# NAVY DEPARTMENT

## THE DAVID W. TAYLOR MODEL BASIN

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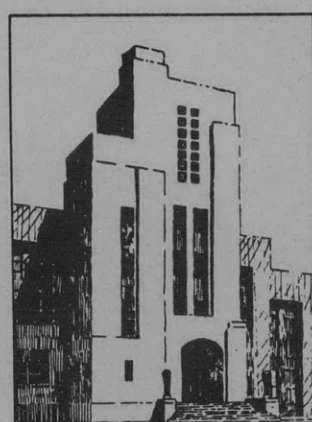
# EXPERIMENTAL ANALYSIS OF THE RECOIL SYSTEM OF THE 8-INCH 55-CALIBER GUNS MARK 20, MOD I

by

E.T. Habib





March 1950

Report C-165

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# EXPERIMENTAL ANALYSIS OF THE RECOIL SYSTEM OF THE 8-INCH 55-CALIBER GUNS MARK 20, MOD 1

by

E.T. Habib



March 1950 Report C-165

## FOREWORD

The new main-battery turret for the CA139-Class cruisers incorporated many novel structural and mechanical features which rendered it capable of firing its three 8-inch 55-caliber guns more rapidly than any of its predecessors. To check its operation, perhaps the most extensive structural investigation ever conducted on turrets was performed. A 1/10-scale structural model was fabricated and tested at the David Taylor Model Basin, and a full-scale pilot turret was tested at the Naval Proving Ground. The results have subsequently been checked by structural firing trials conducted on the USS DES MOINES (CA134), the first naval vessel to carry these new turrets. As its part of the over-all program, the David Taylor Model Basin was given the responsibility of measuring (a) the performance of the turret structure and roller track, (b) the behavior of the recoil-counterrecoil system, (c) the operation of the training buffer, and (d) the motion of the guns and turret during elevating and training exercises.

Apart from the primary objective of confirming the safety and the satisfactory performance of the new turret in advance of construction of the ships themselves, secondary objectives were established to derive experimentally information which could be employed to confirm or refute design criteria for guns and turrets, and for structural assemblies which are similarly loaded.

The results of the recoil-counterrecoil investigation are given in this report. The other results are given in additional reports and memoranda, as follows:

1. "Description of Test of Hydraulic Training Buffer of CA139-Class Pilot Turret," TMB RESTRICTED Report C-38, February 1948.

2. "An Elastic-Tube Gage for Measuring Static and Dynamic Pressures," TMB Report 627, May 1948.

3. "Description of Instruments Employed in the Operational Tests of the Gun-Elevating Systems of the CA139-Class Pilot Turret," TMB RESTRICTED Report C-29, October 1947.

4. "The Measurement of Performance of the Gun-Elevating System of the 8-Inch 55-Caliber Turret," TMB RESTRICTED Report C-163 (in preparation).

5. "The Measurement of Performance of the Training System of the 8-Inch 55-Caliber Turret," TMB RESTRICTED Report C-164 (in preparation).

6. "The Dynamical Response of the Rotating Structure of Turrets with Particular Reference to the 8-Inch 55-Caliber Turret," TMB RESTRICTED Report C-81 (in preparation).

7. "Structural Design Studies of a 1/10-Scale Model of the 8-Inch Gun Girder on the CA139-Class Cruisers," Thesis, Department of Naval Architecture and Marine Engineering, Massachusetts Institute of Technology, 1949.

8. "Schedule of Measurements to be Made by the David Taylor Model Basin during Tests of the CA139 Pilot Turret," TMB Memo 2, CA139 Class/S72-1 of 13 November 1945 (revised 25 April 1947).

9. "Experimental Analysis of Stress and Deformation of a 1/10-Scale Model 8-Inch Gun Turret for the CA139-Class Cruisers," TMB RESTRICTED Report 571, February 1948.

10. "The TMB Tension Dynamometer," TMB Report 605 (in preparation).

11. "The Elastic Behavior of the Rotating Structure of the CA139-Class Pilot Turret with Static Loading," TMB RESTRICTED Report C-166, March 1950.

12. "The Elastic Behavior of the Rotating Structure of the CA139-Class Pilot Turret with Gunfire Loading," TMB RESTRICTED Report C-231 (in preparation).

13. "Natural Frequencies Measured on the CA139-Class Pilot Turret," TMB RESTRICTED Report C-82, December 1948.

Whereas the experimental and theoretical analyses were conducted for this turret investigation to obtain specific data regarding performance, a vast amount of general information was obtained pertaining to the behavior of hydraulic energy-absorbing systems and to the elastic behavior of complex structures subjected to dynamic loading. It is now planned to present these more general results in two separate reports:

1. Considerations for the Design of Complex Structures subjected to Dynamic Loads, as Derived from Experimental Analysis.
2. New Considerations for the Design of Hydraulic Buffers, as derived from Experimental Analysis.

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## ABSTRACT

**Gunfire tests were conducted by the David Taylor Model Basin to determine the performance of the recoil system of the automatic-firing 8-in. 55-Cal. Gun Mark 20, Mod 1. The guns were fired from a full-scale pilot-model turret mounted on land at the Dahlgren Proving Ground. The main sub-assemblies of the recoil mechanism were tested, the principal instruments used being elastic-tube strain type pressure gages, piezoelectric crystal-type pressure gages, accelerometers and displacement gages. The tests, which generally confirmed the soundness of the design, provided an unprecedented amount of analytical data—much of which is applicable to recoil systems in general.**

## INTRODUCTION

A major difference between new heavy cruisers of the CA139 Class and those of the older CA68 Class now in service is a new type of turret featuring rapid-firing 8-inch 55-caliber guns which can be automatically loaded at any elevation. The addition of the machinery for automatic handling of ammunition imposed new demands on space within the turret and increased its total weight. These space and weight requirements as well as the novel loading arrangements necessitated changes in the previous design of various components of a turret. To determine the quality of performance of the modified turret, full-scale trials were deemed necessary. Accordingly, in the interest of both the Bureau of Ordnance and the Bureau of Ships, Navy Department, a full-scale pilot turret was constructed, installed at the Naval Proving Ground, Dahlgren, Virginia, and subjected to elaborate proof tests.[1] These tests embodied a comprehensive set of measurements designed to accumulate accurate information regarding the performance of almost every working part of the turret. Instrumentation, newly developed for this project, enabled recording of the many variables to an accuracy hitherto not considered feasible. Among the tests that the Taylor Model Basin was requested to conduct were tests on the training turret buffer, tests on the operation and response of the training gear and elevating gear during gunfire, tests on the structure which supports the guns, and tests on the recoil system. Reports on these various topics have been, or are in the process of being, written. The analyzed data embody a mass of information which should be of great use toward the design of improved turrets. The recoil-system investigation, with which this report is concerned, had as its primary objective the determination of the response

[1]References are listed on page 62.

of the recoil system to the force set up by gunfire; that is, measurement of the forces resisting recoil and the motion of the recoiling gun, all as a function of time.

Careful planning provided cross-checks on all measurements. Although recoil tests had been performed before, even on a gun of this size, no test had been conducted employing contemporary instruments, and none had provided so thorough a correlation of all design parameters.

The purposes of this report are to describe the recoil system of the gun investigated and the instruments and associated apparatus used, to present the analyzed data, to compare observed and computed results, to make pertinent comments, and to summarize the results.

Briefly these results are:

1. Maximum recoil force developed by the recoil system at 0° gun elevation was 200 kips; at 40° elevation, 219 kips. These values were obtained when a 335-lb projectile was fired; when a 260-lb projectile was fired, maximum recoil forces were 173 kips and 185 kips at 0° and 40°, respectively.

2. Maximum forces and motions occurred when firing a 335-lb projectile.

3. Large-amplitude, high-frequency variations in pressure were found in the recoil hydraulic buffer. Their effect on the strains produced in the gun supports and on the recoil motion of the gun was found to be negligible.

4. Maximum counterrecoil force was 115 kips.

5. Maximum recoil acceleration was 50 g.

6. Maximum recoil velocity was 199 in/sec when the gun was fired at 0° elevation; at 40° elevation, maximum velocity was 216 in/sec.

7. Maximum recoil displacement was 27.6 in. at 40° gun elevation; the air-cylinder pressure was 1450 psi. (If the air-cylinder pressure were 1338 psi as specified in design, and the guns were fired at 60° elevation, maximum recoil displacement would almost certainly exceed the design maximum of 28.0 in.)

8. The use of strain gages on the trunnion bearers, in an attempt to determine total recoil force with only one gage measurement, was found to be unsatisfactory.

9. Strain gages attached to the piston rod of the recoil cylinder measured recoil-hydraulic-buffer force and counterrecoil-hydraulic-buffer force as reliably as did the pressure gages. This measurement and the reading of initial air-cylinder pressure are sufficient for the computation of maximum recoil force.

10. The dynamic factor to be applied to the structural supports of the gun is much less than 2.0; probably about 1.3. In large part the reduction is due to the staggered application of the components of recoil force and to the presence in the structure, immediately after it is loaded, of what appears to be considerable damping.

11. Performance of the instruments employed in the test was found satisfactory. For pressure measurements of the type made in these tests, the elastic-tube gage, developed by the Taylor Model Basin, is felt to be superior to the crystal-type gage.

## THE GUN RECOIL SYSTEM

All modern guns are equipped with recoil systems whose purpose is to decrease the magnitude of the maximum forces acting on the supporting structure when the guns are fired. The recoil system of the guns of the new 8-in. turret is similar to that used for guns of similar caliber in other turrets by the Navy. It consists of three separate components as follows: first, a recoil hydraulic buffer which absorbs the major portion of the energy of recoil; second, a counterrecoil cylinder containing air under high pressure (about 1400 psi) which assists the recoil buffer during recoil and returns the gun to position after recoil, and third a counterrecoil hydraulic buffer which brings the gun to rest smoothly as it is returned to battery. The location of each part of the recoil system is shown in Figure 1. All three components are rigidly attached to the gun slide; the resultant of the resisting forces developed in them acts through the center of mass of the gun slide. The trunnion, which is the axle around which the gun elevates, is attached to the slide and rests within the trunnion bearers. All recoil forces are transmitted to the gun slide, then the trunnion, and finally to the truss and girder structure which supports the guns.

### Recoil Forces

The total force of recoil, which is the force* applied to the structure supporting the guns while the gun is recoiling, is the sum of the four

*There is at all times a reaction at the trunnion bearers in the vertical direction equal to the weight of the entire gun including slide and trunnion. This reaction does not enter into the computation of the recoil force and so is not considered further; it must, however, be considered as a vertical load on the structural supports of the guns. These supports are very rigid in the vertical direction.

An additional load on the structure, also not considered a recoil load, is the torque exerted by the weight of the gun as it moves out of battery, since the gun is then no longer balanced. This torque is resisted by the elevating mechanism.

resisting forces of the recoil system: The recoil-hydraulic-buffer force $F_{rc}$, the counterrecoil-air-cylinder force $F_{crc}$, the counterrecoil-hydraulic-buffer force $F_{crb}$, and the friction force $F_{\mu}$.

Although there is a counterrecoil-air-cylinder force which holds the gun in battery previous to gunfire, this force is in equilibrium with the

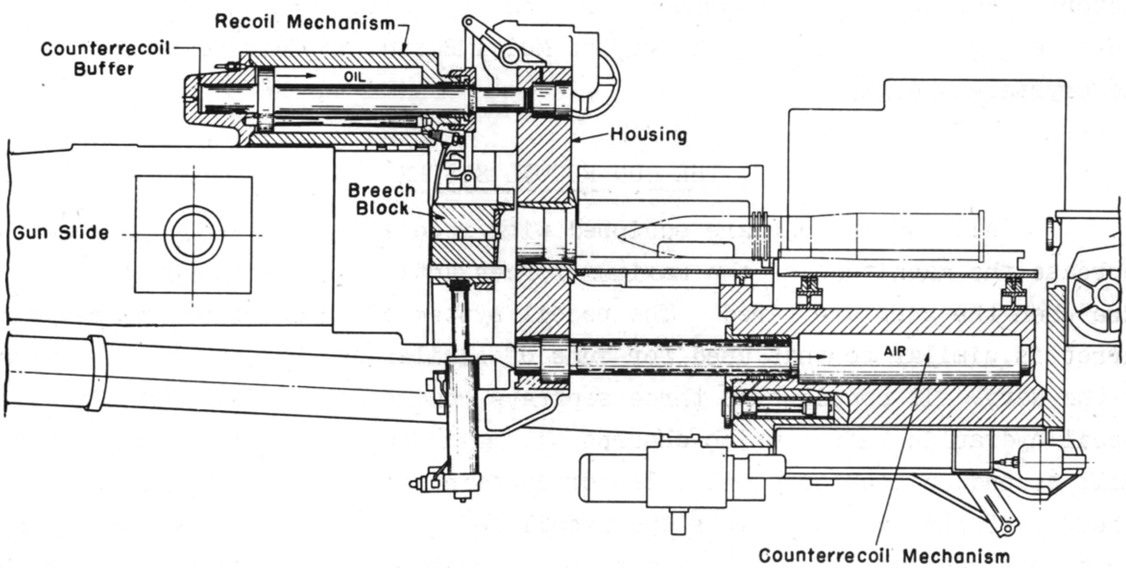


Figure 1a

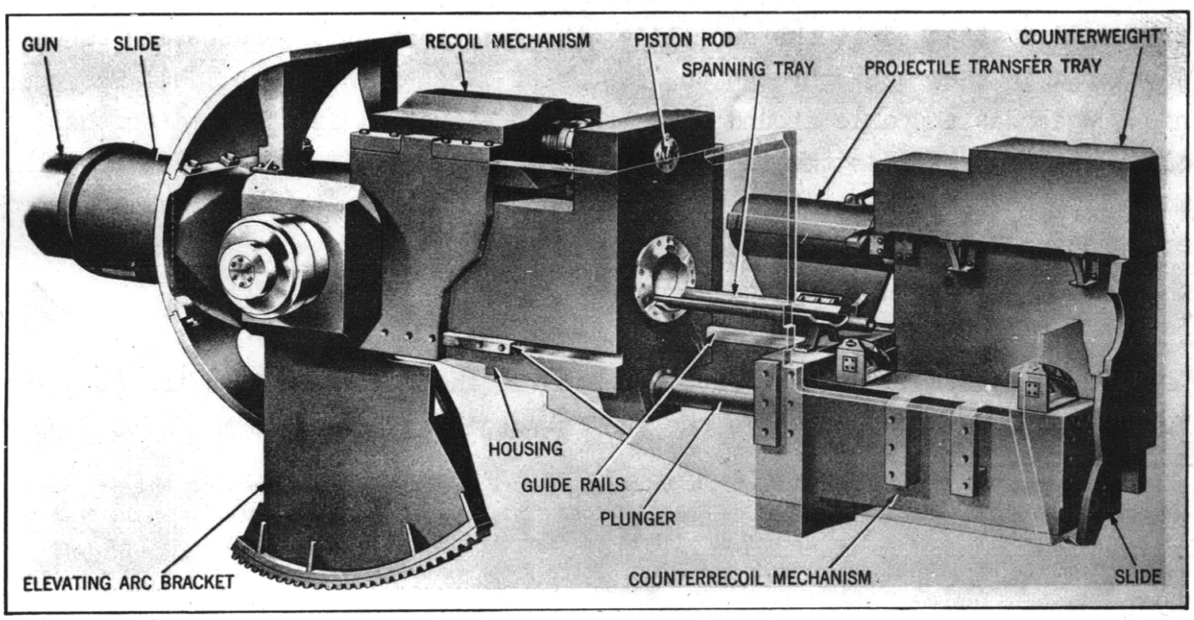


Figure 1b

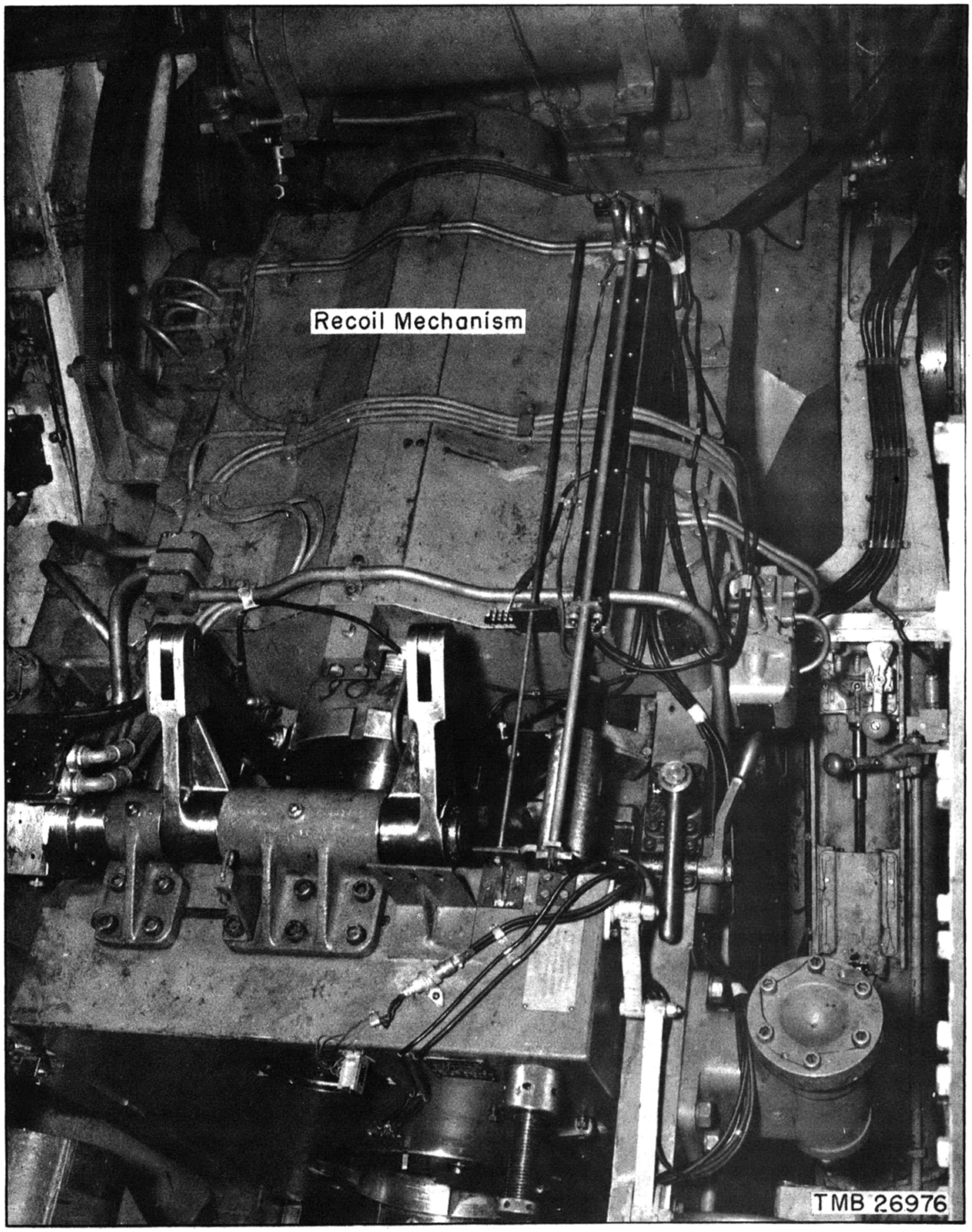


Figure 1c

Figure 1 - Components of the Recoil-Counterrecoil Mechanism

internal tensile stress in the gun slide. There is no force acting on the trunnion bearers, in the horizontal direction, until the gun recoils a short distance; see Figure 2.

The forces controlling recoil of the gun are related by the following equilibrium equation:

$$F_p - \frac{W}{g}\ddot{x} - F_{rc} - F_{crc} - F_{crb} - F_{\mu} + W \sin \alpha = 0 \qquad [1.0]$$

where $F_p$ is the force generated by the burning powder,

$\frac{W}{g}\ddot{x}$ is the inertia force; $W/g$ the mass of the gun, $\ddot{x}$, the acceleration of the gun,

$F_{rc}$, $F_{crc}$, $F_{crb}$; $F_{\mu}$, are the resisting forces developed respectively by the recoil cylinder, counterrecoil air cylinder, the counterrecoil buffer, and friction.

$W \sin \alpha$ is the component of the weight $W$ of the gun in the direction of recoil, where $\alpha$ is the angle of gun elevation relative to the true horizon.

For various phases of recoil one or more of these forces is zero and the equation is simplified. A similar equation may be written relating the motion of the projectile to the force generated by the burning powder.

When the powder charge is ignited a force is generated which causes the projectile to move forward in the gun tube and eventually be ejected. The same powder force acts on the movable portion of the gun, overcoming the counterrecoil-air-cylinder force and forcing the gun out of battery. With the driving forces put on the left and

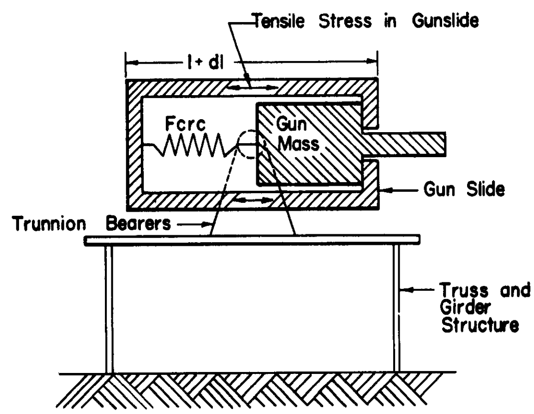


Figure 2a

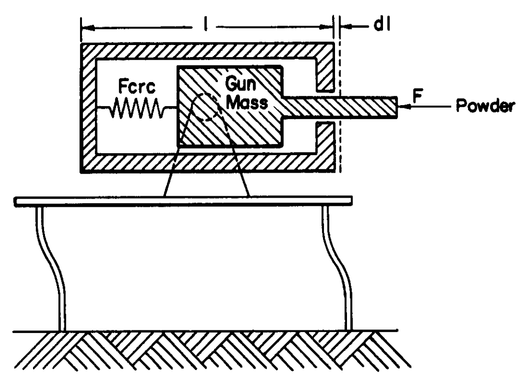


Figure 2b

Figure 2 - Schematic Diagram Showing the Effect of Breaking Contact between Gun Slide and Recoiling Gun

The push of the air-cylinder pressure, which holds the gun in battery, is in equilibrium with a tensile stress in the gun slide. When the gun is fired and begins to recoil, the contact between gun mass and gun slide is broken. Immediately thereafter the air-cylinder force appears as a load at the trunnion bearers.

resisting forces on the right, the equation of motion for the gun is thus:

$$F_p + W \sin \alpha = \frac{W}{g} \ddot{x} + F_{rc} + F_{crc} + F_\mu \qquad [1.1]$$

At the time of maximum acceleration of the gun, all forces except the powder force and the inertia force are small; hence, the maximum acceleration is readily derived from the maximum powder force; or vice versa.

As the projectile moves down the barrel of the gun the force exerted by the powder gases decreases because of increased volume, heat loss to the barrel, motion of the gas particles, etc. When the powder force drops to a value equal to the sum of the resisting forces, the acceleration is zero and maximum recoil velocity has been reached. When the powder force is less than the resisting forces, the acceleration of the gun becomes negative and recoil velocity decreases. The driving force is then given by $F_p + \frac{W}{g} \ddot{x} + W \sin \alpha$. When the powder force is totally dissipated, the equation of motion is

$$\frac{W}{g} \ddot{x} + W \sin \alpha = F_{rc} + F_{crc} + F_\mu \qquad [1.2]$$

When the resisting forces equal the driving force, the motion of the gun ceases, recoil is completed and counterrecoil begins. For this point, and during the initial portion of counterrecoil,

$$F_{crc} = \frac{W}{g} \ddot{x} + W \sin \alpha + F_\mu \qquad [1.3]$$

The acceleration of the gun is still negative but the direction of motion has reversed, and counterrecoil velocity is increasing.

After this particular gun has completed about 6 inches of counterrecoil, pressure develops in the counterrecoil side of the recoil cylinder. Although the pressure is low, the piston area is the full area of the recoil-cylinder piston and considerable resisting force is generated:

$$F_{crc} = \frac{W}{g} \ddot{x} + W \sin \alpha + F_{crb} + F_\mu \qquad [1.4]$$

After the piston enters the counterrecoil buffer, the counter-recoil-buffer force $F_{crb}$, becomes large enough to decelerate the gun. With the driving force written on the left, the equation of motion is now

$$F_{crc} + \frac{W}{g} \ddot{x} = F_{crb} + W \sin \alpha + F_\mu \qquad [1.5]$$

With the gun back in battery and held there by the counterrecoil-air-cylinder force, the force applied at the trunnion bearers drops to zero. A small pressure may persist for a short time in the counterrecoil buffer.

