# UNITED STATES
# EXPERIMENTAL MODEL BASIN

NAVY YARD, WASHINGTON, D.C.

## SERVICE STRAIN TESTS
### TECHNIQUE AND PROCEDURE

EXPERIMENTAL MODEL BASIN
ERECTED 1898
BUREAU OF
CONSTRUCTION AND REPAIR
NAVY DEPARTMENT

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## Technique and Procedure

U.S. Experimental Model Basin
Navy Yard, Washington, D.C.

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# SERVICE STRAIN TESTS

## Technique and Procedure

### INTRODUCTION

Parallel with the development of technique and methods for the study of stresses in full-scale vessels under service loads(1)*, the instruments themselves have undergone extensive modification. The successive phases of this process are here recounted for ready reference.

The instruments in their present form were installed recently on two cruisers, the U.S.S. PHOENIX and the U.S.S. ST. LOUIS, and strain data were taken. As the information thus obtained has related rather to the instruments and technique than to the characteristics of the vessels, the results of these tests are included in the report. Selections from the data are offered as samples of what may be expected from an extended program of service strain testing, and a discussion of the possible application of such methods of observation is included.

### FUNCTIONS AND TYPES OF STRAIN GAGES

The necessary elements of a service strain test are:

1. Measurement of elastic deformation, including relative displacements ranging down to a few millionths of an inch.
2. Autographic recording of the strain data as functions of time.
3. Synchronization of observations at various stations.+

Figure 1 is a schematic illustration of the essential parts of one type of recording strain gage. Such a gage is designed to measure the relative motion between two points in a surface subject to strain and to make a permanent record of this motion for subsequent analysis.

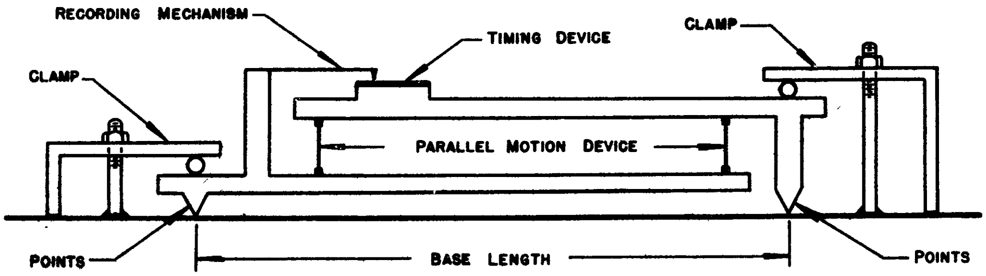

Figure 1 - Diagrammatic Arrangement of Strain Gage

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* Numbers in parentheses designate references at end of report.

\+ The measurement of load, as previously discussed (1), is excluded from present considerations.

Referring to Figure 1, the base length is the distance separating the two points between which relative motion is to be measured. Its choice is governed by considerations of portability, sensitivity, accessibility for mounting, the modulus of elasticity of the material on which the gage is to be used, and extent of essentially uniform strain.

The function of the points is to transfer the relative motion in the material surface to the gage frame. The points must be small enough to permit accurate determination of the base length but sufficiently rigid to prevent errors caused by bending of the points.

The type of gage points has been varied. Some are fitted in drilled holes, some have hardened points which punch their own holes, and some have knife-edges making line contact. Where the points are relied on to hold the gage in position, it is necessary to use two points at one or both ends, or to have knife-edge contact. Where the gage is provided with stabilizing screws or where the required stability is furnished by the gage clamps, however, single points at each end can be used.

The clamps must be provided for attaching the gage to the structure under test. They should hold the gage firmly against the member but should not apply any force component in the direction of the measured strain, since such a force, particularly when it varies with the strain, may bend the gage points and cause errors in strain readings. In one type of mounting roller-bearing clamps are used; these also insure lateral stability of the gage.

The parallel-motion device must permit the relative motion which is to be measured but must resist all other relative motions between the points. In this way the strain is transferred accurately to the offset recording mechanism. The parallel motion design is important, since a mechanism which allows any extraneous motions between the two elements of the gage frame will introduce errors. Sliding bearings, ball bearings, and flexure-plate connections have been used; of these the latter seem to be the best.

