectile from combustion of the primer and propellant and forces the projectile out of the cartridge case and down the bore of the rifle.

As soon as the projectile has moved approximately one-quarter of an inch, the gamma beam is no longer attenuated by the projectile. This change in attenuation results in a voltage signal being fed into the external trigger on the oscilloscope. This voltage rise triggers the sweep of the oscilloscope.

Fig. 4. Sweep shows chamber pressure and bullet position as a function of time as projectile begins moving down bore rifling with detectors at 0, 1.87 and 6.13 inches.



As the projectile continues down the rifle bore, it is accelerated due to the combustion of the powder in the cartridge. The projectile successively intersects the gamma beams of the other collimators located down the barrel. Corresponding voltage changes are indicated on the oscilloscope display of the traces of the successive collimators.

The distance between any two pulses, multiplied by the time-scale factor used on the oscilloscope, gives the time required for the projectile to travel between the corresponding two gamma beams. Since the distances between the gamma beams are known, a displacement-versus-time curve can be obtained. The distance between the collimators and their location along the rifle barrel can be adjusted so that any segment of the barrel can be studied.

In order to obtain a trace of both chamber pressure and bullet travel as a function of time, one of the four-trace plug units is supplied with the input from the strain-gage circuit. After the cartridge is fired, the pressure in the rifle chamber rises, producing a strain on the surface of the barrel and a voltage change in the strain-gage circuit. This voltage change is displayed on the oscilloscope and indicates the instantaneous pressure in the chamber of the rifle.

By use of equations describing the voltage change in terms of strain and strain in terms of chamber pressure, the voltage curve from the strain-gage sweep can be converted to pressure and is found to be directly proportional. (See Figures 4 and 5.)

ONE feature of the experimental "breakthrough" consists of the development of a method for precise determination of time zero, T_o, which is the time when the bullet has moved ⅛-inch from the cartridge case. At this instant the high-speed oscilloscope is triggered by a beam of gamma radiation.

The scope makes a single sweep in one millisecond (1/1,000-second) and displays the voltage change in strain gages used to measure pressure. The sweep of the oscilloscope time scale has fifty subdivisions, indicating that each subdivision measures the changes produced in 20 microseconds (20 millionths of a second). Three traces are shown: A, B, and C. Trace A is of chief interest.

Trace A shows the chamber pressure (measured by strain gages) versus time, from the time the projectile has moved ⅛-inch until the projectile has left the muzzle. In this trace, the pressure is about 25,000 p.s.i. when the projectile has moved ⅛-inch and enters the rifling. The pressure reaches a maximum of about 51,000 p.s.i. about two-tenths of one-thousandth of a second later. The pressure then starts to drop and is only a few thousand p.s.i. when the projectile has reached the muzzle.

Traces B and C are the respective signals from detector B located 1.87 inches and detector C located 6.13 inches down the barrel from the bullet base at the initial bullet position in the cartridge. As the bullet passes detectors B and C, a drop in the signal is produced starting at $T_{B\text{-}1}$ and ending at $T_{B\text{-}2}$ for the detector B and beginning at $T_{C\text{-}1}$ and ending at $T_{C\text{-}2}$ for the second detector C. The pulses from these detectors make it possible to determine the time intervals required for the bullet to reach position B and C down the barrel. This provides velocity information and a pressure-versus-time curve all for a single firing.

The three traces shown in Figure 4 permit many analyses to be made. The pressure curve versus time is proportional to the acceleration versus time if we include a correction for the energy expended in bullet engraving, bore-friction, and other lost work.

One integration of the acceleration-time curve will give a curve proportional to the velocity-versus-time curve. Integration of the velocity-time curve will give the distance of projectile travel versus time.

Two distance of travel measurements are given by detectors B and C which permit evaluation of the factors to convert the integral of the pressure-time curve to the velocity-time curve. Cross plots also permit construction of pressure and velocity curves versus distances of projectile travel. Thus from a single firing, the entire family of internal ballistic relationships for that load combination can be obtained.

Figure 5 shows a negative of another oscilloscope photograph. In this figure the sweep was started at an initial pressure of a few hundred p.s.i. (estimated at about 20 microseconds after the time when the chamber pressure begins to rise from zero). The pressure curve again is indicated by the sweep labeled A in Figure 5.

The slightly curved pressure line from the left-hand edge of the oscilloscope grid to the point indicated as T_o is the oscilloscope sweep and was not drawn by calculation or estimation. During the period in which the pressure builds up in the cartridge chamber from zero pressure, at P_o, to the bullet entrance into the rifling, at T_o, the oscilloscope sweep gives a smooth curve of pressure rise as shown by sweep A in Figure 5.

After the bullet begins to travel, the pressure sweep shows minor oscillations through the remainder of the sweep.

Sweeps B and C in Figure 5 are from radiation detectors located 5.5 and 9.5 inches down the barrel in this firing. The sweeps from the detectors always show continuous irregularities because of background radiation.

It should be noted that the zero pressure scale does not occur at the same point on each oscilloscope photograph and is determined by location of zero voltages in the strain-gage circuit. Therefore, to superimpose the curves, the heavy oscilloscope grid scale must be disregarded, and in the case of sweep A the curves of Figure 4 may be superimposed by alignment of the zero pressure scale in sweep A for the photograph to give correct vertical alignment. Horizontal alignment then is obtained by aligning identical distances of travel on the time scale.

The same powder charge, powder type, primers, bullets, and cases were used in both of the firings shown in Figures 4 and 5.

Numerous additional firings similar to that shown in Figure 5 have been made since the preparation of the first draft of this manuscript. In most observations the oscilloscope sweep showing pressure rise is a smooth curve until a pressure similar to the discontinuity at 25,000 p.s.i. of Figure 5 is reached. Then the sweep oscillates and the data show that a definite period of oscillation occurs of the order of 10 to 20 microseconds. This corresponds to the order of magnitude for the time period required for sonic vibration in steel to travel from the bore of the rifle throat to the strain gage.

It is believed that this signal is produced by the impact of the bullet on the rifling of the barrel and that at time, T_o, as shown in Figure 5, the bullet has traveled about ⅛-inch from its initial position to contact the rifling.

ALTHOUGH a distance of ⅛-inch of bullet travel would seem to be a small factor it actually corresponds to about 100 microseconds of time because of low initial bullet velocity. If this correction is made to the distance-versus-pressure curve for this load, the bullet begins to move when the pressure is about 12,000 p.s.i. and travels ⅛-inch to the rifling while the pressure rises to about 25,000 p.s.i. Obviously much is to be learned by further study.

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