The Recoil Hydraulic Buffer

As the projectile begins to move forward in response to the force exerted by the burning powder, an equal force accelerates the gun in the opposite direction. One of the forces resisting this motion is generated in the recoil-cylinder hydraulic buffer. This buffer consists of a thick-walled steel cylinder filled with liquid,* a piston, a piston rod and three throttling rods; see Figure 3. The piston rod is fastened rigidly to the gun housing and to the piston. Through the piston, three holes are drilled. The

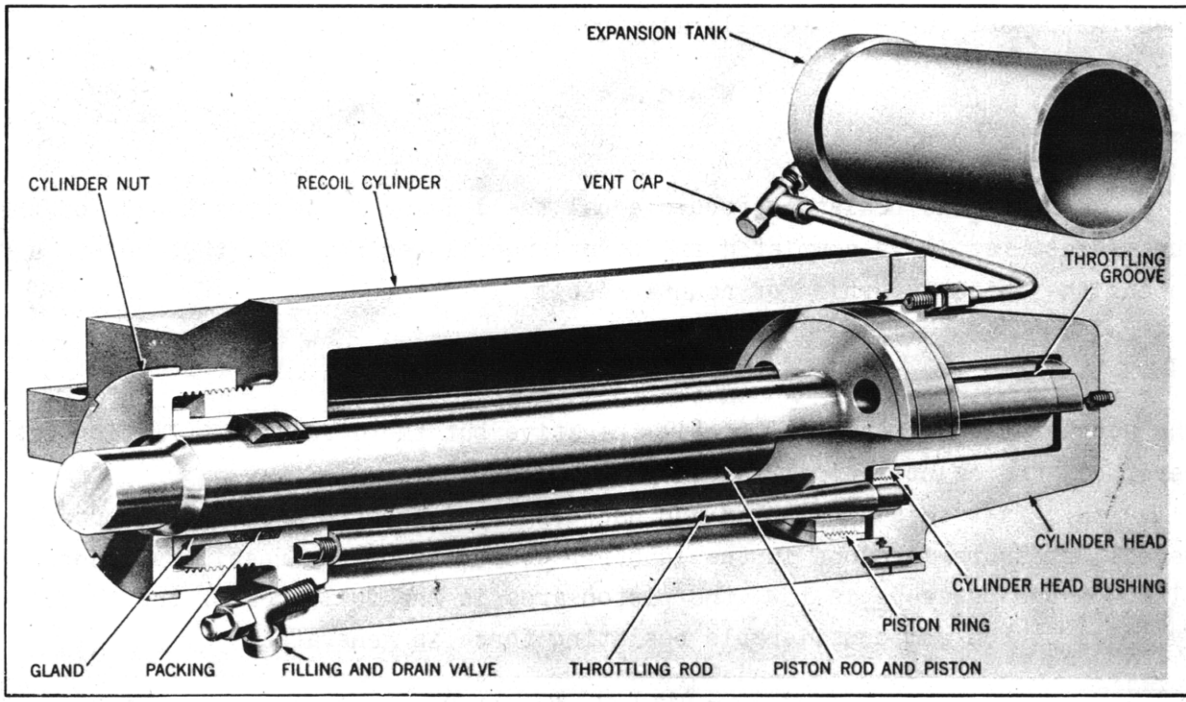


Figure 3 - The Recoil Cylinder Mechanism

The pressure gages used to measure recoil buffer-force were attached through an adapter to the filling and drain valve. The plug in the cylinder head was removed to attach the pressure gage for measuring counterrecoil hydraulic buffer force.

throttling rods, whose cross-sectional area varies along their length, pass through these holes and are attached rigidly to the front and rear of the

*Fluid mixture of the following proportions: 4 gallons glycerine, 1 gallon water, 15 ounces corrosion-inhibiting compound and 20 grams of sodium chromate. Specifications are listed in NAVORD-OS1914.

recoil cylinder, thus providing a variable area of aperture as the piston moves during recoil. As the piston moves back in recoil some of the liquid is forced forward through the apertures in the piston and a pressure is generated in the liquid remaining in the cylinder due to the resistance of the liquid to motion through these apertures.[2,3] The force with which the recoil buffer opposes the motion of the gun can be determined from the pressure in the rear of the recoil cylinder where the fluid has no motion. In this test, this pressure was measured as a function of time by two different type gages: a TMB elastic-tube-type strain gage[6] and a TMB piezoelectric gage,[7,8,9] operated by TMB personnel. In addition, a third gage—a strain-type gage developed by the Ballistic Research Laboratory, Aberdeen, Maryland—measured the same pressure. This gage was operated by personnel of the Naval Ordnance Laboratory, White Oak, Maryland.[10] All three gages were attached to the recoil cylinder through an adapter which was placed on the valve used to fill the recoil cylinder.

A "back pressure" may be generated in the forward end of the recoil cylinder in the following manner. The fluid accelerated through the orifices has a high velocity. In bringing this fluid to rest, energy will be released resulting in both a pressure and temperature rise of the fluid. The true pressure-resisting motion of the gun should then be the difference between the pressure in the recoil hydraulic buffer and the pressure on the opposite side of the piston. Because this latter pressure was believed to be low, it was not measured; however, its existence has been noted.[4,5] The vent to the expansion tank (see Figure 3) would tend to reduce this pressure which should exist during the first 10 or 11 inches of recoil, that is, while the counterrecoil buffer piston is being withdrawn from its cylinder. When the recoil has progressed so that the counterrecoil buffer piston is withdrawn, the back pressure will drop to zero since the volume of liquid being forced through the orifices is less than the volume increase on the counterrecoil-buffer side of the piston. Actually as recoil continues a vacuum is developed in this area. Hence, during counterrecoil, no pressure will build up in the counterrecoil buffer until the partial vacuum is overcome. This will occur when the volume on the counterrecoil-buffer side has been diminished by the product of the piston rod area and the length of recoil. (There is a tacit assumption here that no liquid is present in the expansion tank or that none flows from it into the recoil cylinder during recoil.) If recoil is 28 inches, piston rod volume is $(28) \cdot \left(\frac{\pi}{4}\right) \cdot (5.5)^2 = 665$ in$^3$; piston area = 120.5 in$^2$. The counterrecoil distance necessary to take up the volume is $\frac{665}{120.5} = 5.8$ in. After the vacuum is overcome, some "back pressure" should build up in the recoil cylinder during counterrecoil and should be recorded by the recoil-cylinder pressure gages. In tests of this gun, these gages showed no measurable pressures at this time, i.e., pressures were less than 100 psi.

The Counterrecoil Air Cylinder

The counterrecoil mechanism consists of an air cylinder containing a sliding piston or plunger and a piston rod which is rigidly connected to the housing of the gun; see Figure 4. The air cylinder is loaded to an initial pressure of about 1400 psi, which serves to keep the gun in position while it is being elevated and to return the gun to battery after recoil. As the gun recoils, the compressed air in the cylinder is further compressed, increasing further its resisting force; this force is a substantial part of the recoil force. When the energy of gunfire is expended and maximum recoil is reached, the pressure in the air cylinder forces the gun back into battery. The pressure in this cylinder was measured as a function of time by a TMB elastic-tube gage recording on a Hathaway string oscillograph. Initial pressure was read on the Bourdon-type gage already installed on the air cylinder.

The Counterrecoil Hydraulic Buffer

The purpose of this buffer is to bring the gun to rest smoothly on its return to battery. The buffer, located at the forward end of the recoil cylinder, consists of a heavy cylinder fitted with a piston in which throttling grooves have been cut; see Figure 3. These grooves have constant width but the depth varies along the piston length. As the gun is forced back in counterrecoil by the counterrecoil-cylinder air pressure, the liquid in this buffer is forced past the piston through the grooves in the piston. A pressure is thus generated in the buffer which acts to retard the motion of the gun as it moves into battery. The pressure in this buffer was measured as a function of time by a TMB elastic-tube gage recording on a Hathaway string oscillograph.

Recoil Motion

The acceleration, velocity, and displacement of the gun are intimately related to the forces developed within the recoil system. Hence, knowledge of their variation during recoil and counterrecoil is essential to understanding the functioning of the recoil mechanisms. The relation of motion of forces is given by, and discussed along with, Equation [1.0].

The displacement of the gun takes place in a straight line for all positions of the gun; hence, there are no rotational components.

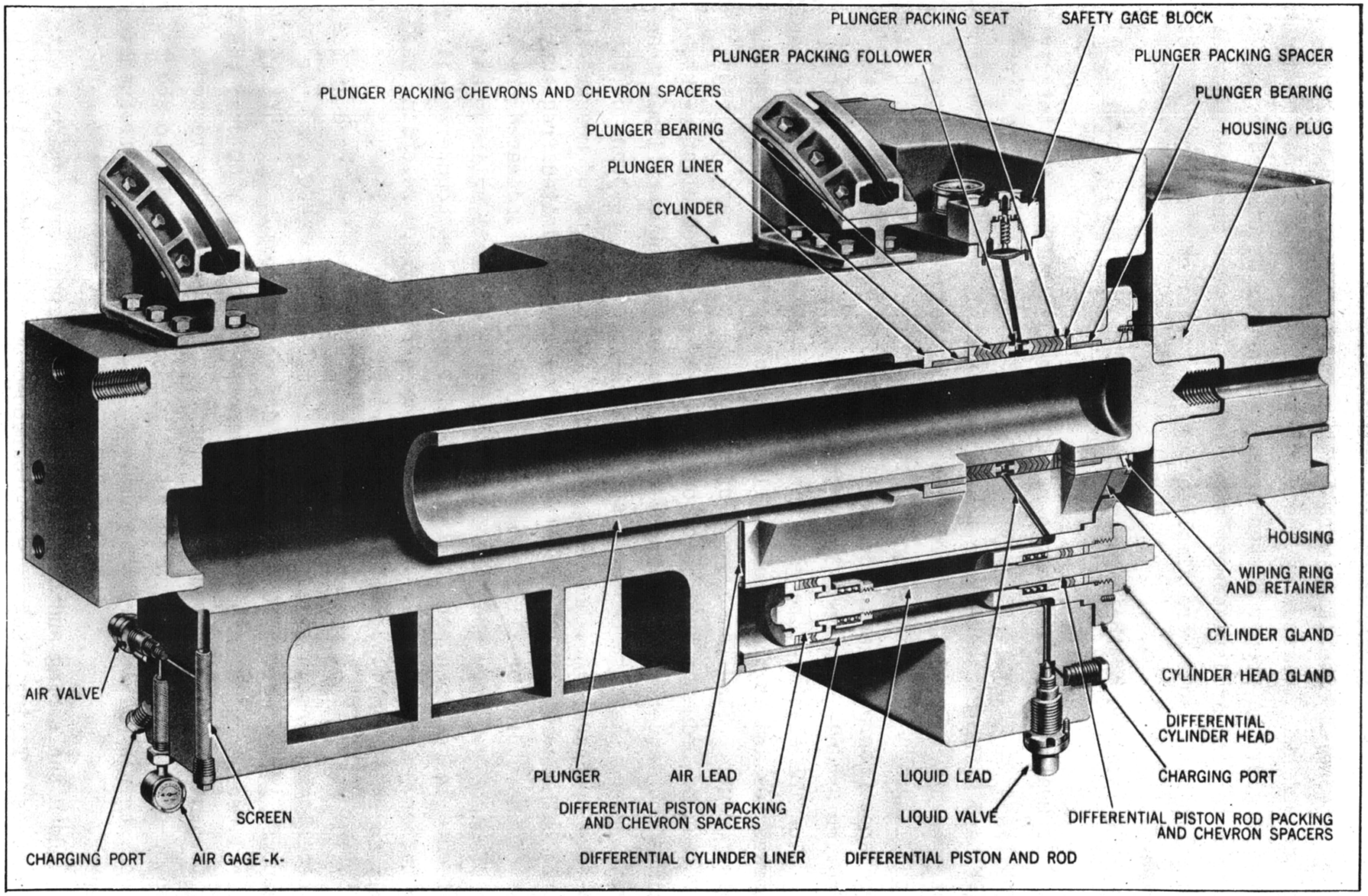


Figure 4 - The Counterrecoil-Air-Cylinder Mechanism - Plunger in Full Recoil Position

To attach the pressure gage used to measure air cylinder force, the air gage K was removed and replaced with an adapter. To this adapter, both the elastic-tube pressure gage and the air gage K were attached.



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## INSTRUMENTATION FOR TEST MEASUREMENTS

Two general quantities were to be measured: force and motion. Force was determined by measuring the fluid pressure in the recoil mechanism and multiplying by the proper piston area. Motion was determined by use of an accelerometer and a displacement gage. All gages were recorded on a string oscillograph; some were simultaneously recorded on a cathode-ray oscillograph.

The location of the gages on the recoil mechanism is shown in Figure 5.

To measure pressure in the recoil hydraulic buffer, two totally different types of pressure gages were employed: a TMB elastic-tube strain-type gage[6] and a TMB piezoelectric tourmaline-crystal gage.[7,8,9] Two separate instruments were used to record each gage: a twelve-channel Hathaway string oscillograph and a six-channel cathode-ray oscillograph built by the Naval Ordnance Laboratory and made available through the courtesy of the Naval Proving Ground. Figure 6 is a block diagram of the instrumentation.

The TMB elastic-tube gage was developed at TMB to measure hydraulic-buffer pressures and is the gage usually employed by TMB personnel for similar measurements. Simultaneous use of the piezoelectric gage was requested by the Bureau of Ordnance as a check on the newly developed elastic-tube gage, since the latter gage was known to have a lower frequency limit than the crystal gage. Results showed that the high-frequency response of the elastic-tube pressure gage, however, was ample for this type of measurement. Use of the cathode-ray oscillograph was dictated by the limited frequency response of the string oscillograph. Preliminary records indicated the existence of high-frequency pressure variations in the recoil cylinder and their absence in the counterrecoil air cylinder and in the counterrecoil hydraulic buffer. Subsequently, the cathode-ray oscillograph recording was used only for the recoil-hydraulic-buffer pressures.

The response of the average galvanometer of the type used in the string oscillograph employed here, is flat from 0 to about 400 cps. At 500 cps, response is down about 10 percent and decreases sharply thereafter. The natural frequency of this type of galvanometer is about 1200 cps; the damping present is usually about 0.65 of critical damping. The response of the cathode-ray oscillograph, on the other hand, is flat from 0 to about 40,000 cps; this band was more than ample to cover the range of frequencies of interest.

Both the string and cathode-ray oscillographs were equipped with timing devices. Timing lines were photographed on the string oscillograph, simultaneously with record taking, at 0.01-sec intervals. Accuracy was

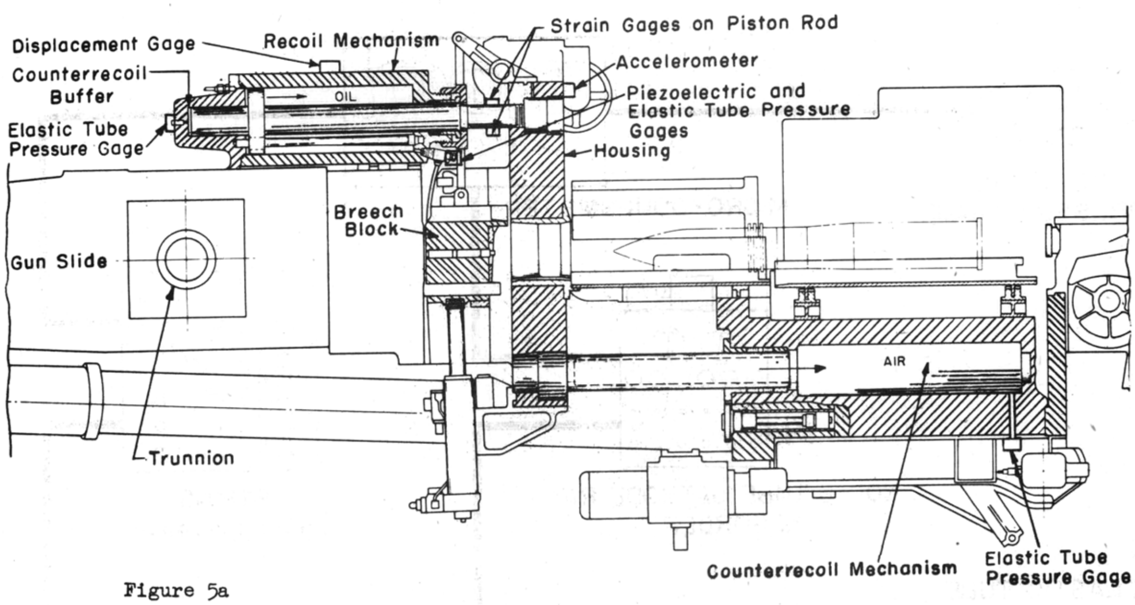


Figure 5a

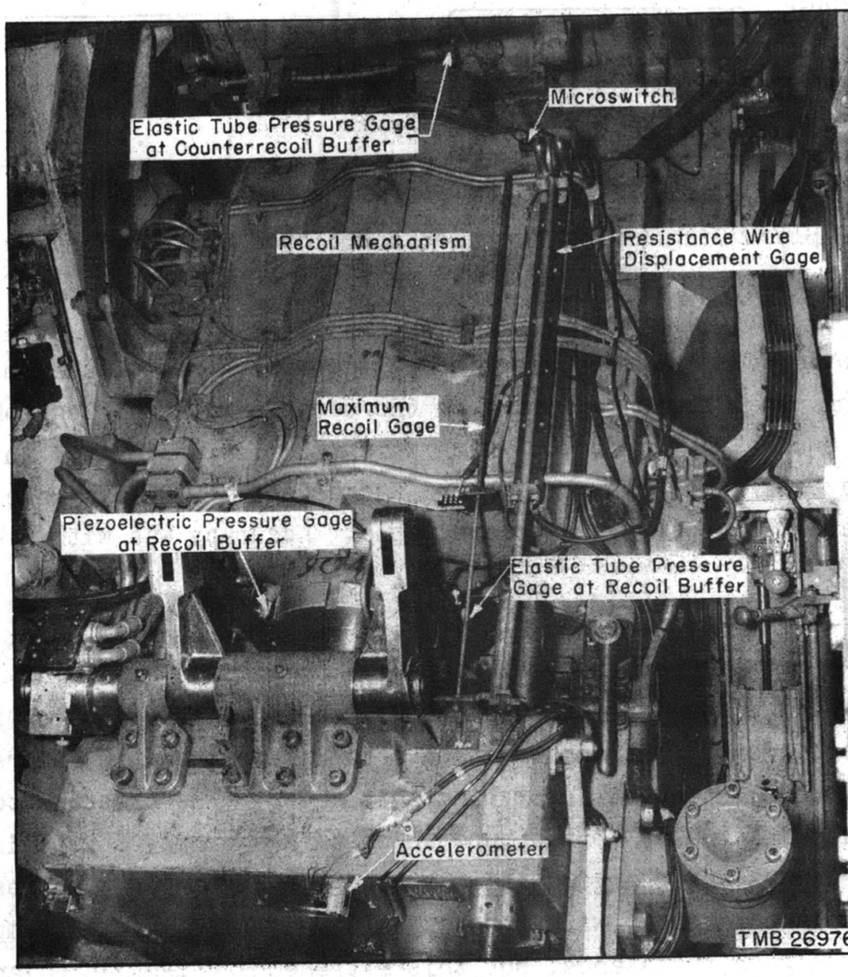


Figure 5b

Figure 5 - Recoil-Counterrecoil Mechanism, Showing Location of Measuring Instruments

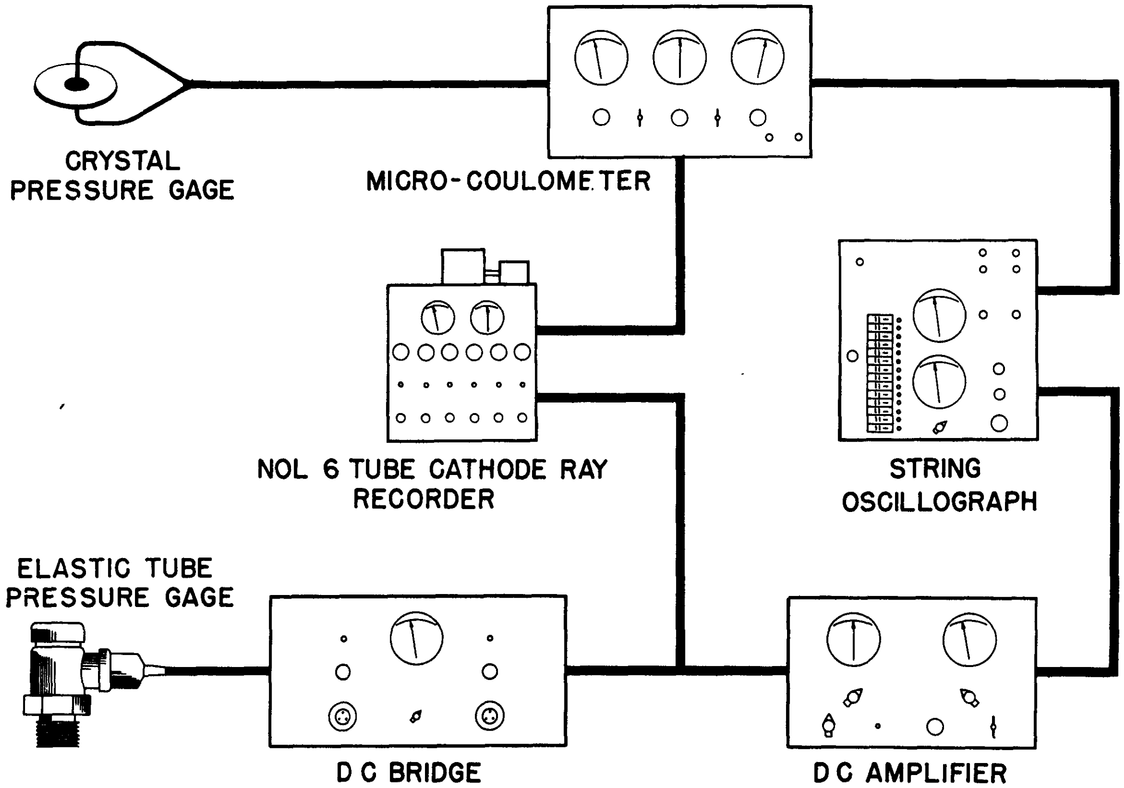


Figure 6 - Block Diagram of Instruments Employed in Recording Pressure

within 0.002 sec or 0.1 percent, whichever was greater, for any interval. A check was provided by the 60-cycle line voltage which was placed on one trace of each string oscillograph. Timing on the cathode-ray oscillograph was provided by two square-wave channels which were recorded at the top and bottom of the film at the same time as a record was taken. A 200-cps wave was used although 40 and 1000 cps were also available. Accuracy was within 0.5 percent.

The Elastic-Tube Strain-Type Gage*

This gage consists of an elastic steel tube around which is cemented a strain-wire element. The construction details are shown in Figure 7, which is taken from the TMB report describing this gage.[6] The pressure to be measured is applied internally to the tube which then expands, stretching the strain-wire element and changing its electrical resistance. The resistance change takes place linearly with respect to strain. Changes in temperature also affect the gage resistance, but this extraneous effect is balanced out by the use of a temperature-compensating strain-wire element.

*Patent No. 2,477,026 issued 26 July 1949.

An important feature of this gage is the removable screw at the end of the pressure chamber which permits bleeding the gage at any time, even after installation, thus venting trapped gases which may impair the recording of high-frequency transients.

The gage itself is calibrated statically by applying a known static pressure to it and measuring the resulting change in resistance, in terms of equivalent strain, on a Baldwin-Southwark SR-4 Strain Indicator.[6] Three gages were also calibrated dynamically in the same fashion as the piezoelectric gages are calibrated, i.e., by subjecting the gages to a known pressure and then suddenly releasing this pressure. Static and dynamic calibrations agreed within 2 percent.

As shown by Figure 6, the elastic-tube gage was used in conjunction with a TMB type-BR1A d-c Wheatstone bridge. The active gage forms one arm of this bridge, the temperature-compensating gage another, and the other two arms are supplied by resistances within the box which carried the remainder of the Wheatstone bridge circuit.