The function of the recording mechanism is to make a permanent trace showing the relative motion between the two elements of the gage frame. Since these displacements are small, they must be magnified for reading or for recording. This is accomplished by any of the following means:

1. Scribing a record to actual scale, which is afterward amplified by optical means for analysis (De Forest gage).

2. Amplifying the motion by mechanical linkages to produce an enlarged original record (EMB long-base gage).

3. Photographing a dial gage operated directly by the relative motion (Whittemore gage).

4. Converting the mechanical motion into an electric signal, with radio amplification (De Forest, Ruge gages).

5. Increasing the base length (EMB tape recording gage).

The timing device is of great importance in the recording mechanism. Uniform motion of the record in a direction transverse to the strain produces a wavy line. The length of this line is proportional to the time and the amplitude is proportional to the strain. Periodic interruptions or marks in the line indicate definite intervals of time. When dial gages are photographed a watch with a large second hand is included in the picture. By operation of these timing devices from a central control station the records for all the gages can be synchronized.

A variety of recording gages have been proposed by different agencies and some have been used with success. Special gages have been used for special purposes, though not always with high precision. No attempt is made here to cover the whole field or to describe gages not actually considered for use at the Experimental Model Basin. The following gages will be described:

A. Scratch Gages
  1. De Forest
    (a) Latchkey
    (b) Rectangular target
    (c) Disk target
  2. EMB
    (a) Rectangular target
    (b) Disk target
B. Long-Base Gages
  1. Tape
  2. Electric
C. Dial Gages
  1. Photo recorder
D. Electronic Gages
E. Stress-Cycle Counters

### Scratch Gages

The basic feature of scratch gages is the production on metal or glass of a minute record of the displacement of the gage points to actual scale. The record is then magnified by optical means in the course of analysis of the data. This magnification is applied also to the time scale, which permits the original record to be very compactly arranged. Several hours' record of usual ship strain cycles can be condensed into the space of a few inches.

### De Forest Scratch Gages

Professor A. V. de Forest was the first to apply this principle in the United States, and several gages of this kind have been marketed under the name of De Forest Scratch Gages.

The simplest of these is lighter and smaller than a latchkey. As shown in Figure 2, it consists of a scratch arm fastened to one gage point and a target fastened to the other. The arm slowly traverses the target, driven by the fulcrum spring, which is manually adjusted to apply the very slight force required. This mechanism separates the scratches for successive strains but the time scale is almost completely indeterminate.

Multiple scratches are made by this gage. Though confusing, these are necessary, as the only practicable means of assuring a good record is to scatter several bits of abrasive dust on the tip of the scratch arm and select the clearest record that results.

The latchkey gage has all the essential elements of a recording strain gage, though it is greatly simplified and reduced in size and weight. A large number of these were tried on the U.S.S. DEWEY but the data obtained were found not amenable to analysis and the experiment was not repeated.

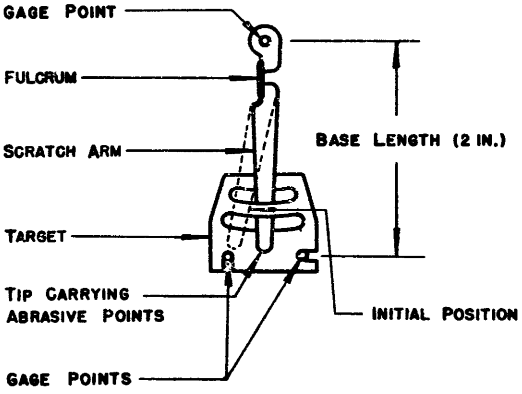


Figure 2 – Latchkey Scratch Gage

Prior to the introduction of the latchkey gage, work had been in progress on a more elaborate scratch gage, for use where lightness and simplicity were less essential. The first of this type tried at the Experimental Model Basin was provided with a single scriber consisting of a diamond ground to suitable form, with pressure adjustment, renewable targets, increased gage-length, and a determinate time scale. This gage is shown in Figure 3. The design of the scribing unit, in general, was satisfactory. The diamond was moved across the target in a series of jumps, as the motor had a reciprocal motion producing a stepped record like that shown in Figure 12. The small target length and the rapidity of the drive limited the operating time to about 20 minutes.

Further changes were incorporated in the later design shown in Figure 4. A second scriber was added for marking a reference line, the method of mounting the diamond points was altered, a disk target replaced the linear type, and the motor was separately mounted.