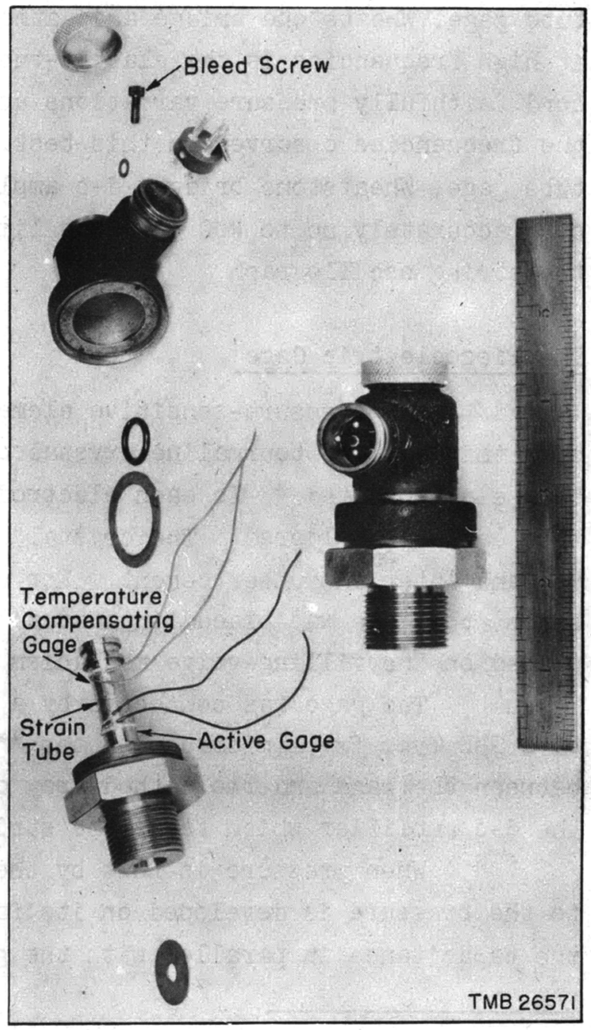


Figure 7 - Components and Assembly of TMB Elastic-Tube Pressure Gage

Changes in the resistance of the active gage unbalance the bridge, and a voltage change is induced at its output terminals. This voltage change is then led to the input of one channel of the cathode-ray oscillograph and also to the input of a TMB Type AM-1A d-c amplifier[12] which feeds one channel of the string oscillograph.

Calibration of the electrical equipment was made before each record was taken. A small known change of resistance was introduced into one arm of the Wheatstone bridge by shunting a small resistance, located in that arm, by a comparatively large resistor. This unbalanced the bridge; the resulting voltage change appeared as a "step voltage" on both the cathode-ray and string oscillographs. Using a smaller shunting resistance produces a larger step. When two such resistances (the second smaller than the first) in succession shunt the small resistance, the calibration record appears as one step superimposed upon the other, the heights of these steps being in a definite ratio. This serves as an excellent check on the amplitude response of the recording system. In some cases, the response steps were not in the computed ratios, and for such cases the steps were averaged for use as a calibration factor.

The natural frequency of the elastic-tube gage, determined during the dynamic calibration was about 6000 cps. This agrees with the natural frequency of the gage vibrating as an organ pipe filled with water.

In the high-frequency system of recording described above—elastic-tube gage, Wheatstone bridge and cathode-ray oscillograph—the limiting factor at high frequencies is the elastic-tube gage. This setup should, however, record faithfully pressure variations up to about 3000 cps, which is well above the frequencies observed in this test. The low-frequency recording—elastic-tube gage, Wheatstone bridge, d-c amplifier and string oscillograph—will record accurately up to 400 cps; the limiting factor being the galvanometer in the string oscillograph.

## The Piezoelectric Gage

The pressure-sensitive element of the piezoelectric gage consists of a thin disc of tourmaline crystal on whose faces metal electrodes have been electroplated.* To each electrode, a wire from a short piece of copper tube cable is soldered. The crystal is then insulated by dipping in melted wax and later in rubber cement. For use in measuring recoil hydraulic pressures, the gage was placed in a steel tube which screwed into the adapter placed on the filling-valve mechanism of the recoil cylinder (Figure 8).

The gage was connected by a 200-ft properly terminated,[13] cable** to a TMB Type Px-1A microcoulometer,*** which was used as an impedance coupler between the gage and the cathode-ray oscillograph and between the gage and the d-c amplifier which feeds the string oscillograph (Figure 6).

When pressure is felt by the gage, a charge directly proportional to the pressure is developed on its faces. This charge is distributed across the capacitance in parallel with the gage; the resulting voltage, applied to

*The plated crystals were obtained from the Stanolind Oil Co., Tulsa, Oklahoma.

**The cable used was coaxial cable of polyethelene dielectric, Type RG-11-U, which may be obtained from the American Phenolic Co.

***The microcoulometer is based on a design by S. Roberts.[14]

the input of the microcoulometer, is recorded simultaneously by both the cathode-ray and string oscillographs.

Calibration of the electrical equipment was obtained by introducing, at the input of the microcoulometer, a voltage step of known magnitude before each record was taken, the voltage output being recorded on both string and cathode-ray oscillographs.

Calibration of the gage itself was obtained by subjecting the gage to a known pressure, releasing this pressure suddenly and measuring the charge developed.[8]

In the high-frequency setup described above (piezoelectric gage, microcoulometer and cathode-ray oscillograph), the limiting factor at high frequencies is the microcoulometer at about 2000 cps.* In the setup employing the string oscillograph, the high-frequency limit is set by the galvanometers of the string oscillograph at about 400 cps. In both cases of recording, the low-frequency response was limited by the time constant of the piezoelectric-gage circuit—theoretically the frequency response was down about 10 percent at 5 cps.

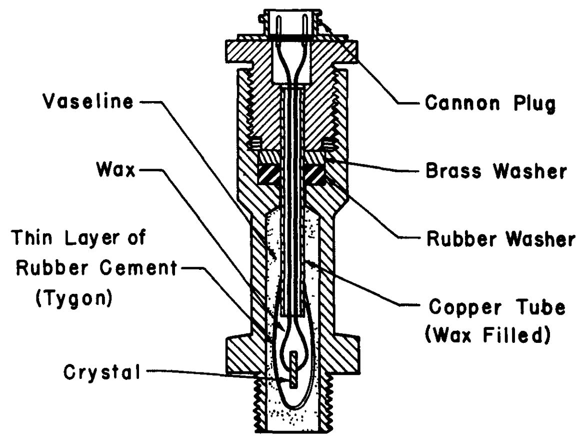


Figure 8 - Piezoelectric Gage

Although the ratio of the gage time constant to the duration of the buffer pressure was theoretically large enough to prevent any appreciable distortion of the record,[9] the experimental records showed zero pressure a short time before the recoil-buffer pressure was actually zero. The calibration step pulse also showed a tendency to decay faster than could be accounted for by the time constant. The discrepancy may possibly be ascribed to imperfect response of the microcoulometer at low frequencies, drift of the amplifier, dielectric absorption of the cable or other causes. Inherently, the use of a piezoelectric transducer for measurement of low-frequency transients, such as in recoil systems, is not satisfactory; the elastic-tube gage is believed to be superior for this type of application.

*In all previous applications by other investigations, and at the time of running of these tests, the response of the microcoulometer was thought to be flat to more than 10,000 cps. Frequency-response curves subsequently run on the instrument, however, revealed that the response was down about 10 percent at 2000 cps. The high-frequency response of the piezoelectric-gage instrumentation was, therefore, unfortunately not as good as that using the elastic-tube gage.

The Accelerometer

Acceleration of the gun during recoil was measured with a 500-g resistance-wire-type accelerometer (Figure 9). The position of the accelerometer on the gun is shown in Figure 5. The instrument incorporates a small mass supported in space by strain-sensitive wires. The wires are connected so as to comprise all four arms of a balanced Wheatstone bridge. When the mass is subjected to an acceleration, the strain wires are stretched, changing their resistance and resulting in an unbalance of the bridge.[11] The a-c bridge voltage of 2200 cps was supplied by a TMB Type-1B Strain Indicator which also served to amplify the voltage output of the accelerometer. The TMB Type-1B Strain Indicator is similar to the Type-1A except that in the 1B, the Wheatstone bridge is completely external. For details of the 1A, see Reference 15.

Calibration of the electrical system was performed before each recording in a manner similar to that used in determining pressures: by comparing the height of the record trace above the base line with the height of a calibration step. This calibration step was obtained by shunting one arm of the bridge with a known resistance, the known resistance corresponding to a known value of acceleration.

Calibration of the accelerometer was performed statically at the Bureau of Standards, Washington, D.C., on a centrifuge. Using the same strain indicator as was used during the tests, the accelerometer was subjected to a known acceleration, and the voltage output read. One arm of the bridge was shunted with a known resistance and again the output was read. This was a direct calibration of the accelerometer and the strain indicator together.

The natural frequency of the accelerometer was determined as about 1300 cps in contrast to the manufacturer's claim of 1600 cps.

The Displacement Gage

Recoil displacement of the gun was measured electrically by use of a resistance-wire gage; the gage location is shown in Figure 5. The gage was constructed as follows, see Figure 10: a thin ribbon of "Advance" metal* 29 in. long was cemented to a strip of bakelite which was screwed to a heavy steel, 1/2-in by 1 1/2-in by 29-in rod. The steel rod in turn was bolted to the gun slide. A brass mount which slid in grooves in the steel rod carried a rotating wheel with a silver rim which made contact with the Advance wire. Two springs pressing against the axle of the wheel insured tight contact

*"Advance" metal is an alloy of 55 percent copper and 45 percent nickel.

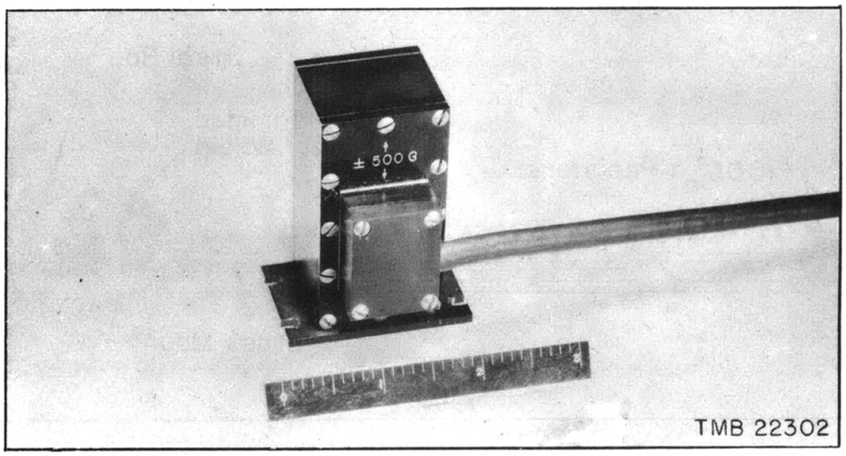


Figure 9a - Photograph of 500-g Accelerometer

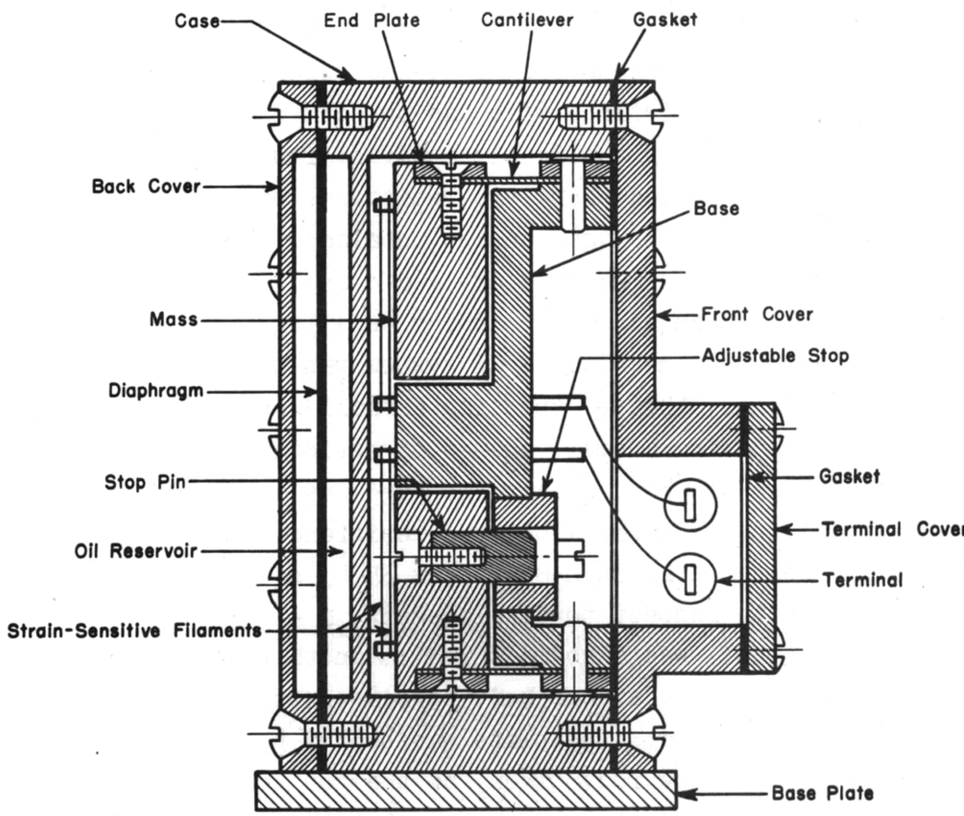


Figure 9b - Cross-Sectional View of Accelerometer

Figure 9 - Statham Accelerometer

The Statham accelerometer utilizes the strain-sensitive wire principle. In order to obtain high sensitivity the strain-sensitive wires serve as supporting springs for the mass or inertia element. In this manner a high ratio of strain to imposed acceleration is obtained. When the mass is subjected to acceleration, the strain wires which comprise a bridge circuit are changed in length thereby unbalancing the bridge circuit. The output signal is amplified and recorded by electronic equipment. The instrument is entirely enclosed, and the case is filled with a silicone fluid which provides the required damping.

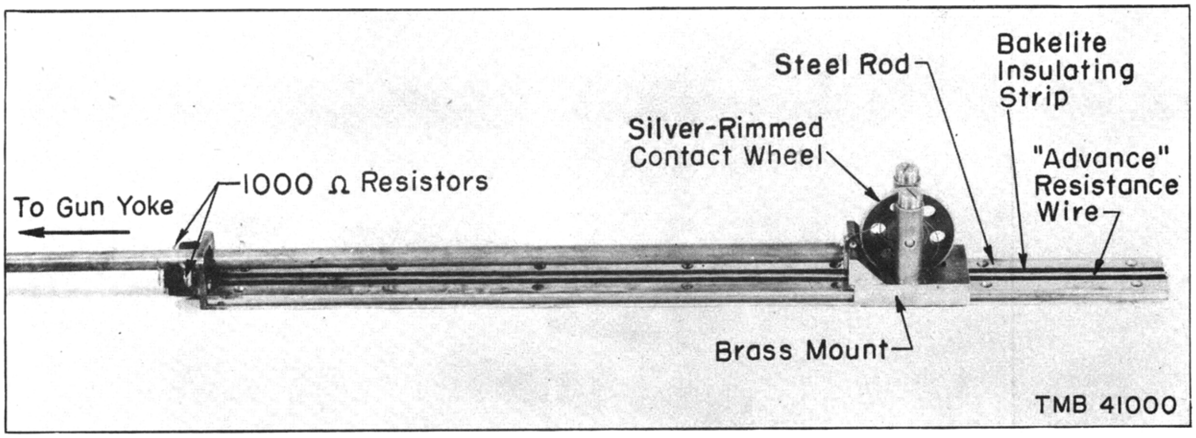


Figure 10 - Gage for Measuring Recoil Displacement

between wheel and resistance wire. The brass mount was connected by a rod to the gun yoke so that, as the gun recoiled, the silver wheel rolled along the resistance wire. This resistance wire was so connected as to form the variable portion of two arms of a slightly modified TMB Type-BR1A d-c Wheatstone bridge.* As the wheel rolled along the resistance wire, the resistance changed in two arms of the bridge, and so unbalanced it. The resulting voltage was then amplified by a TMB Type AM-1A d-c amplifier and recorded as a function of time on a channel of the string oscillograph.

Calibration of the electrical system was performed before each record by the usual method, that is shunting a small resistor in the bridge by a larger one, thus producing a small change of resistance in that arm.

Calibration of the displacement gage was determined by moving the contact wheel various distances along the resistance wire and noting the change in resistance on a Baldwin-Southwark SR-4 indicator. The resistance change was linear with respect to displacement.

Maximum recoil was also measured in another way (Figure 5). A steel rod, bolted to the gun yoke at one end, passed through a hole in a plate and extended some 30 in. beyond. The plate was bolted to the gun slide. A leather washer was forced on the rod. Then, as the gun recoiled, the washer was moved along the rod, its distance from the plate being equal to the maximum recoil. The displacement of the washer was measured after each shot.

As a check on the electrical measurements of displacement, streak photographs were taken during firing. Streak photographs are made with a

*The modification was merely the replacement of the 500-ohm resistors by 1000-ohm ones, the purpose being to hold the bridge output to a low enough level so that it would be linear with respect to change of gage resistance to within 0.5 percent; the ohmic resistance of the Advance wire was 1.38 ohms for the 29 inches used.

moving-film, open-shutter camera. A small lamp, mounted on the gun yoke, recoiled with the gun and produced a continuous line on the film; the film moved at constant speed at right angles to the direction of displacement. A 60-cycle spark put a direct time scale on the film. Another small lamp, mounted on the gun slide (which did not move), served as a zero trace.

Streak photographs, at 0° gun elevation only, were taken by TMB; a second camera, operated by NPG, recorded motion at 40°.

Synchronization of the photographic and string-oscillograph recording was achieved by superimposing a "flash" picture on the film. The flash was actuated by the closing of a microswitch which was connected so as to close after the gun had recoiled a few hundredths of an inch. Closing of the microswitch also placed a step on the string-oscillograph record.

## FIRING SCHEDULE

The service-firing tests, conducted on the pilot turret at the Naval Proving Ground at Dahlgren, are described below. The operation of the turret and the firing of the guns were under the cognizance of NPG. The standard 74-lb powder charge was used for all rounds in the recoil tests.

1. 11 shots from the right gun were fired, at the rate of one or two a day, between 7 July and 15 July 1948. 335-lb projectiles, fired at 0° elevation were used on all eleven shots. On five shots, the three groups of personnel, representing NOL, NPG and TMB, simultaneously obtained complete records. These eleven rounds were the only ones for which pressure from the powder gas was measured, this measurement was made by personnel of NOL and NPG.

2. 31 rounds of a scheduled 50-shot rapid-fire program were fired from the right gun 9 August 1948. The complete program was not carried out because of a breakdown in the automatic-loading mechanism of the gun. Data were taken only on Rounds 5, 6, 11, 12, 20, 21, 30 and 31. 260-lb projectiles were fired on Rounds 5, 6, 11, 12, 20 and 21; 335-lb projectiles on Rounds 30 and 31. Rounds 5, 11, 20, and 30 were fired at 40° elevation of the gun; Rounds 6, 12, 21 and 31 at 0° elevation.

3. 50 rounds were fired from the left gun 11 August 1948. Data were taken only on Rounds 5, 6, 11, 12, 20, 21, 30, 31, 49 and 50. 260-lb projectiles were used on Rounds 5, 6, 11, 12, 20, and and 21; 335-lb projectiles on Rounds 30, 31, 49, and 50. Rounds

5, 11, 20, 30 and 49 were fired at 40° elevation; Rounds 6, 12, 21, 31 and 50 at 0° elevation.

## TEST RESULTS

Table 1 is a summary of the more significant results obtained. In this table, rounds fired from the right gun during the period 7 July to 15 July 1948 are reported as one group; the rapid-fire rounds from the right gun 9 August 1948 as another group, and those from the left gun 11 August 1948 as another group. Rounds are numbered consecutively within each group,

Consecutive columns list the following: shot number, date fired, right or left gun, the projectile weight, the angle of gun elevation, muzzle velocity (measured by NPG and only at 0° elevation), ejection time of projectile* (measured by NPG and only for the rounds of the first group), the maximum recoil-hydraulic-buffer force as measured by the elastic-tube gage recording on the string oscillograph, the counterrecoil-air-cylinder force at the time of maximum recoil force, the maximum total recoil force (including an 8-kip friction force,** constant throughout recoil), the maximum recoil acceleration of the gun as measured by the accelerometer, the maximum velocity of recoil as computed from the displacement curve, the maximum displacement of the gun, the duration of recoil, the duration of counterrecoil, the total duration of recoil and counterrecoil, the impulse imparted to the recoil hydraulic buffer, the impulse of the counterrecoil air cylinder, the total impulse given the recoil system during recoil (including impulse due to friction), the maximum force developed in the counterrecoil air cylinder, and the maximum force developed in the counterrecoil hydraulic buffer.

Figure 11 is the recoil portion of a typical string oscillogram. The complete recoil-counterrecoil oscillogram was about three times as long. From raw data like this recording, the results plotted in Figures 12 to 20 were derived.

In Figures 12, 13, 14, 15, and 16, the data taken for 5 shots of the first group are plotted. Each graph shows the variation with time of the recoil-hydraulic-buffer force, counterrecoil-air-cylinder force, counterrecoil-hydraulic-buffer force, assumed friction force, gun acceleration, velocity and displacement.

Closing of the firing-circuit key was taken as zero time for all shots.

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*The time given is the duration from the closing of the firing key until the base of the projectile left the muzzle.

**See page 41 for the derivation of this value of friction.

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# TABLE 1

## Results of the Recoil Tests

| Shot Number | Date | Right or Left Gun | Weight of Projectile | Elevation of Gun | Muzzle Velocity | Ejection Time of Projectile | Maximum Recoil Hydraulic Buffer Force (Faired) | Air Cylinder Force At Time of Maximum Recoil Force | Maximum Total Recoil Force Including Friction | Maximum Acceleration in Recoil | Maximum Velocity in Recoil | Maximum Displacement in Recoil | Duration of Recoil | Duration of Counterrecoil | Total Duration of Recoil-Counterrecoil | Impulse Imparted to Recoil Hydraulic Buffer | Impulse Imparted to Air Cylinder | Total Impulse Imparted to Recoil System Including Friction | Maximum Force Developed in Air Cylinder | Maximum Force Developed in Counterrecoil Hydraulic Buffer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1948 | | lb | degrees | ft/sec | sec | kips | kips | kips | in/sec² x 10³ | in/sec | in. | sec | sec | sec | kipsec | kipsec | kipsec | kips | kips |
| 4 | 9 July | Right | 335 | 0 | 2429 | 0.034 | 132 | 57 | 197 | 18.5 | 195 | 25.1 | 0.285 | 0.56 | 0.85 | 18.4 | 18.2 | 38.7 | 73 | 158 |
| 5 | 12 July | Right | 335 | 0 | 2435 | 0.038 | 138 | 55 | 201 | 16.5 | 199 | 25.1 | 0.275 | 0.56 | 0.84 | 17.8 | 17.6 | 36.9 | 73 | 150 |
| 6 | 13 July | Right | 335 | 0 | 2434 | 0.032 | 130 | 58 | 196 | 26.5 | 194 | 24.5 | 0.265 | 0.52 | 0.79 | 16.0 | 17.3 | 35.4 | 76 | 158 |
| 10 | 15 July | Right | 335 | 0 | 2433 | 0.035 | 133 | 58 | 199 | 19.0 | 201 | 25.0 | 0.275 | 0.56 | 0.84 | 17.8 | 18.6 | 38.5 | 78 | 152 |
| 11 | 15 July | Right | 335 | 0 | 2447 | 0.036 | 134 | 46 | 188 | 17.5 | 198 | 26.5 | 0.295 | 0.76 | 1.05 | 19.6 | 15.6 | 37.3 | 62 | 125 |
| RAPID FIRE | | | | | | | | | | | | | | | | | | | | |
| 6 | 9 Aug | Right | 260 | 0 | 2613 | | 104 | 59 | 171 | 24.4 | 177 | 22.9 | 0.28 | 0.50 | 0.78 | 13.6 | 18.9 | 34.7 | 77 | 158 |
| 11 | 9 Aug | Right | 260 | 40 | | | 113 | 59 | 180 | 18.5 | 188 | 26.6 | 0.32 | 0.90 | 1.22 | 18.3 | 22.1 | 43.0 | 82 | 73 |
| 12 | 9 Aug | Right | 260 | 0 | 2599 | | 104 | 59 | 161 | 18.3 | 183 | 22.9 | 0.27 | 0.51 | 0.78 | 12.8 | 18.0 | 32.2 | 77 | 162 |
| 20 | 9 Aug | Right | 260 | 40 | | | 118 | 59 | 184 | 18.1 | 187 | 27.0 | 0.32 | 0.89 | 1.21 | 18.8 | 22.2 | 43.6 | 82 | 66 |
| 21 | 9 Aug | Right | 260 | 0 | -- | | 106 | 59 | 173 | 19.8 | 180 | 22.9 | 0.27 | 0.50 | 0.77 | 13.0 | 17.7 | 32.9 | 77 | 164 |
| 30 | 9 Aug | Right | 335 | 40 | | | 150 | 59 | 217 | 23.0 | 216 | 27.6 | 0.30 | 0.87 | 1.17 | 23.9 | 20.8 | 47.1 | 83 | 68 |
| 31 | 9 Aug | Right | 335 | 0 | 2430 | | 139 | 59 | 206 | 22.1 | 204 | 24.9 | 0.27 | 0.50 | 0 77 | 16.7 | 17.6 | 36.4 | 79 | 164 |
| 5 | 11 Aug | Left | 260 | 40 | | | 116 | 59 | 183 | 20.0 | 184 | 26.2 | 0.32 | 1.10 | 1.42 | 18.7 | 22.6 | 43.9 | 81 | 54 |
| 6 | 11 Aug | Left | 260 | 0 | 2566 | | 110 | 59 | 177 | 20.3 | 158 | 22.1 | 0.27 | 0.60 | 0.87 | 13.4 | 17.1 | 32.7 | 76 | 132 |
| 12 | 11 Aug | Left | 260 | 0 | 2584 | | 107 | 58 | 173 | 16.7 | 175 | 22.4 | 0.28 | 0.58 | 0.86 | 12.5 | 18.2 | 32.9 | 76 | 126 |
| 20 | 11 Aug | Left | 260 | 40 | | | 124 | 60 | 192 | 18.2 | 178 | 25.9 | 0.32 | 0.99 | 1.33 | 19.8 | 22.2 | 44.6 | 81 | 68 |
| 21 | 11 Aug | Left | 260 | 0 | 2588 | | 108 | 59 | 175 | 19.1 | 174 | 22.6 | 0.28 | 0.57 | 0.85 | 12.7 | 18.2 | 33.1 | 77 | 125 |
| 30 | 11 Aug | Left | 335 | 40 | | | 152 | 60 | 220 | 18.7 | 210 | 27.2 | 0.30 | 1.00 | 1.30 | 23.3 | 21.1 | 46.8 | 83 | 69 |
| 31 | 11 Aug | Left | 335 | 0 | 2392 | | 139 | 59 | 206 | 20.2 | 201 | 24.6 | 0.27 | 0.57 | 0.84 | 16.3 | 18.6 | 37.1 | 79 | 129 |
| 49 | 11 Aug | Left | 335 | 40 | | | 153 | 59 | 220 | 17.1 | 223 | 27.5 | 0.30 | 0.99 | 1.29 | 23.3 | 21.7 | 47.4 | 83 | 67 |
| 50 | 11 Aug | Left | 335 | 0 | 2375 | | 137 | 59 | 204 | 19.8 | 197 | 24.5 | 0.27 | 0.57 | 0.84 | 16.4 | 18.8 | 37.4 | 79 | 127 |



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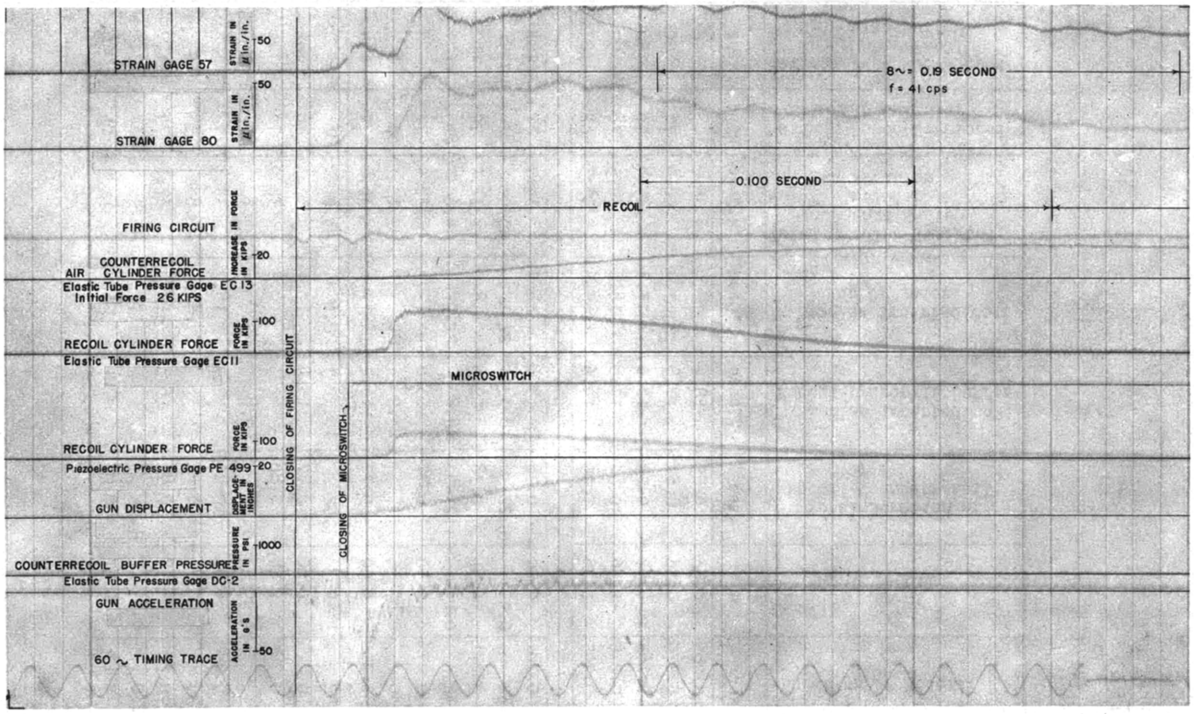


Figure 11 - Typical String Oscillogram; Round 50; Left Gun at 0° Elevation Projectile Weight, 335 lb; 11 August 1948

Figures 17, 18, 19, and 20 show similar data for Rounds 6, 11, 30, 31—taken from the second group—except that the velocity-time history is not derived. As shown in Table 1, in Round 6 a 260-lb projectile was fired at 0°; in Round 11, a 260-lb projectile at 40°; Round 30, a 335-lb projectile at 40°; and Round 31 a 335-lb projectile at 0°.

In Figure 21 recoil forces are plotted against displacement. The curves are derived from those shown in Figure 11. This form is convenient for comparison with the design recoil- and counterrecoil-velocity curves—shown as Figure 22 which is a replot of Drawing 255029, U.S. Naval Gun Factory, Washington, D.C.

In Figure 23, the variation of recoil forces and motion with time are shown on an expanded time scale. This allows closer study of the interplay of the recoil forces during initial recoil.

## Recoil Hydraulic Buffer Force

In Table 1 and in the plotted curves of Figures 12 to 20, the recoil-hydraulic-buffer force illustrated was obtained from the pressure measured by the elastic-tube gage and recorded on the string oscillograph. Rapid variations in pressure were ignored; the curves shown are faired curves. The

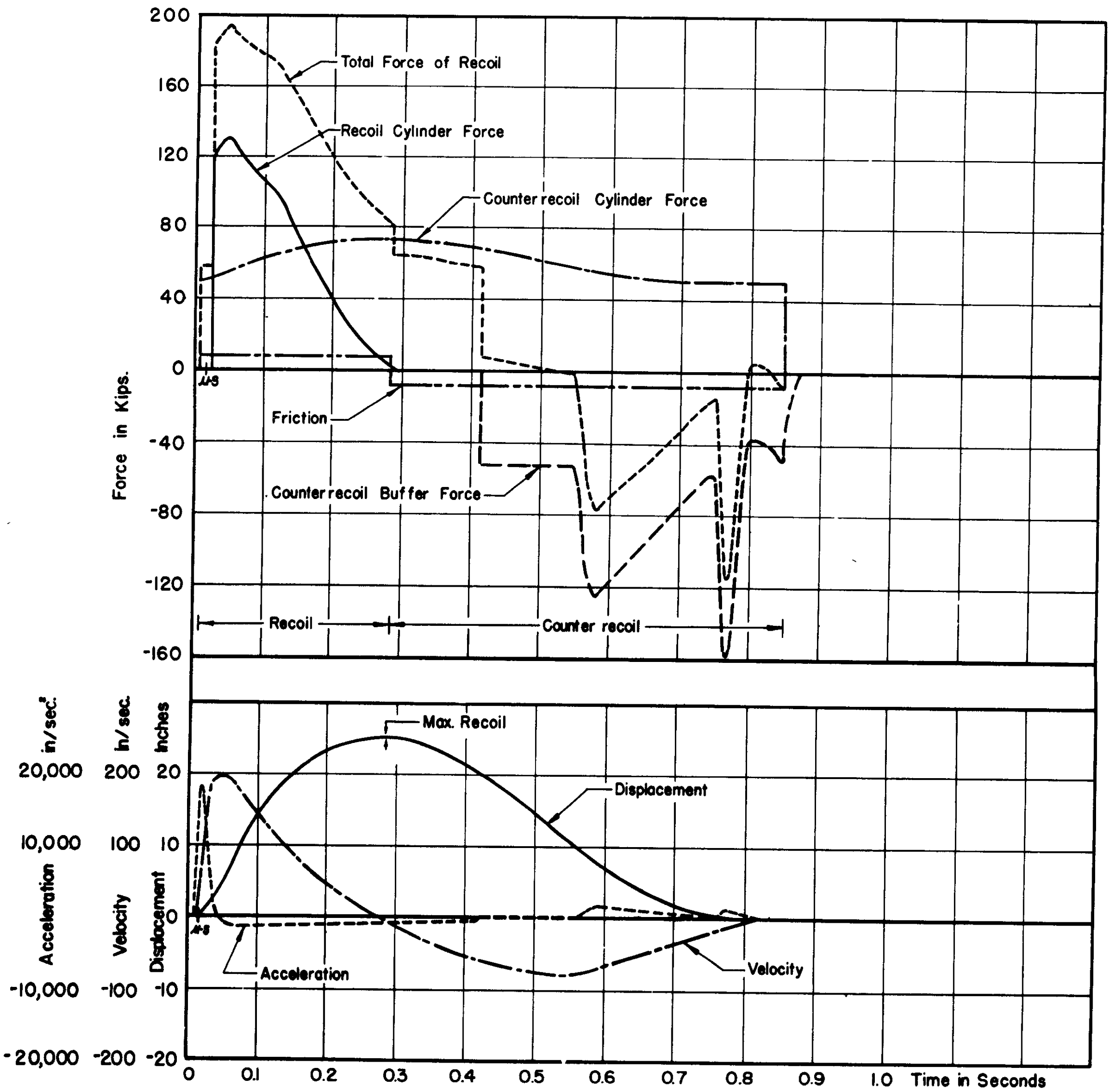


Figure 12 - Recoil Curves; Round 4; Right Gun at 0° Elevation; 9 July 1948; Projectile Weight, 335 lb.

justification for this will be discussed later. Pressure in the recoil hydraulic buffer was converted to force by multiplying it by the equivalent piston area, 97.0 sq. in. This area was computed as the total piston area diminished by the sum of the piston-rod, throttling-rod and orifice areas. The throttling-rod and orifice areas vary with the stroke. In addition, orifice area must be multiplied by a coefficient in order to account for the decreased pressure on some portions of the piston due to flow near the orifices.[3] The total piston area was 132.7 square inches; piston-rod area, 23.7 sq. in. After making the necessary corrections, it was found that the sum of throttling-rod and orifice areas varied between 10.7 and 12.2 sq. in. as the stroke

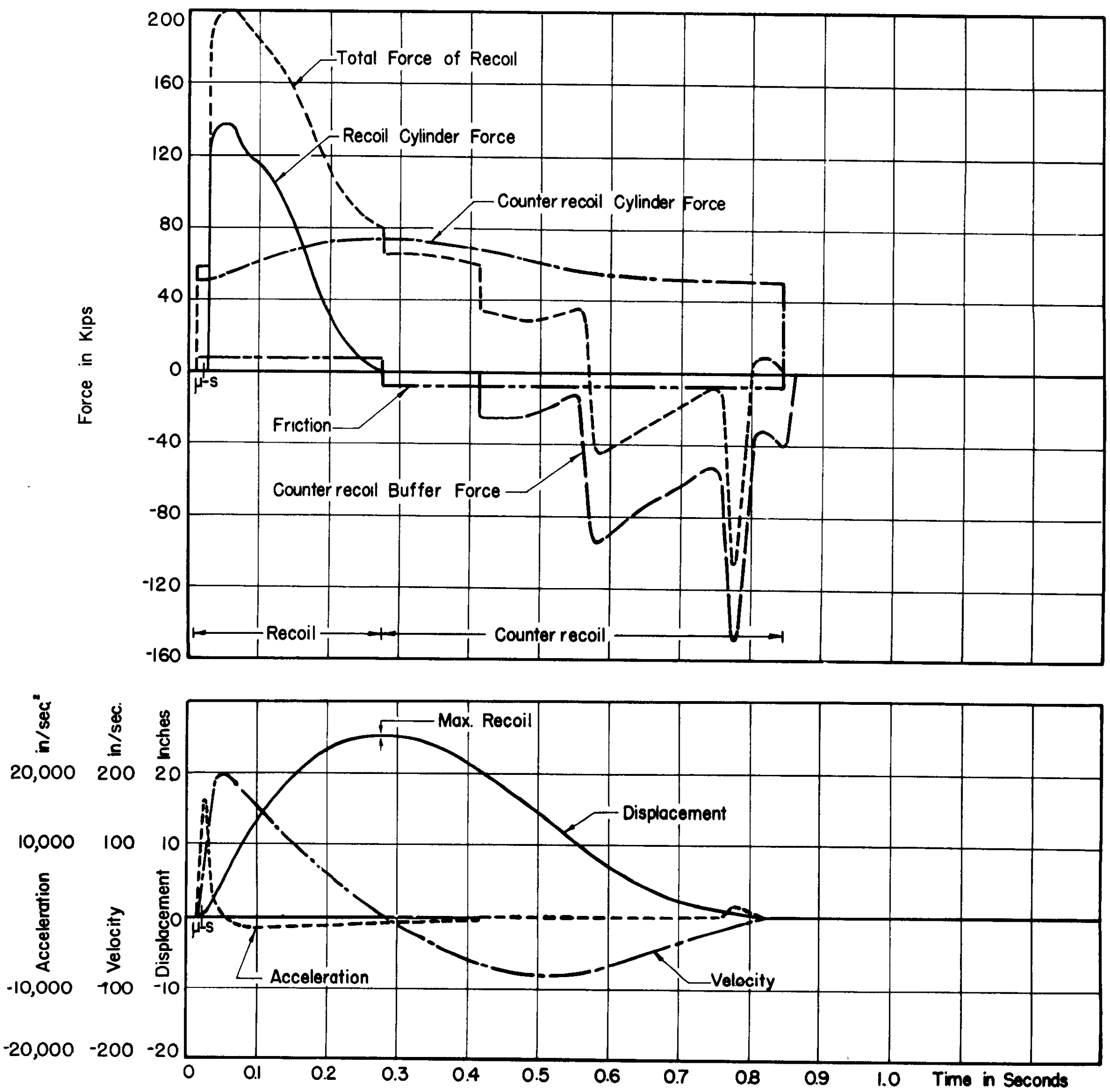


Figure 13 - Recoil Curves, Round 5; Right Gun at 0° Elevation; 12 July 1948; Projectile Weight, 335 lb.

ranged from 9 to 28.0 in; for stroke ranging from 4 to 8 in. (which is the recoil distance within which maximum pressure occurred) this area varied from 12.0 to 12.2 in$^2$. If a value of 12.0 is used, the equivalent piston area is 97.0 in$^2$. The error introduced by using this value is less than 0.3 percent in the region of maximum pressure and not more than 1 percent for any portion of recoil. This error was negligible.

The maximum force generated within the recoil buffer averaged about 135 kips, with a mean deviation of ±3 kips, for rounds fired at 0° elevation, using a 335-lb projectile and fired from either the right or the left gun. The variability in this force for the 8 rounds noted is well indicated by the

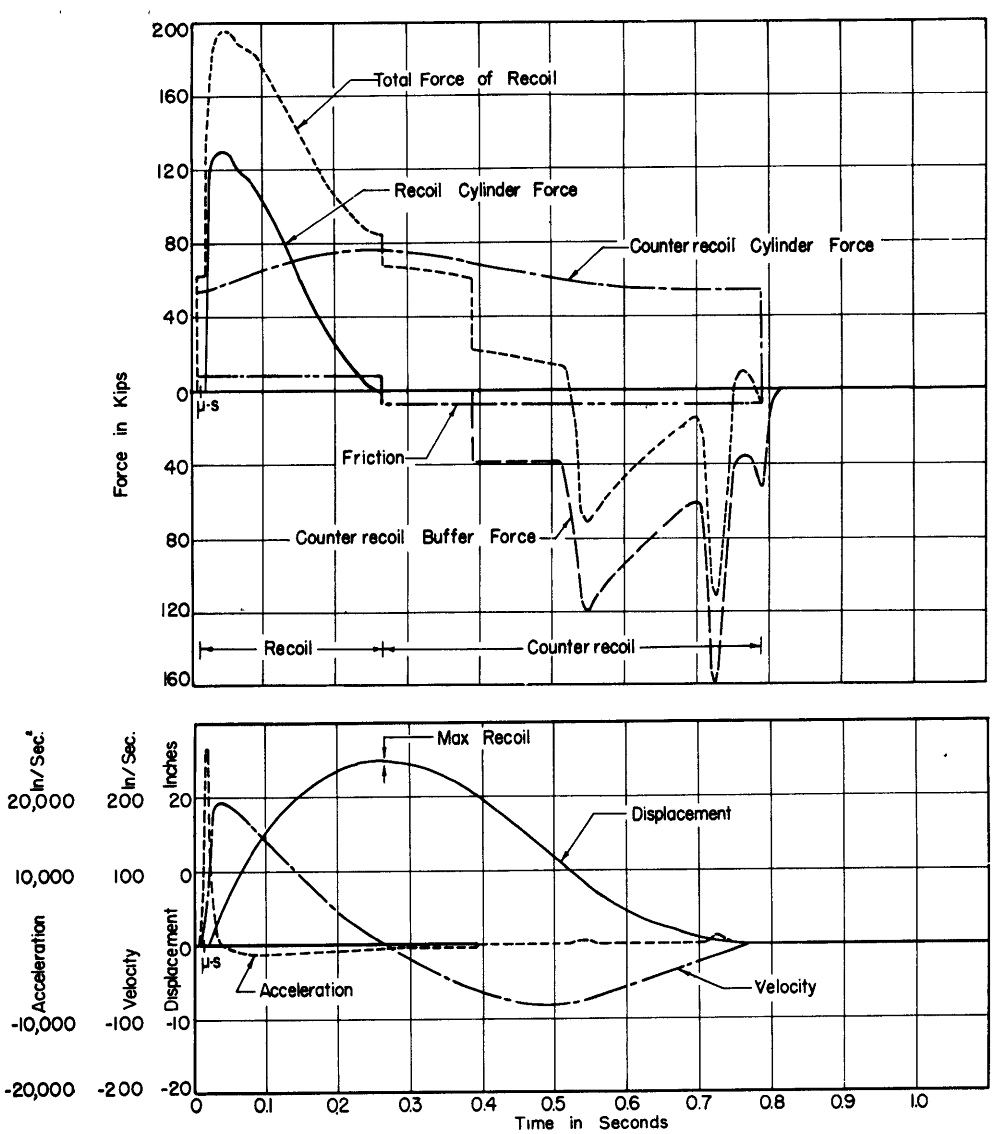


Figure 14 - Recoil Curves, Round 6; Right Gun at 0° Elevation; 13 July 1948; Projectile Weight, 335 lb.

mean deviation; the absolute magnitude of this force, however, is better indicated by 135 ± 10 kips; see Appendix 1.

Rounds fired at 40° elevation produced a somewhat greater force of about 152 kips. If the projectile fired was a 260-lb missile, the maximum recoil-buffer force was somewhat lower, averaging about 106 kips at 0° elevation and 118 kips at 40°.

The recoil-buffer force should be proportional to the ratio of the square of the recoil velocity to the square of the orifice area.[2] Maximum recoil-buffer force occurred when the gun had recoiled about 5 in. Since the orifice area in this region is varying to some degree (at 4.0 in., orifice

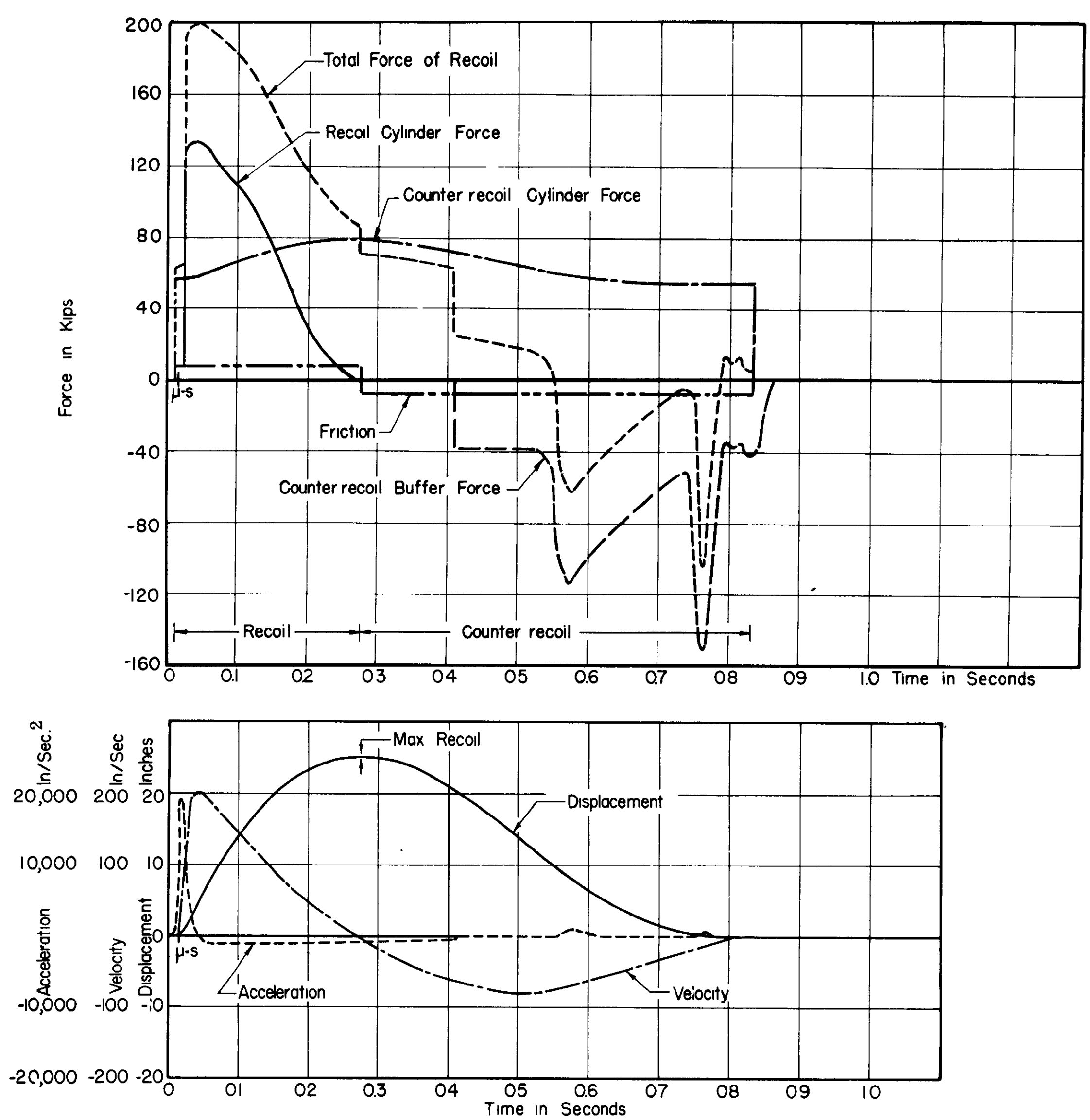


Figure 15 - Recoil Curves; Round 10; Right Gun at 0° Elevation; 15 July 1948; Projectile Weight, 335 lb.

area is 5.34 sq in; at 6.0 in., it is 5.68 sq in.) a small variation in the position of the gun when maximum recoil velocity occurs will affect the recoil-buffer force somewhat; e.g., ±1 in. of displacement would mean ±8 percent of recoil-buffer force provided the maximum recoil velocity were the same. The displacement of the gun at the time of maximum recoil velocity, and the maximum recoil velocity itself will be influenced greatly by the amount of air present in the recoil fluid. That air was dissolved in the liquid would seem to be evidenced by the fact that no measurable pressure was generated within the recoil buffer during the initial 10 or 15 milliseconds

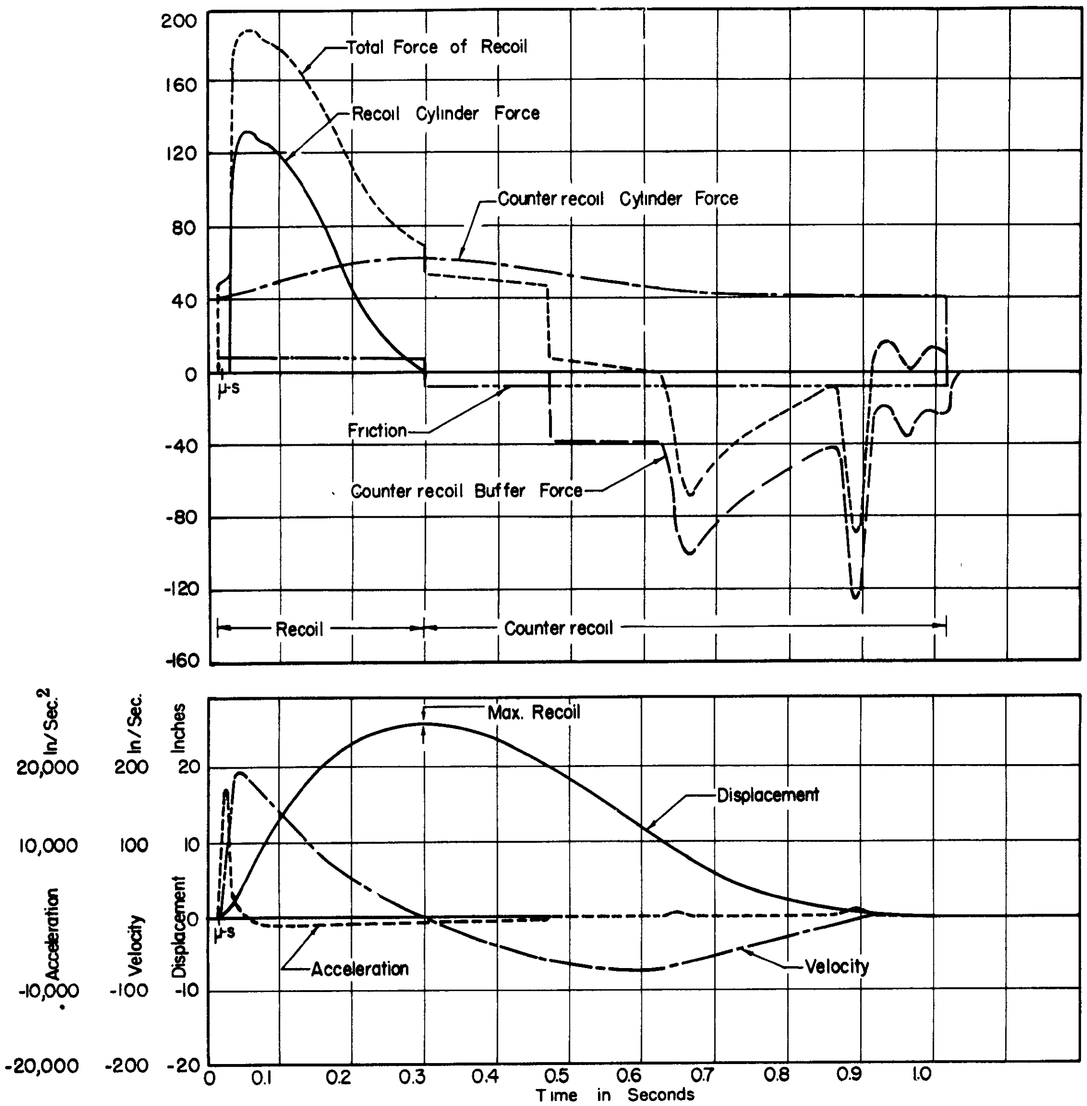


Figure 16 - Recoil Curves; Round 11; Right Gun at 0° Elevation; 15 July 1948; Projectile Weight, 335 lb.

after the gun began to recoil, although the buffer piston was moving with considerable velocity; see Figure 23.