The target, shown in Figure 4, is supported on a circular table which rotates on ball bearings about an axis fixed with respect to one set of gage points. Two diamonds scratch the target, one fixed with respect to the axis of rotation, the other following the relative motion of the gage points. Thus, one diamond scratches a circle or zero reference line and the other a line that departs radially from a circle by the amount of the measured strain. The diamonds are mounted on hinged supports that can be swung out of the way to remove the target. Each of the supports consists of two plates riveted together near the hinged end. At the opposite end, a ball mounted in the outer plate bears on the target and maintains this plate at a fixed distance from the target surface. Coil springs connected to the plate hold the ball snugly against the target. The inner plate supports the diamond. A spring-lever

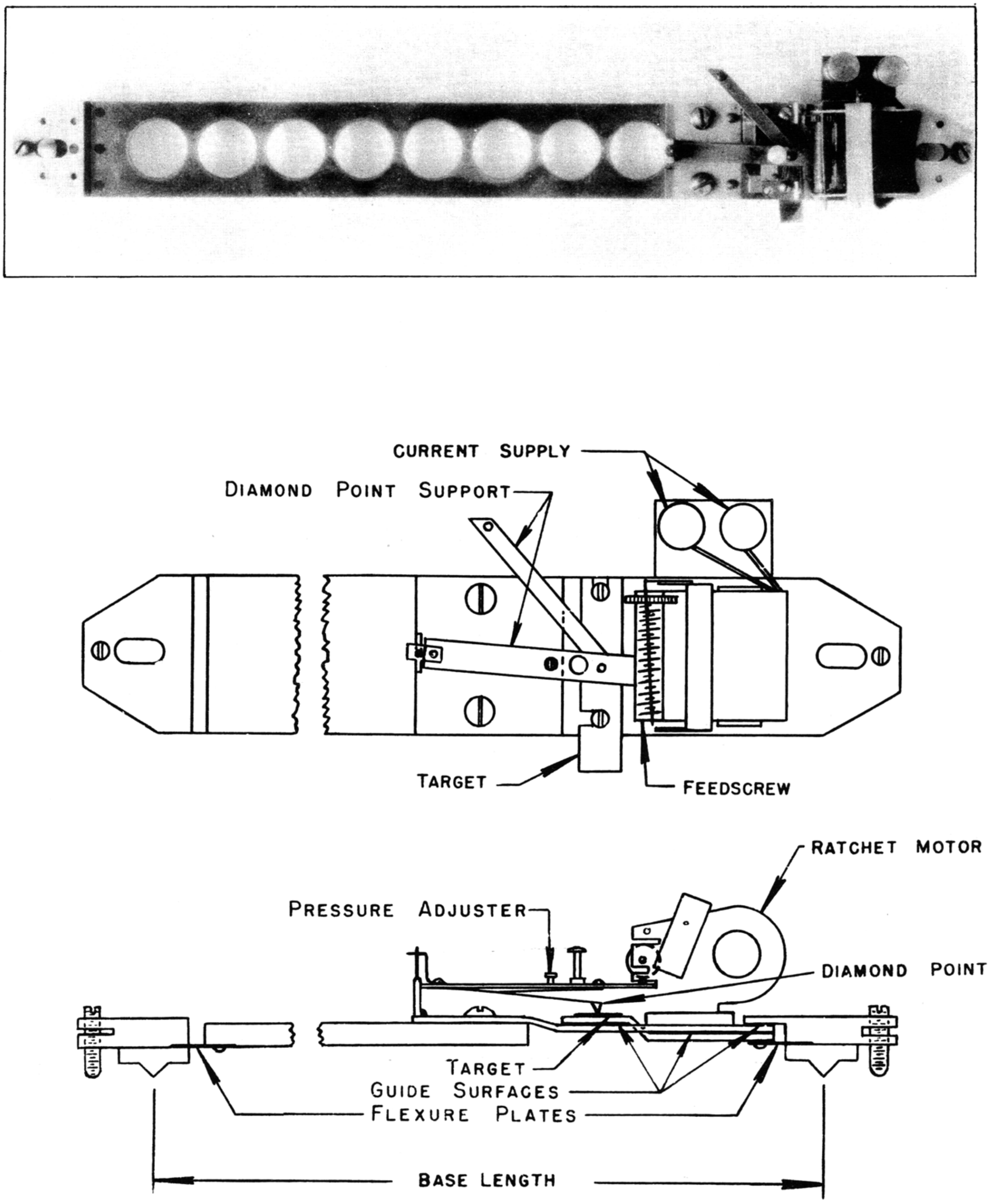


Figure 3 – De Forest Single Diamond Scratch Gage

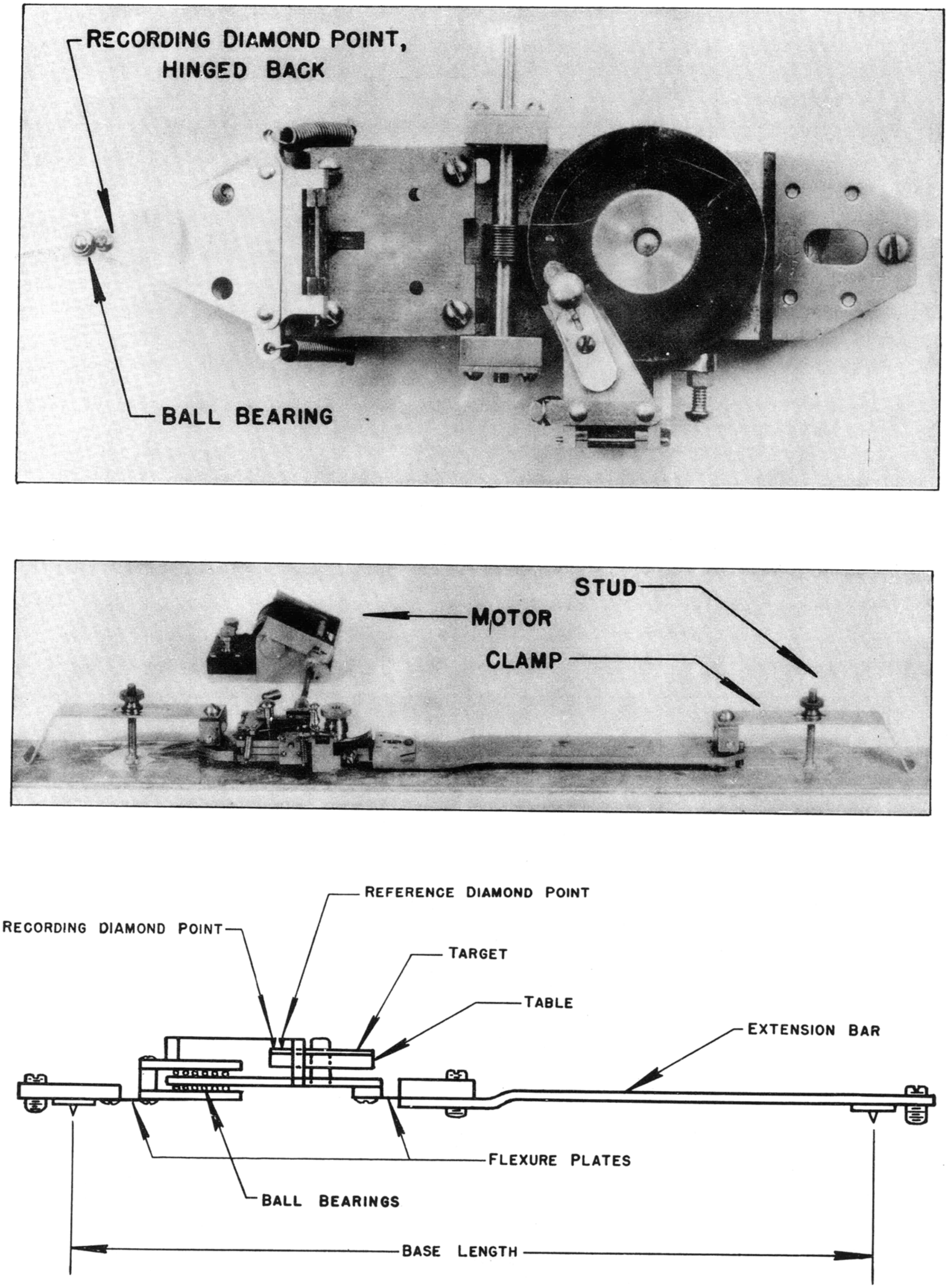


Figure 4 – De Forest Disk Scratch Gage

system between the two plates is operated by an adjustment screw to regulate the diamond pressure on the target.

Lateral stability of the gage is obtained by using two gage points at each end. Parallel motion of the diamond points is effected by means of ball bearings moving in linear grooves. A tapered pin is inserted in the two members to hold the gage in the middle of its travel while mounting. Gage holes are not drilled; the hardened points make their own holes as the clamps are tightened. Rollers between the gage and clamps reduce friction and straining of the gage points by the clamps. The base length of 3 inches can be increased to 9 inches by using extension bars.