If the orifice area at the time of maximum buffer force at 0° elevation be assumed the same as that at 40°, an estimate of the maximum recoil buffer force at 40° can be made:

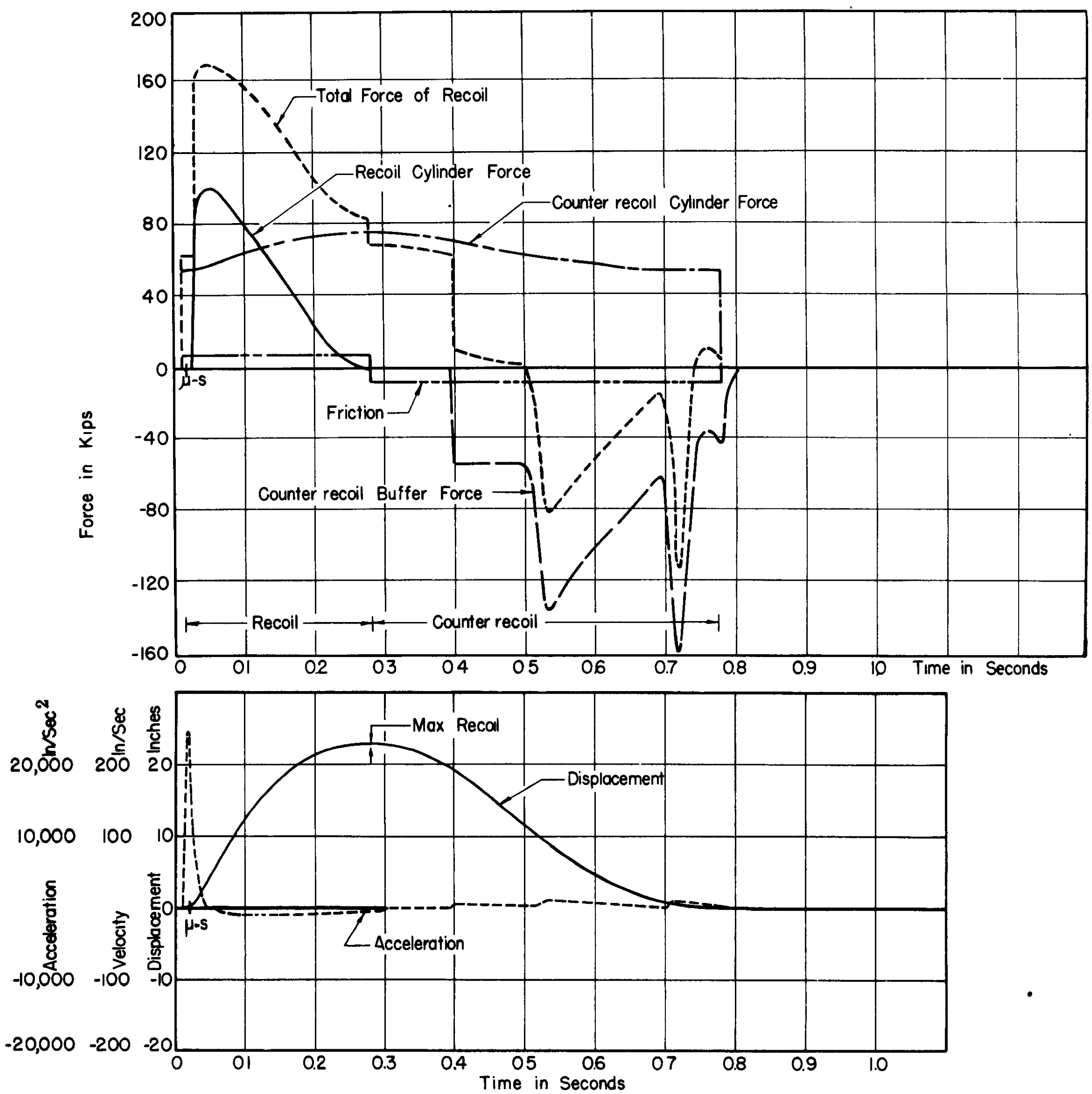


Figure 17 - Recoil Curves; Round 6; Right Gun at 0° Elevation; 9 August 1948; Projectile Weight, 260 lb.

For a 335-lb projectile,

$$F_{40^\circ} = F_{0^\circ} \cdot x \left(\frac{V_{40^\circ}}{V_{0^\circ}}\right)^2$$

$$135 \times \left(\frac{216}{199}\right)^2 = 157 \text{ kips.}$$

The measured force was 152 kips.

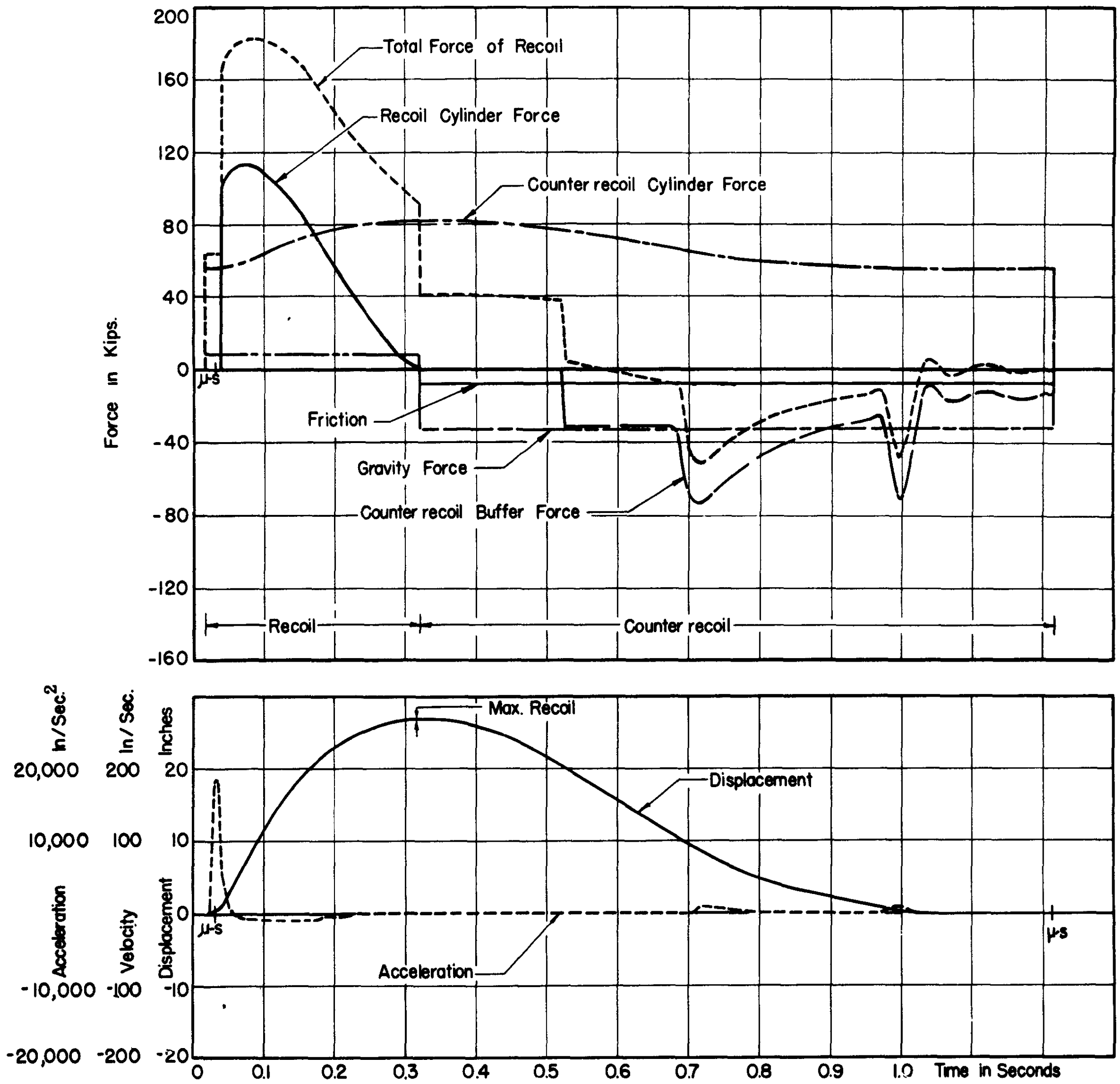


Figure 18 - Recoil Curves; Round 11; Right Gun at 40° Elevation; 9 August 1948; Projectile Weight, 260 lb.

For a 260-lb projectile,

$$F_{40°} = 106 \times \left(\frac{184}{175}\right)^2 = 117 \text{ kips}$$

The measured force was 118 kips.

The increase in recoil-buffer force, observed when a 335-lb projectile rather than a 260-lb projectile is fired, is probably due to the increased recoil velocity of the gun occurring from a more sustained acceleration. This latter results from a more sustained and higher powder force which in turn is due to the greater time spent by the projectile within the barrel of the gun. The increased duration is made evident by the lower ejection

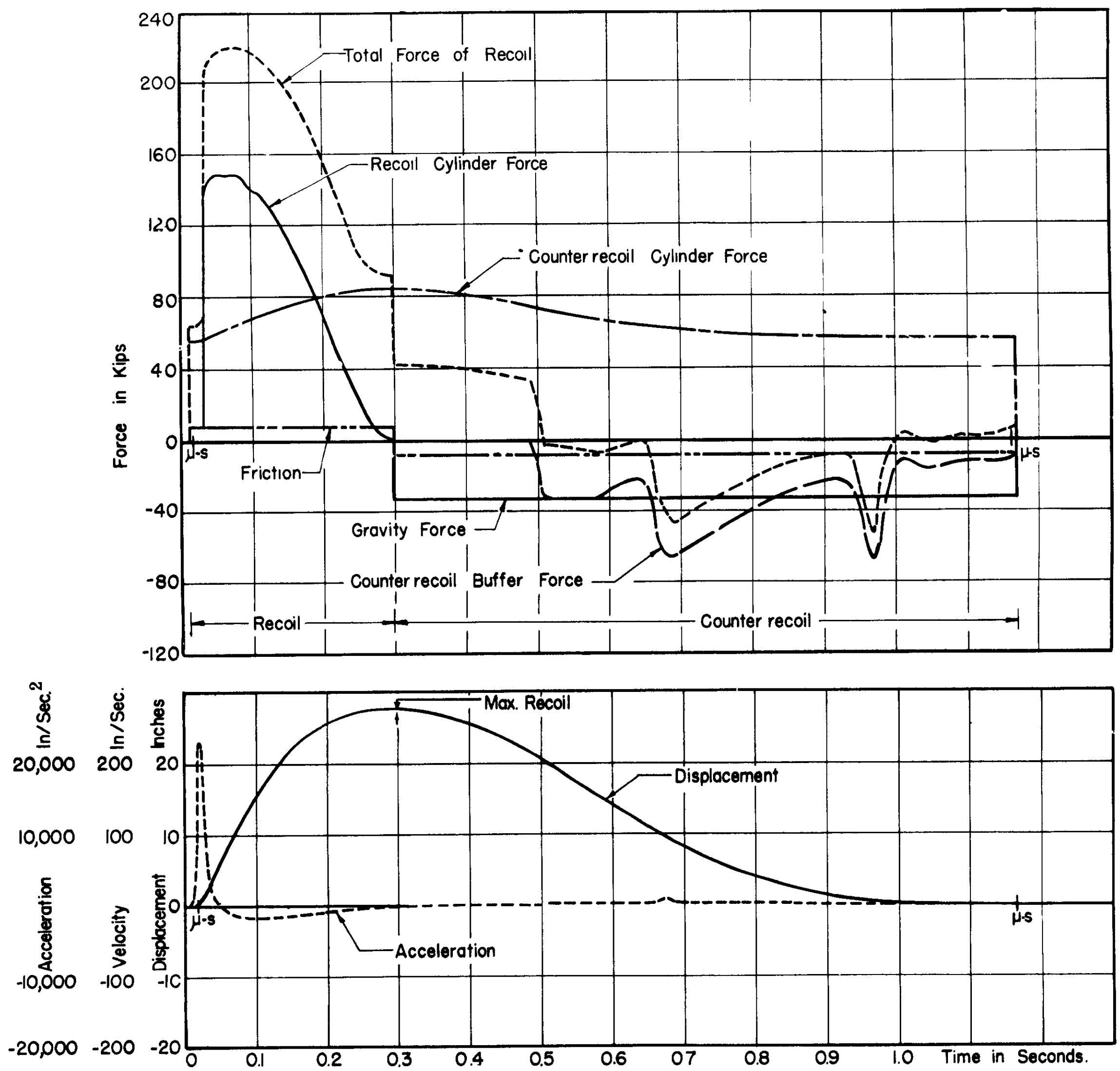


Figure 19 - Recoil Curves; Round 30; Right Gun at 40° Elevation; 9 August 1948; Projectile Weight, 335 lb.

velocity of the heavier projectile. (Assuming that a higher ejection velocity means a higher average velocity within the barrel, a smaller time within the barrel is spent by the lighter projectile.) The increased period of acceleration is of the order of 2 milliseconds and could not be discerned on the accelerometer records.

It is to be noted that although the ejection velocity of the heavier projectile is less, its momentum is markedly greater; about 25 x $10^3$ in-lb for the 335-lb projectile as compared to 21 x $10^3$ in-lb for the 260-lb projectile. The increase is much the same whether the left or right gun is fired. Also to be noted is the fact that the momentum imparted to the projectile is only about 2/3 of the impulse imparted to the recoil system.

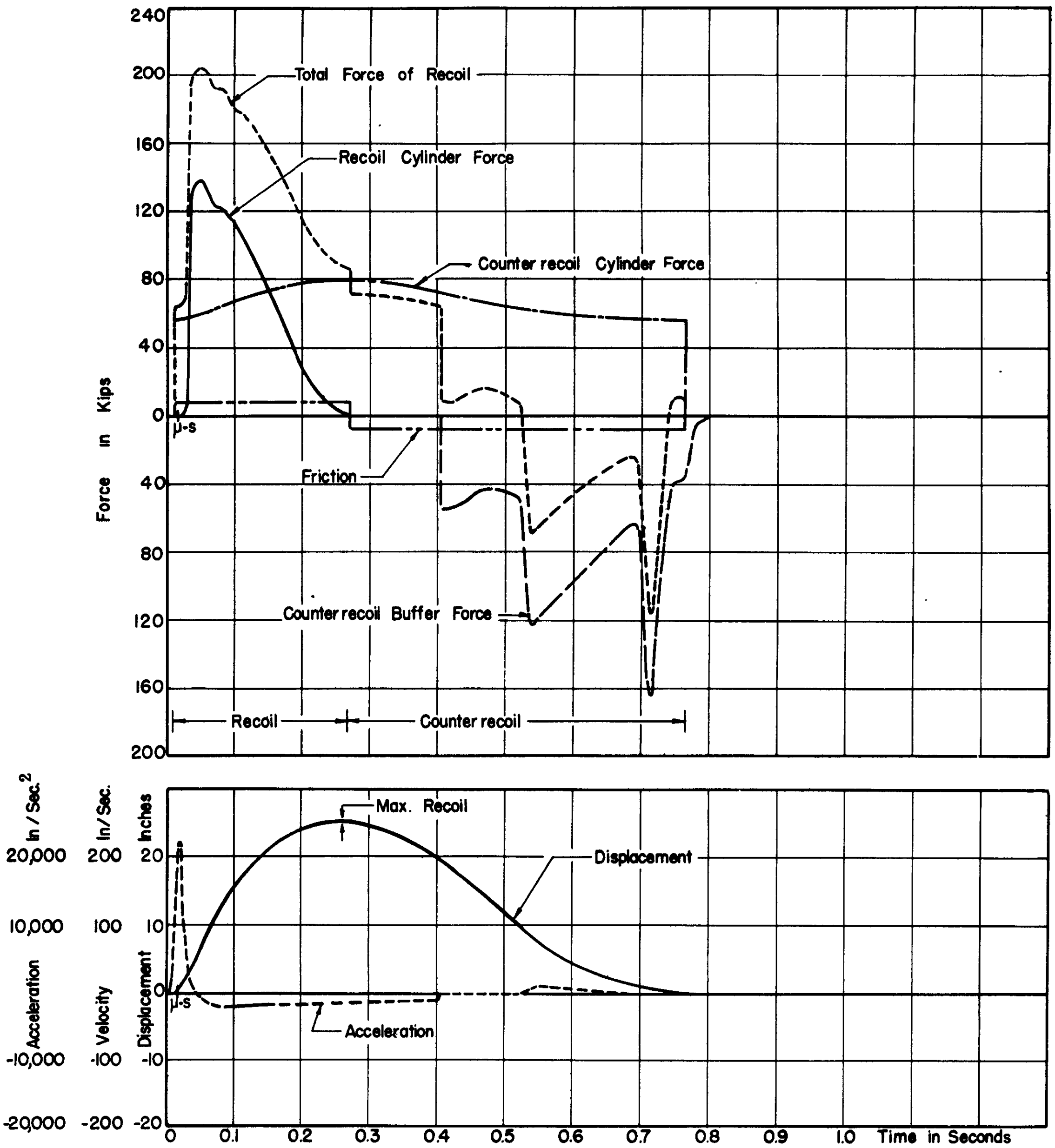


Figure 20 - Recoil Curves; Round 31, Right Gun at 0° Elevation; 9 August 1948; Projectile Weight, 335 lb

The increase in recoil-buffer force when the gun is fired at 40° rather than 0° elevation is also due to a more sustained powder force. Elevating the gun results in a reduction of the powder force available for acceleration of the projectile since part of the powder force now is exerted in lifting the weight of the projectile against gravity. Although the velocity of gun recoil is increased, the ejection velocity of the projectile should be less. No measurements of ejection velocity were made at 40°.

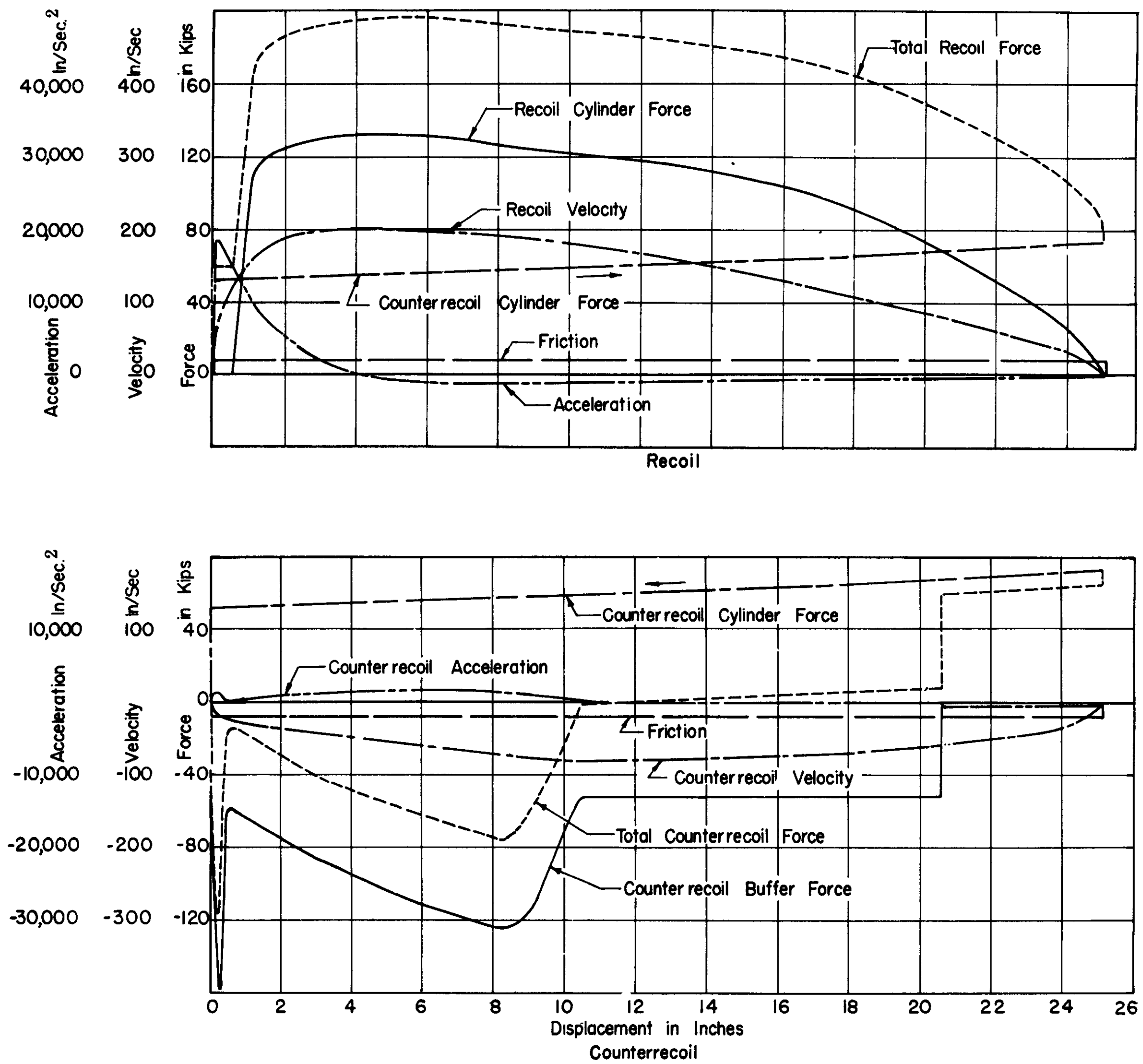


Figure 21 - Recoil Curves Plotted against Displacement; Round 4, Right Gun at 0° Elevation; 9 July 1948 Projectile Weight, 335 lb.

## High Frequency Variations in Pressure

Some 10 milliseconds after the firing switch is closed, the gun begins to recoil; in an additional 10 or 15 milliseconds, pressure appears in the recoil hydraulic buffer. The initial portion of this pressure record is accompanied by high-frequency variations in pressure of appreciable amplitude which, however, die out in about 30 milliseconds. The fundamental frequency of these pressure variations appears to be about 670 cps; often strong harmonics are present, raising the apparent frequency to about 1200 or 1300 cps. Figures 24 and 25 are cathode-ray-oscillograph records showing pressure as recorded simultaneously by the elastic-tube pressure gage and the piezoelectric

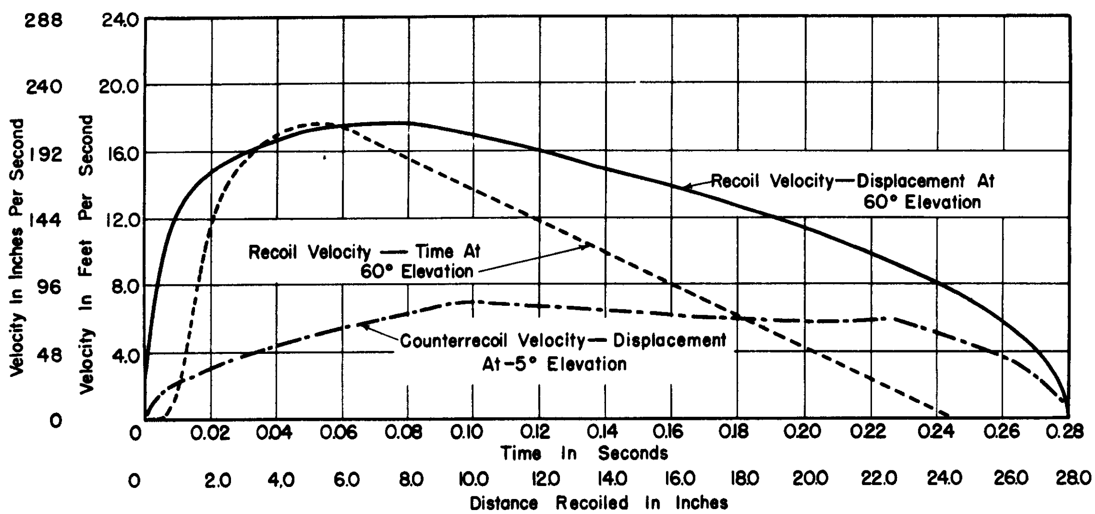


Figure 22 - Theoretical Velocity Curves

These curves were retraced from Naval Gun Factory Drawing 255029; they are to be compared with the experimental curves shown in the preceding figures; projectile weight 335 lb.

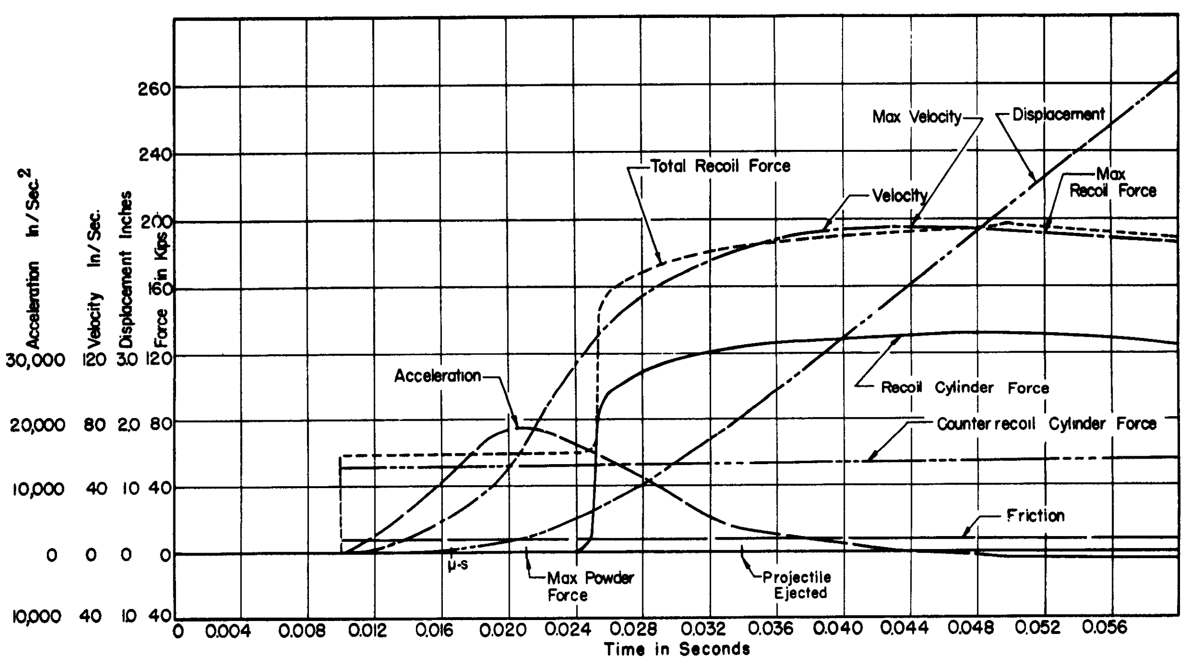


Figure 23 - Recoil Curves during Initial Recoil; Round 4; Right Gun at 0° Elevation; 9 July 1948; Projectile Weight, 335 lb

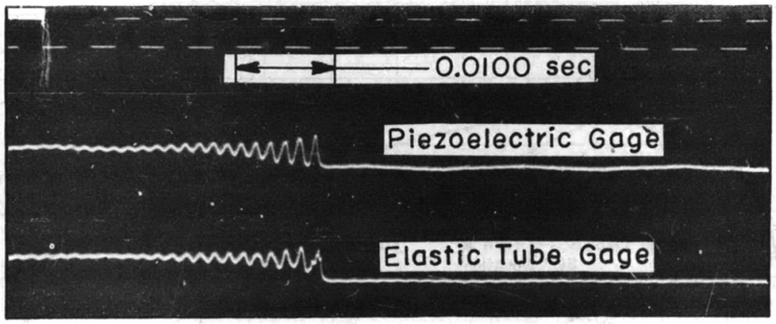


Figure 24a - Round 4; 9 July 1948

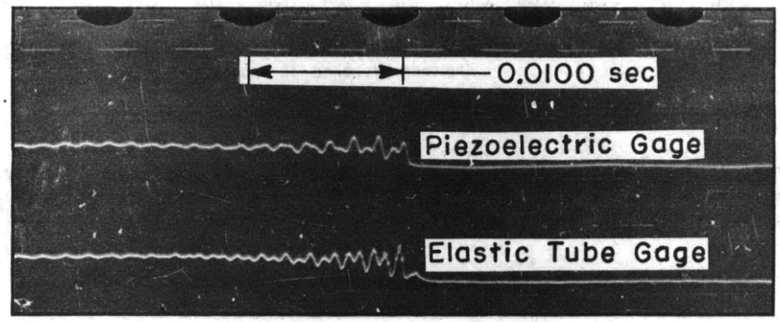


Figure 24b - Round 5; 12 July 1948

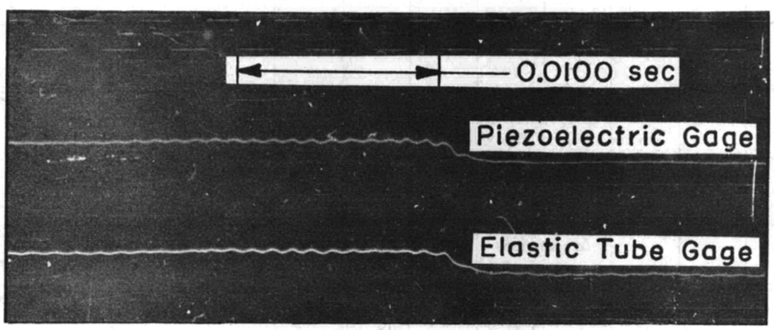


Figure 24c - Round 31; 9 August 1948

Figure 24 - Cathode-Ray Oscillograms of Recoil Hydraulic Buffer Pressures

All three are from the right gun at 0° elevation, 335-lb projectile. The square wave at the top of each record has a period of 0.005 sec.

gage. In general, there is not a point-for-point correspondence between the elastic-tube pressure record and that of the piezoelectric gage, although when the fluctuations are less violent, as in Figure 24c, the agreement is closer. On the string oscillograph, where higher frequencies cannot be recorded, the point-for-point correspondence appeared excellent. Other points to be noted are these: the pressure fluctuations are not reproducible from

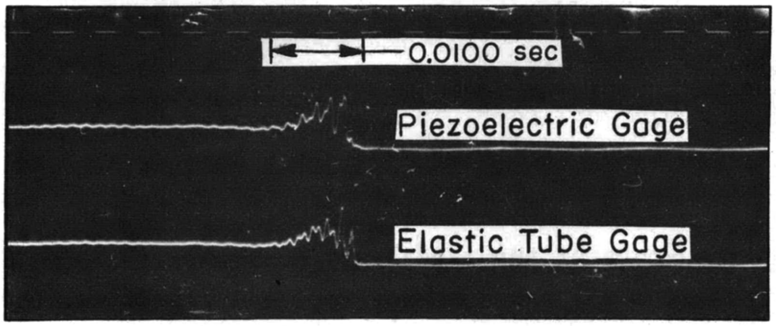


Figure 25 - Cathode-Ray Oscillograms of Recoil Hydraulic Buffer Pressure

This oscillogram illustrates an instance of large amplitude pressure with a duration of about 0.010 sec.

shot to shot either as to frequency or amplitude; the initial peak may or may not be greater than the faired maximum value; sometimes the fluctuations are superimposed upon a relatively straight faired line—as in Figure 24c—and sometimes there is a hump in the record upon which the fluctuations are superimposed—as in Figure 25.

Why these high-frequency fluctuations appear has been determined only qualitatively. The frequencies present seem to be of the order of the natural frequency of the recoil cylinder vibrating as a liquid-filled organ pipe, so that perhaps the fluctuations are reflections of pressure generated by the sudden impact of the piston striking the liquid in the cylinder.

The natural frequency of the recoil cylinder considered as a closed organ pipe filled with water is given by

$$f = \frac{c}{2l} = \frac{60 \times 10^3}{2 \times 30} = 1.0 \times 10^3 \text{ cps}$$

where c is the velocity of sound in water and $l$ is the length of the recoil cylinder. If the recoil cylinder were filled with glycerine, its natural frequency would be

$$f = \frac{c}{2l} = \frac{77 \times 10^3}{2 \times 30} = 1.3 \times 10^3 \text{ cps}$$

where c now is the velocity of sound in glycerine.

The fundamental frequency observed was about 670 cps.

If the radial frequency of the recoil cylinder (vibrating as an alternately contracting and expanding ring) be computed,[17] then

$$f = \frac{1.1}{2\pi}\,\frac{c}{r} = \frac{17{,}000 \times 12}{6.28 \times 7.8} = 4.6 \times 10^3 \text{ cps}$$

where c is the velocity of sound in steel and r is the mean radius of the recoil cylinder.

The fundamental flexural frequency of the recoil cylinder, considered as a thin circular cylinder, is given by:

$$f = \frac{0.81}{2\pi}\frac{ct}{r^2} \quad \frac{0.81 \times 2.04 \times 10^5 \times 4.1}{6.28 \times (7.8)^2} = 1.8 \times 10^3$$

where t is the thickness of the recoil-cylinder wall.

The pressure generated in the recoil cylinder as a result of impact of the piston upon the liquid in the cylinder is given by

$$p = \rho cv = \frac{75 \times 60 \times 10^3 \times 200}{1728 \times 386} = 1.3 \times 10^3 \text{ psi}$$

where p is the pressure,

$\rho$ is the mass density of the liquid,

c is the speed of sound in water, and

v is the velocity of impact.

This value compares fairly well with the amplitude of the pressure variations present.

A similar high frequency ($1.0 \times 10^3$ cps) variation in pressure, persisting for about 0.01 seconds, was noted at the beginning of the counterrecoil-hydraulic-buffer pressure record. At this time counterrecoil velocity was about 60 in. per sec so that the calculated amplitude of pressure would be about 400 psi. Actual amplitudes were of this order.

Whether the pressure gages as located see the same pressure-time history as occurs at the rear of the recoil cylinder is doubtful. The relatively long and tortuous travel (there are about five right angle bends in the path) of the pressure from the rear of the recoil cylinder, through the valve used for filling the cylinder and through the adapter to the gages, probably tends to distort the pressure pulse.

Even a small amount of air in the tubing leading to the gages would cause serious distortion of the pressure record because instead of the liquid merely transmitting the pressure wave, enough liquid would have to move into the tubing to compress the air to the same pressure. The time to move this liquid would represent a time delay between pressure in the recoil buffer and pressure as detected by the pressure gages.

Precautions were therefore taken to remove air from the tubing leading to the gages and from the gage housings. The elastic-tube gage was provided with a screw, which when loosened, permits the gage to be bled, see Figure 7. The piezoelectric gage had no provision for bleeding; to prevent accumulation of air in its housing, it was carefully packed with vaseline before attaching to the recoil cylinder. The gage was packed while the housing was hot enough to melt vaseline, permitted to cool and then enough melted vaseline was added to fill the gage housing completely.

The elastic-tube gage was bled and the piezoelectric gage repacked every time the recoil cylinder was filled. In spite of this precaution, it is possible that gases accumulated within the gages, especially in the piezoelectric. Each time this gage was removed for repacking, it was noticed that the vaseline was churned and that some had disappeared.

If a faithful record of the high-frequency variations in pressure in the recoil cylinder were required, then some means of mounting a pressure gage directly on the recoil cylinder would have to be found, such as a hole for the gage tapped directly into the recoil cylinder. High-frequency fluctuations of short duration had no effect on the motion of the gun, however, and no chatter was observed on the displacement records. It is fortunate, also, that sinusoidal variation of recoil load of a frequency higher than about 300 cps is unimportant so far as the structural supports of the gun are concerned. This is so because the forced response, including the initial transient, of an elastic system which approximates a single-degree-of-freedom system (the truss and girder supporting structure for the guns), to a sinusoidal disturbance of frequency three or more times that of the natural frequency of the system, is less than one-half of the static response.* Hence, it is permissible to fair through vibrations of this sort on the pressure record because nowhere, on any of the strain gages placed on the various members of the truss and girder structure, could strains of appreciable amplitude of a frequency higher than 100 cps be detected.

No high-frequency pressure variations could be detected in the air-cylinder pressure record. A small-amplitude high-frequency ($1.0 \times 10^3$ cps) -

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*The response of an undamped single-degree-of-freedom system starting from rest to a periodical disturbing force P sin $\omega t$ is given, according to Timoshenko,[17] by

$$x = \frac{P}{k} \frac{1}{1 - \frac{\omega^2}{p^2}} \left(\sin \omega t - \frac{\omega}{p} \sin pt\right)$$

where x is the response, P/k is the static response, $\omega$ is the circular frequency of the disturbance, p is the natural circular frequency of the structure and t is the time. If $\omega \geq 3p$, the maximum value of $x = \frac{1}{2}\frac{P}{k}$. As $\frac{\omega}{p}$ increases, the maximum value of x decreases. If damping is present, the maximum value of x is further decreased.

pressure variation was found at the beginning of the counterrecoil-hydraulic-buffer record which is felt to be pressure reflections in the recoil cylinder produced by the impact of the piston upon the liquid in the buffer.

Counterrecoil-Air-Cylinder Force

The increase in counterrecoil-air-cylinder force during recoil was obtained from the pressure change measured by an elastic-tube gage recording on a string oscillograph. The initial counterrecoil-cylinder force was taken from the pressure read on a Bourden-type gage immediately before firing. Pressure was converted to force by multiplying it by the area of the counterrecoil cylinder piston: 38.5 square inches. The compression of air in the counterrecoil air cylinder was found to follow the adiabatic law; the pressure therefore, depended only on the gun displacement and the initial pressure. After 50 shots had been fired from the left gun over a period of about 1/2 hour, the pressure in the counterrecoil air cylinder, as read on the Bourden-type gage, was found to read the same as the pressure before firing. Figure 26 shows the theoretical increase of air-cylinder pressure with displacement for two values of k and compares the two curves with the pressure as measured with an elastic-tube gage. The values of k, 1.41 and 1.20, are respectively the adiabatic one and the one used by the Bureau of Ordnance in designing the counterrecoil mechanism.[24]

The increase in counterrecoil-air-cylinder force over its initial value by the time maximum total recoil force was reached was only about 4 kips. This increase was so small that the conditions of firing (gun elevation or type projectile fired) had little effect on it.

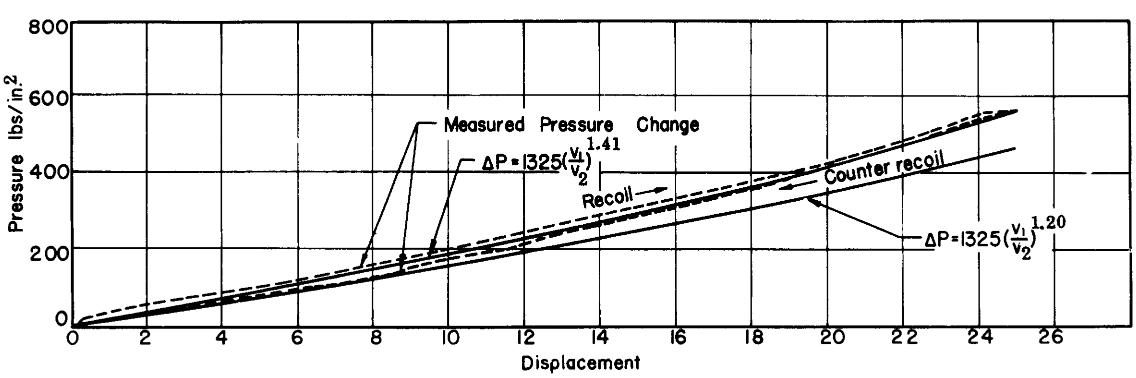


Figure 26 - Variation of Air-Cylinder Pressure with Displacement
Round 4, 9 July 1948

The measured change in pressure is compared with the theoretical pressure for two values of k.

The maximum counterrecoil-cylinder force for each shot is listed in Table 1.

Friction Force

The equation of motion during counterrecoil is given by:

$$F_{crc} = F_{crb} + W \sin \alpha + F_\mu + \frac{W}{g} \ddot{x} \qquad [1.4]$$

where $F_{crc}$ is the air-cylinder force,

$F_{crb}$ is the counterrecoil-hydraulic-buffer force,

$W$ is the weight of the recoiling gun,

$\alpha$ is the angle of elevation of the gun,

$F_\mu$ is the friction force, and

$\ddot{x}$ is gun acceleration.

It is seen that all factors of Equation [1.4] except $F_\mu$, are known or were measured with respect to time for all rounds of the recoil tests, so that the computation of $F_\mu$ should be a straightforward matter. Unfortunately, the factors of [1.4] are large compared to $F_\mu$, so that even a small percentage error in them was large enough to completely mask $F_\mu$.

By integrating the above equation with respect to time, between the time of beginning of counterrecoil and the end of counterrecoil, a satisfactory relation was obtained. Note that

$$\int_{t_1}^{t_2} \frac{W}{g} \ddot{x} \, dt = \left[\frac{W}{g} \dot{x}\right]_{t_1}^{t_2} = 0$$

where $t_1$ and $t_2$ are the beginning and end of counterrecoil respectively. Then

$$\int_{t_1}^{t_2} F_{crc} \, dt - \int_{t_1}^{t_2} (F_{crb} + W \sin \alpha) dt = \int_{t_1}^{t_2} F_\mu \, dt \qquad [1.6]$$

The quantities on the left side of [1.6] were plotted, the areas planimetered and then (assuming that it remained constant throughout recoil) the magnitude of the friction was computed. A value of 8 kips was obtained as an average of about 10 different rounds; the mean deviation being 3 kips.

The 8-kip friction force checks well with the 6.5-kip friction force assumed in the design of the recoil system.[24]

Total Recoil Force

The maximum recoil force transmitted to the trunnion bearers at 0° elevation of the gun averaged 200 kips; the mean deviation for the 8 rounds noted was ±5 kips. This force is the sum of the recoil-buffer force, the counterrecoil-air-cylinder force and the friction force. (Variation in the maximum recoil force from shot to shot is probably due almost entirely to variation of maximum recoil-buffer force provided the initial air-cylinder pressure is kept the same.)

The one round where maximum recoil force appeared to be somewhat lower than the average was fired when the initial counterrecoil-air-cylinder pressure was quite low, about 1100 psi; this was Round 11 in Group 1. It is to be noted that the recoil stroke was significantly greater on this round than for any other round fired at 0° elevation. The impulse of the recoil system, however, was much the same.

When a 335-lb projectile was fired at 40° elevation, the total re coil force was 219 kips. The total recoil force when a 260-lb projectile was fired at 0° elevation was 173 kips; at 40°, 185 kips.

## Counterrecoil-Hydraulic-Buffer Force

The counterrecoil-buffer force plotted in the above figures resulted from the measurement of pressure in the counterrecoil buffer—by an elastic-tube gage recording as a function of time on a string oscillograph. The conversion from pressure to force during the initial portion of counterrecoil was made by multiplying the pressure by the equivalent piston area of the recoil-cylinder piston, including the piston rod area—about 120.5 sq in. When the counterrecoil-buffer piston entered the buffer, the measurement became complicated by the fact that the pressure in the buffer proper, which was the pressure measured by the gage, was not the same as the pressure acting on the recoil-cylinder piston and this latter pressure was unknown. The solution used was to assume that the unknown pressure on the recoil cylinder piston decreased linearly with time from the moment the piston entered the buffer so that it was zero when all but about 1/2-in. stroke remained. It was at this time that the pressure began to build up to a maximum. The basis of this assumption was that force corrected in this way agreed well with force measured by a strain gage placed on the piston rod.

The maximum force generated in the counterrecoil buffer is listed in Table 1. For the right gun, at 0° elevation, it was 160 kips—somewhat more than the maximum force developed in the recoil hydraulic buffer at the same elevation. The force transmitted through the trunnion bearers to the gun supports, however, was much less, 115 kips, because there the net force is the difference between the air-cylinder force and the sum of the counter-recoil-buffer and friction forces. For the left gun, maximum counterrecoil buffer force was somewhat less, 130 kips, probably because of a difference in orifice areas due to the clearances.

During counterrecoil at 40° elevation, the resisting force of the counterrecoil buffer was augmented by that necessary to lift the gun against gravity. The force acting at the trunnions was therefore very small; see Figures 18 and 19. The time of counterrecoil was almost doubled when the angle of fire was changed from 0° to 40°. Duration of recoil and counterrecoil are listed in Table 1.

Acceleration

The acceleration plotted in Figures 12 to 20 inclusive and listed in Table 1, is that measured by a Statham 500-g accelerometer and recorded on the string oscillograph. Rapid fluctuations in the record were ignored; the curves plotted are faired curves. The actual oscillogram of the record may be seen in Figure 11. The maximum acceleration of the gun, as shown by Table 1, averaged 20 x $10^3$ in/sec$^2$ or 51 g's for the 21 shots listed. All shots were lumped together although a small difference in maximum acceleration (about 0.6 g) should exist between shots fired at 0° and 40°. The mean deviation was 2 x $10^3$ in/sec$^2$ or 10 percent. In Table 2 the maximum acceleration as measured using the Statham accelerometer is compared with values derived from

TABLE 2

| Shot Number | Maximum Acceleration | | Maximum Velocity | |
|---|---|---|---|---|
| | Measured in/sec$^2$ | Computed from Displacement Record in/sec$^2$ | From Accelerometer Record in/sec | From Displacement Record in/sec |
| 4 | 18.5 x $10^3$ | 20.0 x $10^3$ | 230 | 195 |
| 5 | 16.5 | 14.2 | 220 | 199 |
| 6 | 26.5 | 15.2 | 425 | 194 |
| 10 | 19.0 | 13.2 | 240 | 201 |
| 11 | 17.5 | 17.3 | 230 | 198 |

the displacement record for the 5 rounds of Group 1. The results generally agree, and differences between the two values are ascribed to inaccuracies in experimental records as well as errors in numerical differentiation of the displacement record.

The measurements of the acceleration with time were the least satisfactory of the TMB measurements from the point of view of accuracy. In common with other accelerometers, this one suffered from the usual accelerometer difficulties: excitation of its natural frequencies to the point where the record was severely obscured and insufficient damping. A suitable electronic filtering network was designed after early measurements showed that damping was not present in the instrument to the extent claimed by the manufacturer. The unit was not, however, completed in time for this test. Nevertheless the maximum acceleration as given by the average of either Table 1 or 2 is probably correct to within 10 percent.

Since the instrumentation of the accelerometer was set so that the maximum acceleration of the gun gave a record about 1 in. high on the string oscillograph, acceleration of the gun during the remainder of recoil and for counterrecoil was almost impossible to read, being of the same order as the error in reading the record—about 2 g. The calculation of the acceleration-time curve in counterrecoil from the counterrecoil forces suffers from a similar cause. Maximum counterrecoil acceleration computed this way for the right gun was 2.2 g; for the left gun, 1.6 g.

Displacement

The displacements plotted in Figures 12 to 20, inclusive, are those measured with the electric resistance-wire gage. The maximum recoil displacement listed in Table 1 was measured with the leather-washer and steel-rod apparatus described above. Before plotting the displacement-time record it was corrected to agree with this reading. Before correction, agreement was within 3 percent. The displacement gage was also checked by comparing the records obtained with it with photographs taken with a streak camera. Agreement throughout recoil was excellent. Hence, this measurement was felt to be very satisfactory.

Under similar conditions of gunfire during the rapid-fire tests, maximum recoil displacement of the gun varied no more than 0.4 in., less than 1 1/2 percent. The increase in maximum displacement when a 335-lb projectile was fired at 40° rather than at 0° was 2.7 in.; when a 260-lb projectile was fired, the increase was 3.8 in. When the firing of a 335-lb projectile was compared with one of 260 lb at 0° elevation of gun, the increase was 2.1 in.; at 40° elevation, the increase was only 1.1 in.

Recoil maximum displacement was quite sensitive to initial counter-recoil-air-cylinder pressure. Of importance is the fact that if the initial air-cylinder pressure had been that specified in design,[24] 1338 psi, maximum recoil probably would have exceeded 28.0 in. when the gun was fired at 40° At 60° elevation, such as would occur at maximum gun elevation with ship roll of 20 degrees, it almost certainly would have.

Velocity

The velocity plotted in Figures 12 to 16 and listed in Table 1, is that computed from the slope of the displacement-time records. The average maximum velocity at 0° when 335-lb projectile was fired was 199 in/sec; at 40°, 216 in/sec. When a 260-lb projectile was fired at 0°, maximum velocity was 175 in/sec; at 40°, 184 in/sec.

The increased recoil velocity of the gun when it was fired at high elevation and with a heavy projectile was due to a more sustained powder gas pressure, see page 31.

The maximum recoil velocity, as determined from the acceleration record and from the displacement record, is listed in Table 2 for the 5 rounds fired from the right gun in Group 1. The value read from the displacement record is believed to be more nearly correct.

## ADDITIONAL RESULTS

In addition to the measurements described in the preceding pages, some measurements were made of the strains in the trunnion bearers during the recoil tests. Also, for a few days of the structural firing tests, strain in the piston rod of the recoil cylinder of the right gun was recorded.

### Strain Gages on Trunnion Bearers

Recoil force is transmitted to the truss and girder structure supporting the guns through the trunnion bearers. In an attempt to measure the forces of recoil transmitted to the supporting structure, strain gages were placed on the trunnion bearers at various positions. The strains measured by the gages were read for various loads, applied only at 0° elevation, during the full-scale static tests[16] and strain-load curves plotted. From these plots it was determined that a load of 10 kips produced a strain of 4.0 microinches/inch in Gage 57; the same load induced a strain of 2.7 microinches/inch in Gage 80. The relation of load to strain was linear. It was hoped that the recoil force-time curve during firing could be obtained merely by recording the strain-time output of one of these gages; that is, by using the trunnion bearers as dynamometers, their calibration having previously been obtained from the full-scale static tests. Provided the natural frequency of the dynamometer is high enough, provided it is placed against an unyielding structure, and provided it is essentially a single-degree-of-freedom system, such use is possible.

The experimental setup was the following. Electric resistance strain gages were cemented to the trunnion bearers. A temperature-compensating gage (mounted so as to be insensitive to strain in the trunnions) was placed near by. The "active" gage and the "temperature-compensating" gage formed adjacent arms of a Wheatstone bridge circuit. The remaining two arms of the bridge were supplied by a TMB Type-SM 5A strain indicator which also provided the bridge voltage, the necessary amplification and a calibration circuit. Strains in the trunnion bearer unbalanced the bridge, the resulting voltage was amplified by the strain indicator and recorded on high frequency galvanometers* in the Hathaway oscillograph. Unfortunately malfunctioning of the calibration circuit introduced an uncertainty of as much as 20 percent in the records.

The records obtained during firing were quite different from the recoil force-time curve obtained from the pressure-gage data. Figure 27 is a comparison of strains measured by Gages 57 and 80 with the recoil force

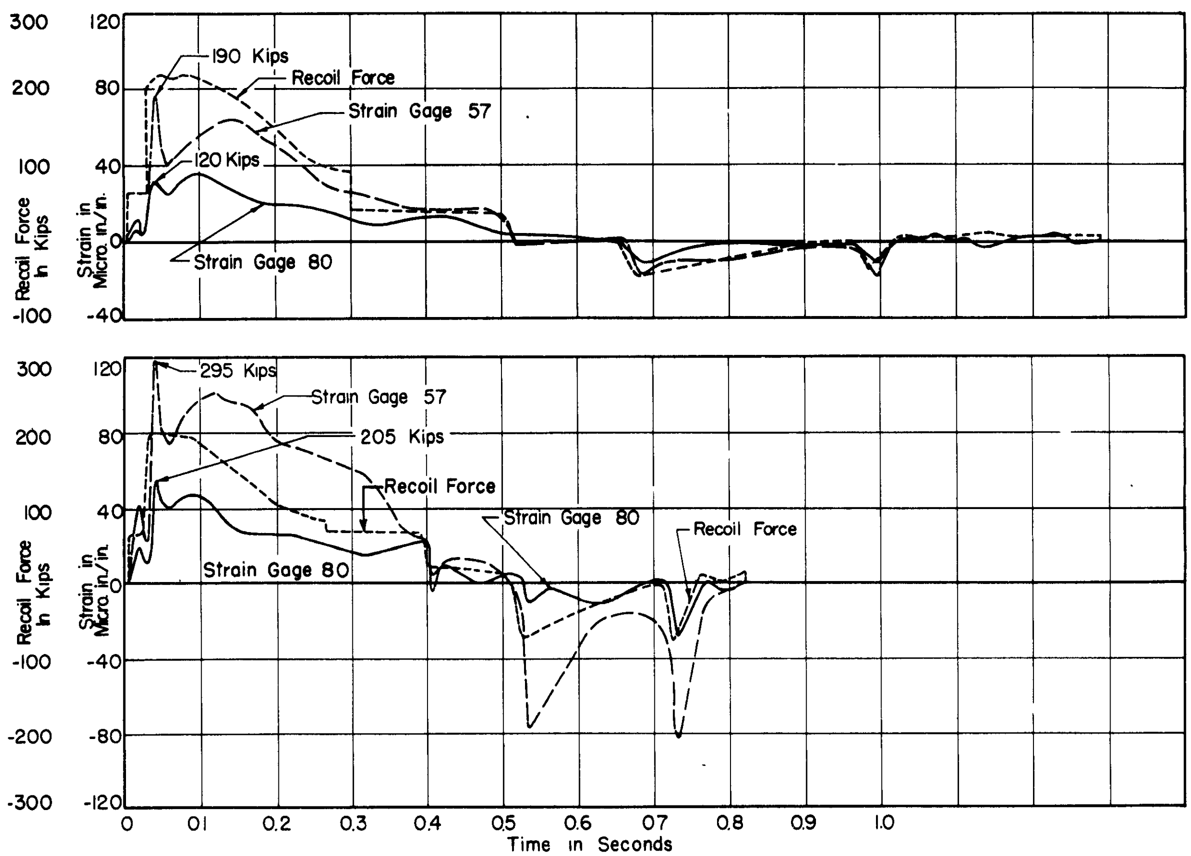


Figure 27 - Strain in the Trunnion Bearers and Total Recoil Force versus Time; Rounds 49 and 50, Left gun at 40° and 0° Elevation; 11 August 1948

*The galvanometers were special ones whose response was flat from 0 to 750 cps but which needed a current input of about 12 milliamperes. The Type-SM 5A strain indicator is designed to drive such galvanometers; its frequency response is flat to 1000 cps.

measured by the pressure gages for Rounds 49 and 50, 11 August 1948, from the left gun. Strain Gage 57 was cemented to the trunnion bearer of the left girder, Gage 80 on that of the left truss. The curves plotted are faired as can be seen from the actual oscillogram for Round 50, reproduced in Figure 11 The correlation is not good on three counts; (a) there is a phase shift between the two records, in particular maximum recoil force does not occur at the same time on both records, (b) the shape of the force picture is not the same on the two records, and (c) the values for maximum force do not agree.

The explanation of the discrepancy has already been given; the requirements for a good dynamometer were not met. The fundamental frequency of the structure, as recorded by the strain gages, appeared to be about 41 cps, corresponding to a natural period of about 0.024 second (Figure 11). Thus, the frequency of the trunnion bearer acting as a dynamometer was too low to follow the rapid rise of recoil force applied at the trunnions.

Preliminary examination of strains recorded at the various stations on the truss and girder structure during the structural firing tests indicate that all strains of appreciable magnitude have a natural period of 0.01 second or longer.

## Strain Gage Measurements on the Piston Rod of the Recoil Cylinder

As a check on the force as measured by the pressure gages, the recoil-buffer force was measured by recording, on a string oscillograph, the strain induced in the recoil buffer piston rod as a function of time.* This measurement was not a part of the recoil investigation, the data being recorded during seven days of the structural-firing trials only, and only on the right gun. Two 500-ohm electrical strain gages were cemented on opposite sides of the buffer piston rod about 3 in. from the gun yoke. These gages were connected in series and formed one arm of a 1000-ohm Wheatstone bridge. (Rigging them in this manner eliminates sensitivity to bending.) Two similar temperature-compensating gages, placed on the gun housing, formed another arm of the bridge. The other two bridge resistances were contained in a TMB Wheatstone bridge, Type BR-1A, which also supplied the d-c voltage and the electrical calibration system. Besides using 1000-ohm resistances for the bridge, 90 volts d-c supply was used instead of 45.

Agreement between these two methods of measuring recoil buffer force was quite good. Figures 28 and 29 show plots of this force as measured by an elastic-tube pressure gage and by the strain gage on the piston rod. It was

*It is assumed that the piston rod is an axially loaded bar so that $F = EA\,e$ where F is the loading force, E is the modulus of elasticity = $30 \times 10^6$ psi, A is the piston rod area, and e is the measured strain.

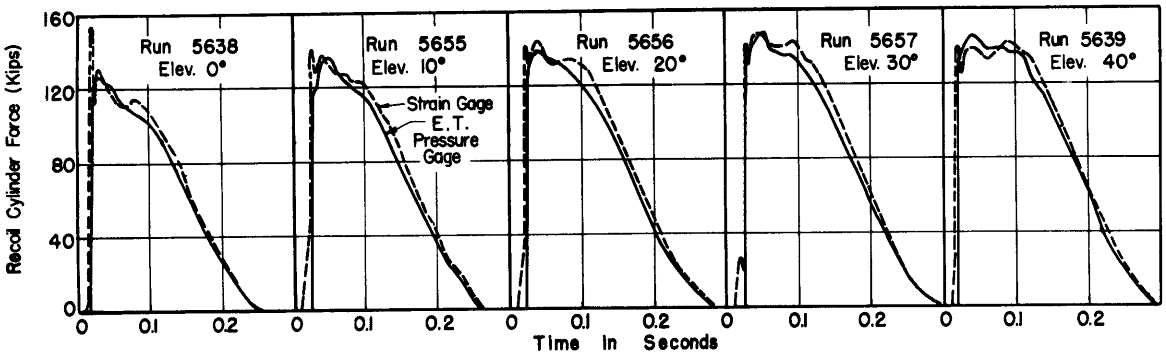


Figure 28 - Recoil-Buffer Force as Measured by the Elastic-Tube Gage and by Strain Gages on the Piston Rod; 14 October 1948, Right Gun, 335-lb Projectiles

The variation in recoil buffer force with gun elevation is also depicted.

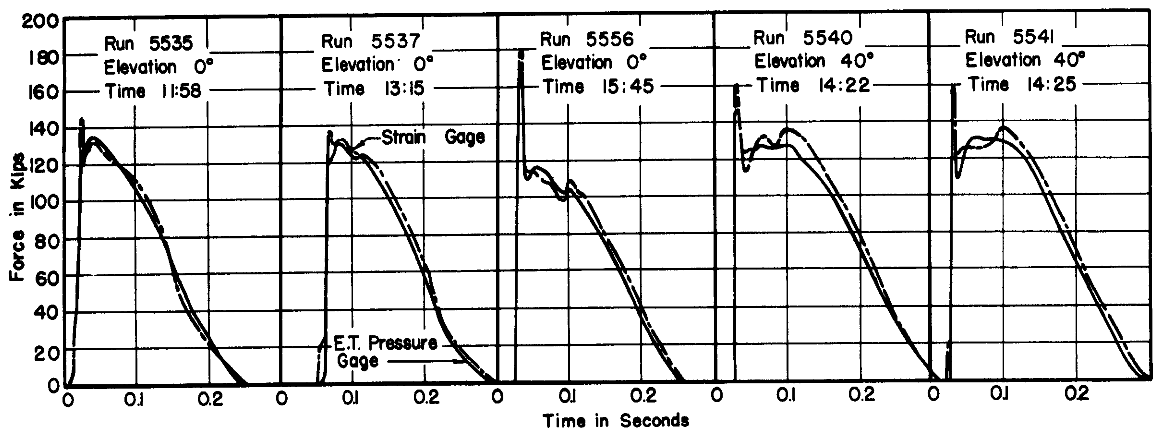


Figure 29 - Recoil-Buffer Force as Measured by the Elastic-Tube Gage and by Strain Gages on the Piston Rod; 1 October 1948, Right Gun, 335-lb Projectiles

The anomalous faired peak force of high amplitude and duration about 0.01 second is illustrated. Zero time was taken arbitrarily.

concluded that this strain-gage arrangement measured recoil-buffer force (and also the counterrecoil-buffer force) as reliably as the pressure gages.

Thus, measuring the strains in the piston rod and reading the initial air pressure in the counterrecoil air cylinder are sufficient for computation of maximum recoil force.

## Variation in Recoil-Buffer Force with Gun Elevation.

Besides showing the agreement between recoil-buffer force, as measured by the strain gage on the piston rod and that determined from the elastic-tube pressure gage, Figure 28 also illustrates the variation in recoil-buffer force for various gun elevations. It is seen that in addition to the increase in the maximum recoil-buffer force with gun elevation, the area under the force-time curve (impulse) increases. The shape of the curve changes from almost a triangle at 0° elevation to a trapezoid at 40° elevation.

Anomalous Peak Pressure in Recoil-Buffer.

Figure 29 shows plots of recoil-buffer force obtained from shots fired on 1 October 1948. On this graph Run 5556 illustrates a type of recoil buffer force-time curve which is quite different from those shown in Figures 11 to 19, inclusive. Although frequent records of this sort appeared during the structural firing trials, none of the records obtained during the recoil investigation period, 7 July to 11 August 1948, seemed to be of this character. A cathode-ray oscillogram of this type pressure record is pictured in Figure 25.

The predominant characteristic of these records is a very high initial force of about 180 kips with a duration of about 0.01 second. This is is to be compared with 135 kips—the average of the rounds at 0° listed in Table 1. Forces of this magnitude, and even larger ones, have been recorded in the type of record shown in Figure 24, but their period has been much smaller—about 0.001 second—and they appeared as symmetrical vibrations about the faired force curve. If this high initial force is ignored, the maximum recoil-buffer force is usually not significantly different from the 135 kips average; sometimes, however, it is as low as 115 kips. The impulse imparted to the recoil buffer appears to be the same for either type of force-time curve.

Figure 29 indicates that with progressive firing during one day, the initial peak force became more and more pronounced. Records taken during the training system trials on 4 March 1948, however, show the initial peak force high on the first shot and not appearing on the second and subsequent shots. Figure 25 is a reproduction of the cathode-ray oscillogram for the first shot of 4 March 1948. Subsequent shots recorded on this day looked much like Figure 24. Repeated firing thus sometimes brought on, and sometimes eliminated, the anomalous peak pressure.

Preliminary measurements of strains in the structural supports of the guns[19] do not indicate increased strains resulting from this anomalous peak pressure.

In Figure 29, Run 5537, the trace of recoil force, as shown by the strain gage on the piston rod, shows measurable force before any force appears on the elastic-tube gage record. This was usually the case. The force, calculated as that necessary to accelerate the mass of the piston rod and piston of the recoil system, is in fair agreement with the measured force.* The natural frequency of a single-degree-of-freedom system consisting of a spring (the piston rod) and mass (piston + 1/3 piston rod) is of the same order as the observed frequency.**

## ESTIMATED ACCURACY OF MEASUREMENTS

Table 3 lists the sources of error for each gage. The error in the gage factor is the mean deviation of readings obtained during laboratory calibrations of the gages.

TABLE 3

Percent of Error in a Single Measurement

| Source of Error | Gage | | | | | |
|---|---|---|---|---|---|---|
| | Elastic-Tube Pressure Gage | Piezoelectric Pressure Gage | Strain Gage on Piston Rod | Strain Gages on Trunnions | Accelerometer | Displacement Gage |
| Gage Factor | 1 | 3 | 2 | 2 | 2 | 1 |
| Reading Records | 4 | 4 | 4 | 4 | 10 | 2 |
| Recording Equipment | 4 | 5 | 4 | 20 | 10 | 2 |
| Total for Single Measurement | 9 | 12 | 10 | 26 | 22 | 5 |

Reading of the oscillograph records introduced some error; e.g., the maximum height from the faired recoil-buffer pressure record averaged about 0.5 inch. In measuring this height on the oscillograph paper, an uncertainty

*The equivalent weight of the piston and piston rod was taken as 250 lb. Peak acceleration of the gun was about 50 g.

$$F = m\,a = \frac{250}{g} \times 50\ g = 13 \times 10^3 \text{ lb}$$

The measured force from the strain gage record was 10 to 40 kips.

**If the piston rod is considered as a spring loaded by a 250-lb weight, the natural frequency of the spring system computes as about 200 cps.[17]

$$f = \frac{1}{2\pi}\sqrt{\frac{EA\,g}{W}} = 200 \text{ cps}$$

The observed frequency of initial strain in the piston rod was about 400 cps.

of about 0.02 in. existed because of warpage in the paper, misalignment of zero line, inaccuracy in setting and reading a scale, etc. Much of this probably was random error so that when several readings were averaged, the error was reduced. Some error, however, may have been systematically repeated by the person reading the records, e.g., drawing a zero line always tilted in the same direction. Some error may also have been introduced in the processing of the film, e.g., the lens used in making photographic prints may distort the print near the edges.

Imperfect performance of the recording equipment introduced additional error. Calibrations of electrical apparatus were made at convenient intervals before and after gunfire; these indicated that operational performance was not perfect.

Taking these errors into consideration, the error of a single measurement is given by the total at the bottom of Table 3; if several measurements are averaged, the accuracy is improved.

When more than one gage is used to record the same phenomenon, an empirical check on estimated errors is obtained. In this test, such cross-checks were possible, not only on the gages themselves, but also on the recording electrical equipment (see the appendix). The recorded data seem to indicate that over-all accuracy, of a single measurement in the field, of better than 10 percent was rather difficult to attain.

Although the error in a single measurement may be 10 percent, differences of less than 10 percent in measurements made by a particular gage may be significant. For instance, the maximum pressure in the recoil buffer when the gun was fired at 0° elevation was 1390 psi as measured by the elastic-tube gage recording on the string oscillograph (see the appendix). This figure is in doubt by about 5 percent or 70 psi. When the gun was fired at 40° elevation, the pressure recorded by the same instrumentation was 1560 psi; a figure which is also in doubt by 70 or 80 psi. The difference between the pressures, 170 psi, barely covers the possible error in each pressure so that one might conclude that it was not significant. This, however, is not correct; the increase in pressure when the gun is fired at 40° rather than at 0° is significant. Most of the possible error is systematic error which would be present in readings at each elevation, but absent in the difference between readings. For the purpose of computing the difference between pressures at 0° and 40° gun elevation, those pressures are probably accurate to 1 or 2 percent; the difference is therefore accurate to about 50 psi.

This study of experimental error in dynamic measurements is one of the most elaborate ever conducted, and may serve to dissolve the illusion of precision that many experimental analysts have believed possible with this type of equipment.

## FURTHER DISCUSSION

The forces measured in the recoil system are of interest to two groups of designers: one group designs the recoil system; the second, the truss and girder structure supporting the guns. The first group strives to achieve the most efficient energy-absorbing recoil system; the second would prefer the force of recoil proportioned in such a manner that a minimum dynamic effect on the supporting structure is produced.

### Recoil Forces

From the viewpoint of the first group, the most effective shape for the recoil load-vs-time curve would be a rectangle* since this would permit the maximum amount of impulse absorption (or of energy) by the recoil system for a given length of recoil. This was the goal aimed at. The most severe condition expected would occur when the gun was fired while making an angle of 60° with the horizon. Under this condition, the gun was expected to recoil 28.0 in. in a time of 0.245 second. Throughout the stroke, a total recoil force of 205 kips, including a 6.5 kips friction force was to be generated by the recoil system. A counterrecoil-cylinder initial pressure of 1338 psi was specified.[24]

In Figure 30 the design recoil force for 60° elevation is compared with that measured at 40° elevation. 40° elevation is the maximum angle to which the gun could be elevated in the pilot turret. The additional 20° elevation was allowed in design for roll of the ship. If we subtract the component of the weight of the gun due to the additional 20° elevation from the design recoil force, a simple approximation of the design recoil load at 40° is obtained. This force too, is plotted in Figure 30. Also shown is the brake recoil force as specified by the Bureau of Ordnance for structural design purposes, 215 kips at all gun elevations. It is understood that this value was obtained from considerations of design data and preliminary measurements of recoil pressure to which had been added a 25-percent safety factor to account for additional unknowns of recoil action. This value of brake load is specified in Ordnance Pamphlet 1112.

*Note that if the recoil load-time curve is a rectangle, the curve of recoil load versus displacement is also rectangular.

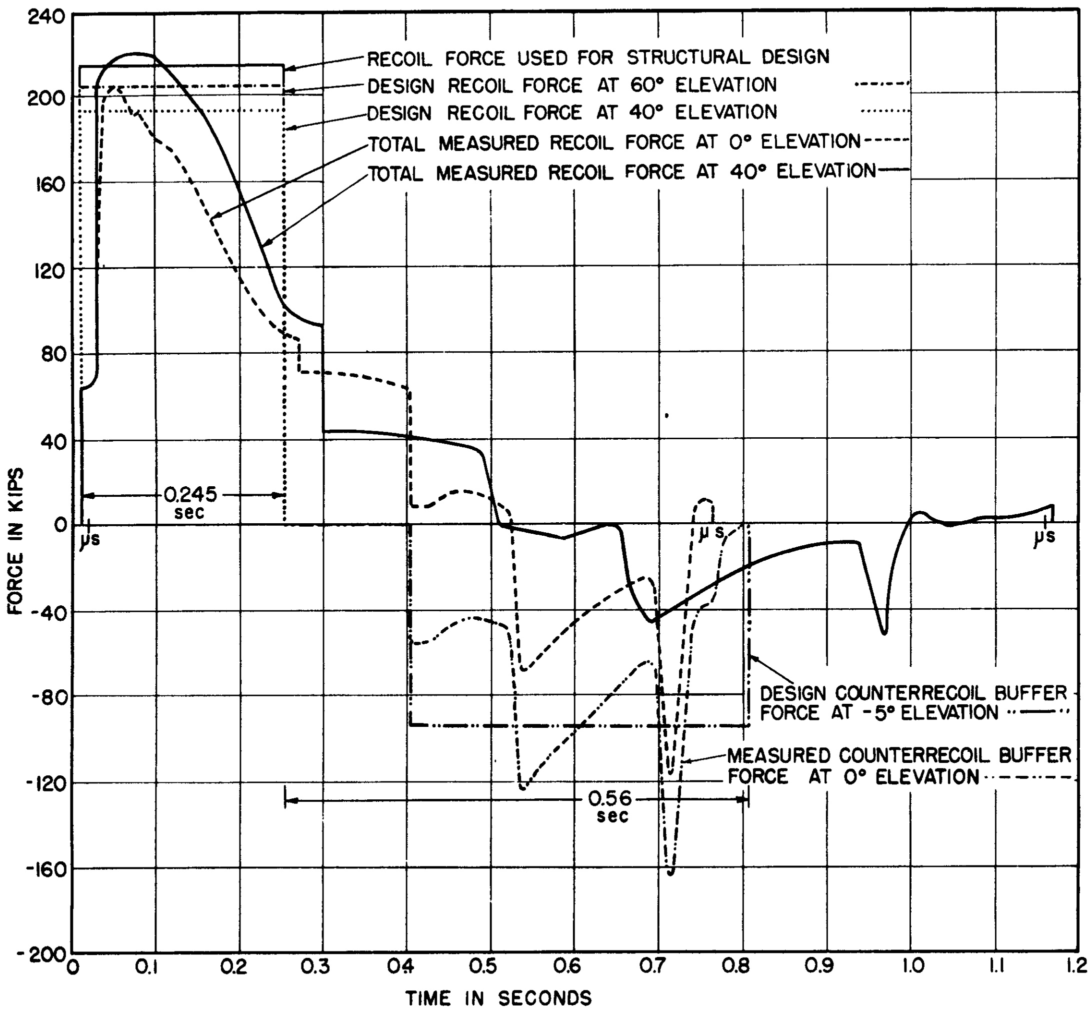


Figure 30 - Total Recoil Force at 0° and 40° Elevation of Gun

Measured and design total recoil force are to be compared at 40° elevation. Measured counterrecoil-buffer force at 0° elevation is to be compared with design counterrecoil-buffer force at -5° elevation.

Comparing the 40° design and experimental curves, it is seen that the maximum measured force exceeded that of design by 13 percent, (219 kips as against 194 kips), but that the design and measured impulse were much the same. Design recoil impulse is 47.6 kip-seconds. Measured recoil impulse was 47.1 kip-seconds, of which 9.7 was due to the weight of the gun. Of particular interest is the fact that the motion of gun was arrested within the specified recoil distance and in a smooth fashion. It is to be noted however, that if the elevation angle had been 60° instead of 40° and the counterrecoil-air-cylinder pressure 1338 psi instead of 1450 psi, the specified recoil distance of 28.0 in. would probably have been exceeded.

At first glance, the lack of agreement between design and experiment seems evident; especially during the later portion of recoil. Considering buffer theory however, we find that the force generated in a hydraulic buffer is inversely proportional to the square of the orifice area. When the gun has recoiled about 24 in., we find that the design orifice area is about 2 sq in. and that the possible variation in orifice area—due to tolerances on the recoil cylinder, recoil piston, throttling rods and throttling holes—could be as much as 0.64 sq in., or about 1/3 of the design area. Actual recoil-cylinder force could therefore, in this region, differ from the design value by 60 or 70 percent and yet be in good agreement with buffer theory. Even in the region where design orifice area is a maximum, 5.72 sq in., the area is in doubt by ±10 percent.

To test buffer theory, then, the clearance areas must be known more precisely. It is suggested, therefore, that when the guns in the pilot turret be dismantled, the actual dimensions of the components of the recoil hydraulic buffer be determined more precisely. If possible, the ratio of clearance to orifice area should be reduced in future buffer design.

Counterrecoil Force

The counterrecoil buffer was designed so that the force opposing counterrecoil would be constant during counterrecoil. If after a recoil of 28.0 in., the gun went back into battery depressed at an angle of 5°, a constant braking force of 95 kips was expected to be generated in the counterrecoil system. The duration of counterrecoil was to be 0.56 second. The assumed air-cylinder pressure at the beginning of recoil was 1892 psi, a figure arrived at by assuming a k of 1.21 and an initial air pressure of 1338 psi. In Figure 30, the design counterrecoil-buffer force at -5° elevation is compared with the measured counterrecoil-buffer force at 0° elevation in the right gun. The actual initial air-cylinder pressure was 1450 psi; the actual pressure at the beginning of counterrecoil was 2050 psi.

Comparison of actual counterrecoil brake force with design shows that the shape of braking force is far from rectangular. It is probable however that improvement would have to come after actual orifice areas were determined more accurately. Such refinement would be desired especially for the design of guns which fire more rapidly than this one.

It is to be noted that the present design of counterrecoil buffer, although not fulfilling design predictions as to variation of brake force with time, did fulfill the most important design goal: arresting the gun motion in a smooth fashion within the prescribed distance.

Strength of Gun Supports

With regard to the strength of structural supports of the gun, the lack of agreement between design and measured recoil force in the initial portion of recoil must be regarded as a fortunate accident. Had the rectangular force-time curve been achieved, the dynamic factor* would probably have been higher. Application of the recoil-buffer force at a time somewhat later than the air-cylinder force accounts partially for the lowering of the dynamic factor. In addition, the presence of what seems to be considerable damping** in the structure during the initial 80 milliseconds of recoil, further reduces the dynamic factor. These two factors, neither of which was noted by McGoldrick in his excellent summary of tests on turrets,[20] seem to account for the low dynamic factor measured in the structural firing tests on this turret,[19] and in similar tests.[21,22,23]

In Figure 31, the plots show the response of a single-degree-of-freedom, elastic system to several disturbances. In the same figure, a separate plot depicts both the response of a strain gage located on a trunnion bearer and the total recoil force which caused it, as a function of the natural period of the gun supports. The actual round of fire for which the data are taken is Round 50 from the left gun, 11 August 1948. The actual oscillogram is shown as Figure 11. The resemblance between this plot and the one with 30 percent initial damping should be noted.

## CONCLUSIONS

1. For an initial air-cylinder pressure of 1400 psi, the maximum total recoil force developed by the recoil system when a 335-lb projectile was fired by either gun at 0° elevation averaged 200±10 kips. When the elevation was increased to 40°, the maximum recoil force increased to 219 kips. When a 260-lb projectile was fired at 0° elevation, maximum recoil force averaged 173 kips; at 40° elevation, 185 kips. The values were similar for both guns.

2. The above values of maximum recoil force were obtained after high-frequency (above 600 cps) pressure variations were ignored. Some few records showed a high-amplitude pressure of as much as twice the faired pressure in

*Dynamic factor in a single-degree-of-freedom, elastic system is defined as the ratio of the maximum strain induced by a dynamic force, to the strain induced by a static force of the same magnitude. For a detailed discussion of this subject see Reference 18.

**Although the initial portion of the strain records seems to indicate a large amount of damping, the later parts of the same records show oscillations which do not die out quickly, thus contradictorily indicating only small damping; e.g., see the recording of Gages 57 and 80 in Figure 11, page 24. The apparent contradiction possibly could be eliminated by considering the turret as a multi-degree-of-freedom system.

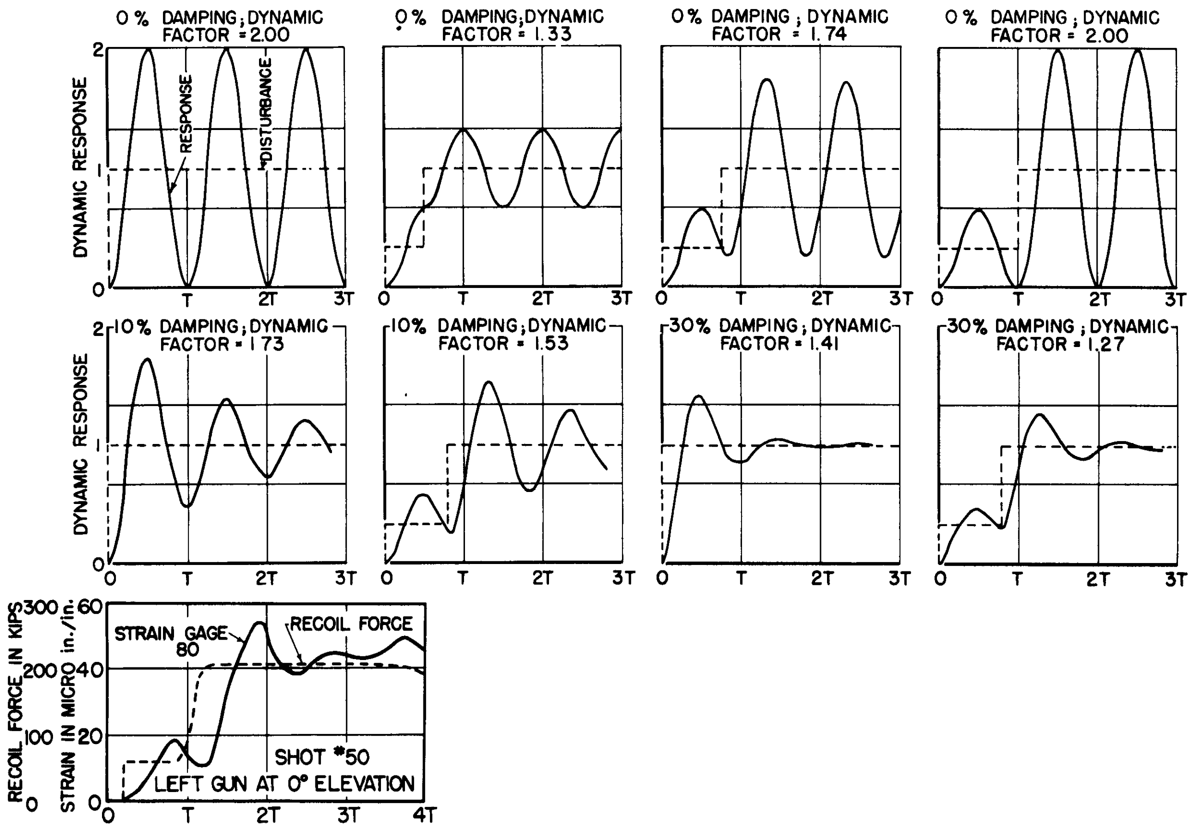


Figure 31 - The Computed Response of a Single-Degree-of-Freedom Elastic System to Various Rectangular Pulses - The Measured Response of the Trunnion Bearers to Initial Recoil Force

Computed response is the ratio of dynamic strain produced by the sudden application of the disturbance, to the static strain induced by the slow, steady application of the same disturbance. The effect of staggered application of force and of the introduction of damping are illustrated. For comparative purposes, the dynamic strain measured by a gage on the trunnion bearer and measured recoil force are also plotted. The oscillogram from which the measurements were taken is that of Round 50; left gun at 0° elevation; 11 August 1948. The actual oscillogram is shown as Figure 11.

The abscissa for all plots is "T", the natural period of the vibrating, elastic system. The period associated with Strain Gage 80 was about 0.024 second.

the recoil cylinder which persisted for 0.01 second. If this peak were ignored, values of recoil force equal to those tabulated would be obtained.

3. Maximum force generated in the counterrecoil buffer at 0° elevation in the right gun was 160 kips. The recoil force acting at the trunnions, however, was only 115 kips because it is the difference between the air-cylinder force and the sum of the counterrecoil-buffer and friction forces. In the left gun, counterrecoil-buffer force was somewhat less, about 130 kips. Maximum counterrecoil force, on the left gun, was only about 85 kips.

4. Design and measured forces in recoil and counterrecoil differ considerably; probably in large measure due to orifice areas introduced by clearances which cannot be considered in the design.

5. The maximum recoil acceleration developed averaged 20 x $10^3$ in/sec$^2$, or about 51 g. The mean deviation was 10 percent. Maximum counterrecoil acceleration was about 2 g.

6. Maximum recoil velocity when a 335-lb projectile was fired at 0° elevation was 199 in/sec; at 40°, 216 in/sec. When a 260-lb projectile was fired at 0° elevation, maximum velocity was 175 in/sec.; at 40°, 184 in/sec.

7. Maximum recoil displacement repeated to within 1 1/2 percent under similar conditions of gunfire. The maximum displacement measured was 27.6 in. at 40° elevation, firing a 335-lb projectile; air-cylinder pressure 1450 psi.

Recoil displacement was quite sensitive to initial counterrecoil-air-cylinder pressure. If the air-cylinder pressure were 1338 psi (as specified in design) and the guns were fired at 60° elevation, maximum recoil displacement would almost certainly exceed the design maximum of 28.0 in.

8. Large-amplitude, high-frequency (600 to 6000 cps) pressure variations were found in the recoil hydraulic buffer. The effect of these variations on the strains produced in the structural supports of the guns is shown theoretically to be negligible.

9. The use of strain gages on the trunnion bearers, in an attempt to determine total recoil force with only one gage measurement, was found to be unsatisfactory.

10. Strain gages cemented to the piston rod of the recoil cylinder measured recoil-hydraulic-buffer force and counterrecoil-hydraulic-buffer force as reliably as did the pressure gages. This measurement and the reading of the initial air-cylinder pressure are sufficient for the computation of maximum recoil force.

11. The dynamic factor to be applied to the structural supports of the guns is much less than 2.0; probably about 1.3. In large part the reduction is due to the staggered application of the components of recoil force and to the presence in the structure immediately after it is loaded, of what appears to be, considerable damping.

12. Performance of the instruments employed in the test was found satisfactory; for pressure measurements of the type made in this test, the elastic-tube pressure gage is superior to the crystal gage.

## ACKNOWLEDGMENTS

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## APPENDIX

### COMPARISON OF PRESSURE GAGES

As stated in the text, recoil-cylinder-hydraulic-buffer pressures were recorded by two types of gages, an elastic-tube strain-type gage and a piezoelectric crystal-type gage; both gages recording simultaneously on both string and cathode-ray oscillographs. Table 4 lists the faired maximum pressures recorded by each gage on both types of recorders. The average maximum pressure, followed by the mean deviation, for both type gages and recorders is listed at the bottom of the table.

Study of the table reveals that while readings were fairly consistent within a column, the averages for the four columns differ considerably. Further, the differences are somewhat larger than the mean deviations.

The differences between columns are not a function of the type gage or the type recording; e.g., the E.T. gage pressures on the string oscillograph are <u>lower</u> than those on the cathode-ray oscillograph while the piezoelectric gage pressures on the string oscillograph are <u>higher</u> than those on the cathode-ray oscillograph. Also the pressures measured by the E.T. gage and recorded by string oscillograph are <u>lower</u> than those measured by the piezoelectric gage and recorded on string oscillograph while the pressures measured by the E.T. gage on the cathode-ray oscillograph are <u>higher</u> than those measured by the piezoelectric gage and recorded on the cathode-ray oscillograph.

It appears that the systematic errors in measuring the pressure, whether from reading the records or from malfunctioning of the instruments, is such that the average of the maximum pressures is not known to any better than 100 psi (about 10 kips of force).

TABLE 4

Faired Maximum Pressures

| Shot Number | Projectile Weight pounds | Elevation Angle degrees | Elastic-Tube Gage Pressure psi String Oscillograph | Elastic-Tube Gage Pressure psi Cathode Ray | Piezoelectric Gage Pressure psi String Oscillograph | Piezoelectric Gage Pressure psi Cathode Ray |
|---|---|---|---|---|---|---|
| 4 | 335 | 0 | 1360 | 1500 | 1510 | 1430 |
| 5 | 335 | 0 | 1420 | 1400 | 1530 | 1440 |
| 6 | 335 | 0 | 1340 | 1430 | 1340 | 1340 |
| 10 | 335 | 0 | 1370 | 1440 | 1500 | 1460 |
| 11 | 335 | 0 | 1380 | 1490 | 1420 | 1460 |
| 6 | 260 | 0 | 1070 | 1090 | 1150 | 1080 |
| 11 | 260 | 40 | 1170 | 1270 | 1340 | 1240 |
| 12 | 260 | 0 | 1070 | 1160 | 1150 | 1120 |
| 20 | 260 | 40 | 1220 | 1340 | 1320 | 1280 |
| 21 | 260 | 0 | 1090 | 1050 | 1170 | 1120 |
| 30 | 335 | 40 | 1550 | 1560 | 1650 | 1620 |
| 31 | 335 | 0 | 1420 | 1480 | 1550 | 1410 |
| 5 | 260 | 40 | 1200 | 1350 | 1380 | 1280 |
| 6 | 260 | 0 | 1130 | 1350 | 1200 | 1320 |
| 12 | 260 | 0 | 1100 | 1170 | 1290 | 1190 |
| 20 | 260 | 40 | 1280 | 1320 | 1350 | 1280 |
| 21 | 260 | 0 | 1110 | 1210 | 1290 | 1110 |
| 30 | 335 | 40 | 1560 | 1600 | 1750 | 1580 |
| 31 | 335 | 0 | 1430 | 1530 | 1600 | 1410 |
| 49 | 335 | 40 | 1580 | 1600 | 1750 | 1530 |
| 50 | 335 | 0 | 1410 | 1500 | 1600 | 1360 |
| **Averages** | | | | | | |
| | 335 | 0 | 1390 ± 30 | 1470 ± 40 | 1510 ± 60 | 1410 ± 20 |
| | 335 | 40 | 1560 ± 10 | 1590 ± 20 | 1720 ± 40 | 1580 ± 30 |
| | 260 | 0 | 1100 ± 20 | 1170 ± 70 | 1210 ± 60 | 1160 ± 70 |
| | 260 | 40 | 1220 ± 30 | 1320 ± 20 | 1350 ± 20 | 1270 ± 20 |

The pressure in the recoil hydraulic buffer was also measured by NOL personnel, who used a strain-type pressure gage developed by the Ballistic Research Laboratory, Aberdeen, Maryland. To permit comparison of the high-frequency pressure variations measured by the BRL gage with that measured by the TMB elastic-tube type gage, the TMB data for five shots fired in July 1948 are plotted in Figures 32 to 36. These data were requested by the Bureau

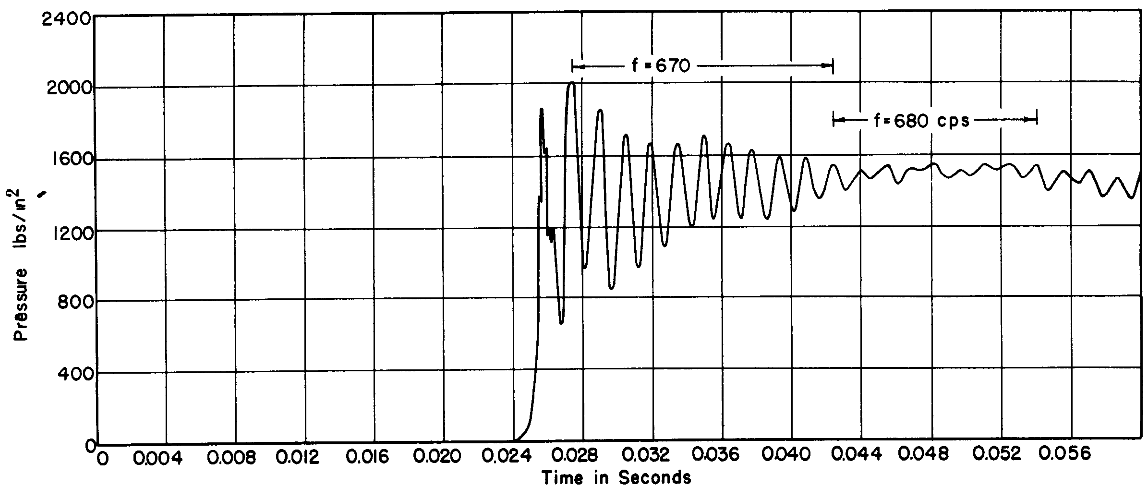


Figure 32 - Recoil-Buffer Pressure versus Time, Round 4; 9 July 1948

The measurements were taken with the elastic-tube gage recording on cathode-ray oscillograph.

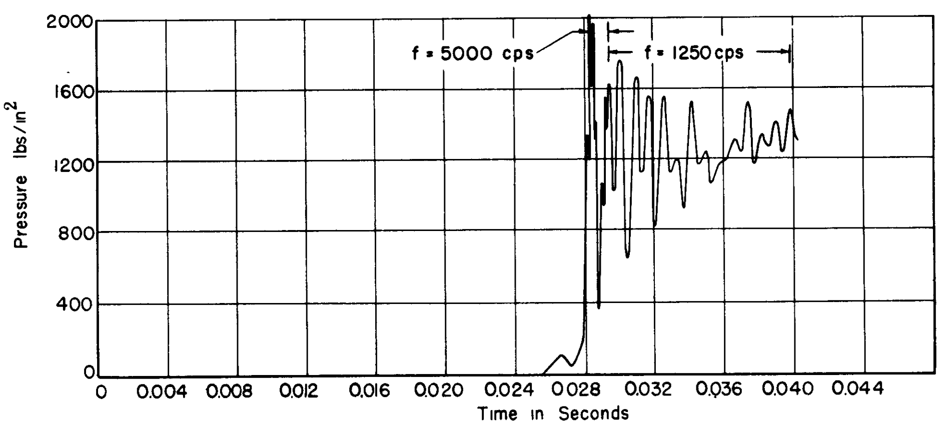


Figure 33 - Recoil-Buffer Pressure versus Time, Round 5; 12 July 1948

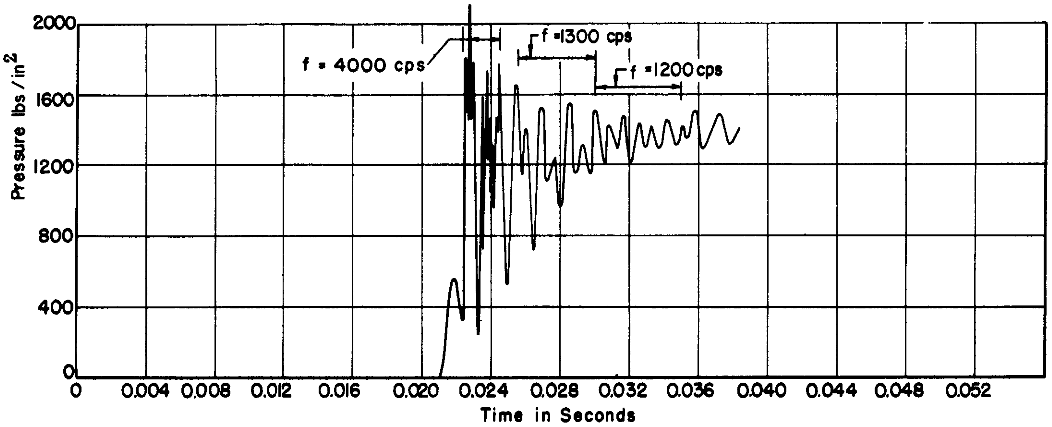


Figure 34 - Recoil-Buffer Pressure versus Time, Round 6; 13 July 1948

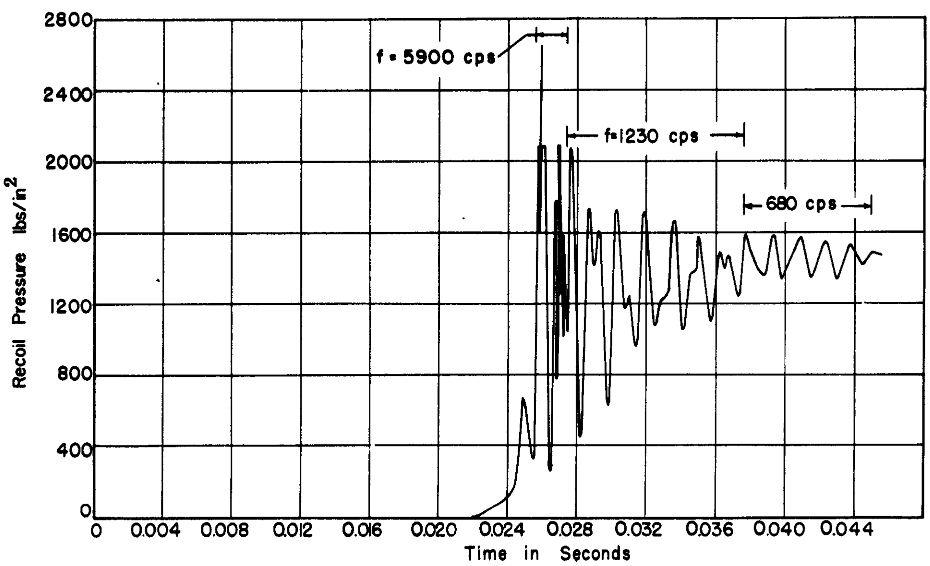


Figure 35 - Recoil-Buffer Pressure versus Time, Round 10; 15 July 1948

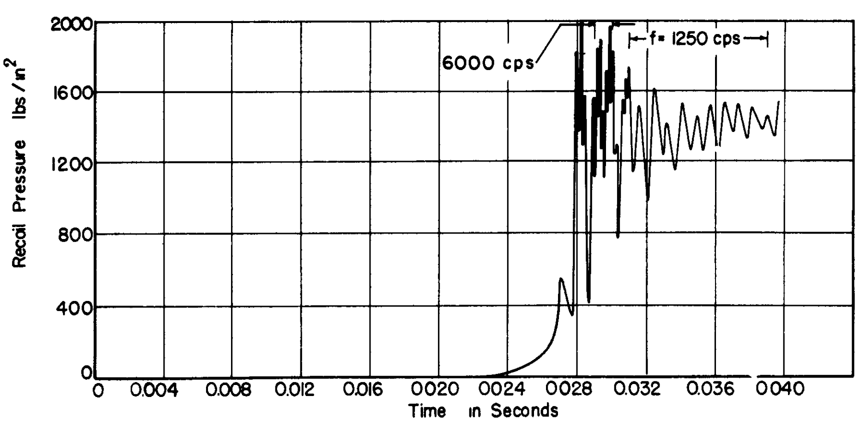


Figure 36 - Recoil-Buffer Pressure versus Time, Round 11; 15 July 1948

of Ordnance. The NOL data for the same five shots are available in Reference 19 and the comparison is to be made by BuOrd. Since comparison of the high-frequency variations in pressure was desired, the TMB data used were those recorded on the cathode-ray oscillograph. Preliminary comparison of the data obtained by NOL and TMB indicated excellent "point for point" agreement as to frequency of the pressure. Some differences, however, were observed in the magnitude of the pressure but these could easily be ascribed to error in reading the records. The agreement between the gages is thus felt to be very good.

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