The target is driven, as shown in Figure 4, by an independently mounted reciprocating motor, working through a flexible shaft and a worm. The motor consists of an electric coil and a steel rocker arm. Energizing the coil rotates the arm about one-sixth of a revolution against a spring. When the circuit is opened, the spring returns the arm to its original position. The motor shaft is connected to the arm by a ratchet and is turned one tooth of the ratchet each time the coil is energized. Intermittent energizing of the coil at convenient intervals, say one second, is obtained by means of a chronometer. A stepped record from which the seconds can be counted is thus obtained. The time of a complete revolution of the target is about one hour.

This type of gage, with its screwed joints and movable parts in the scratch-arm connections, records other motions in addition to those between the gage points. The stepped record is not satisfactory, and the compact diamond support and pressure control does not permit accurate adjustment.

### EMB Scratch Gages

Concurrently with the developments by Professor De Forest, the problem was attacked by the Experimental Model Basin; the gage shown in Figure 5 was the first solution obtained. A rectangular target is used, but the drive is continuous. Time is marked by a solenoid hammer which, by a gentle tap, causes a local interruption of the otherwise smooth record, as shown in Figure 13. The target is fastened by clips to a movable table. A rotating screw, driven by an independently mounted variable-speed motor through a flexible shaft and worm reduction gear, provides rectangular transverse motion of the table. The time for a complete traverse is about 35 minutes. An automatic stop cuts out the motor circuit at the end of the traverse to prevent jamming of the screw threads. A clutch is provided which disengages the electric drive to permit manual operation of the table.

The diamonds are mounted on leaf springs, with screw adjustment of the diamond pressure. A cam which can be actuated mechanically or electrically lifts the diamonds about one-eighth inch off the target for changing targets.

The original targets, 1 inch by 3 inches, were of glass plated with silver. The diamond scraped through the silver, but did not cut the glass; this insured a uniform depth and thickness of line and allowed greater latitude in the diamond pressure adjustment. The records thus obtained were good, but the targets tarnished badly with age. To prevent this, a thin lacquer coat was put over the silver as a protection. It was possible to obtain a fair record by scratching through the lacquer. However, the lacquer dried and shrunk with age and peeled off, bringing the silver with it. Recently, other coatings have been tried. Aluminum-coated glass prepared by the evaporation method seems quite satisfactory. Chromium-plated brass targets have also been used but this requires stiffening the spring supports.

A second type of scratch gage, with a circular target, was made by modifying a Whittemore hand strain gage; see Figure 6. The dial micrometer is replaced by a small rotating table driven by an independently-mounted electric motor. A circular chromium-plated brass target is supported face down on the table and overhangs it sufficiently to permit scratching the record on the underside of the target. This eliminated lifting the diamond points. The diamonds are mounted on long springs provided with adjustment screws. One revolution of the target is made in about one hour. A small electric hammer provides the time record. After this gage was used on the U.S.S. PHOENIX, a slower motor was substituted which makes the time of a complete revolution about four hours.

After the refinements and simplifications described this form of recording scratch gage was adopted and sixteen are now being prepared for use. It will be referred to as the EMB Recording Scratch Gage.

### Long-Base Gages

When strain is uniform, or when only an average value over a considerable length of structure is desired, it becomes easier to obtain relative displacement in measurable amounts without amplification. Thus, in the U.S.S. CUYAMA tests, an instrument having a base length of 24 feet was used, and maximum displacements of the order of 1/4 inch were obtained; this permitted the use of simplified electric recording (3). A similar setup was also used in static tests on the U.S.S. PRESTON (4).

A purely mechanical recorder with a maximum base length of six feet as shown in Figure 7, has recently been built. It gives a record immediately open to inspection, traced on paper fed continuously as in the usual type of tape chronograph.

Amplification of this gage is obtained by the use of 10 x 1 multiplying linkage. The record is scratched on waxed paper by a stylus. A second fixed stylus makes the reference or zero line. The receiver drum of the recorder is driven by a small constant-speed motor. The rate of feed is about one inch per minute, so that a 50-foot roll of paper will run continuously for ten hours.

The base length can be varied between four and six feet by means of a long screw which also serves to make the final adjustment of the position of the stylus on the paper. After all adjustments are made, two bolts firmly lock the assembly.

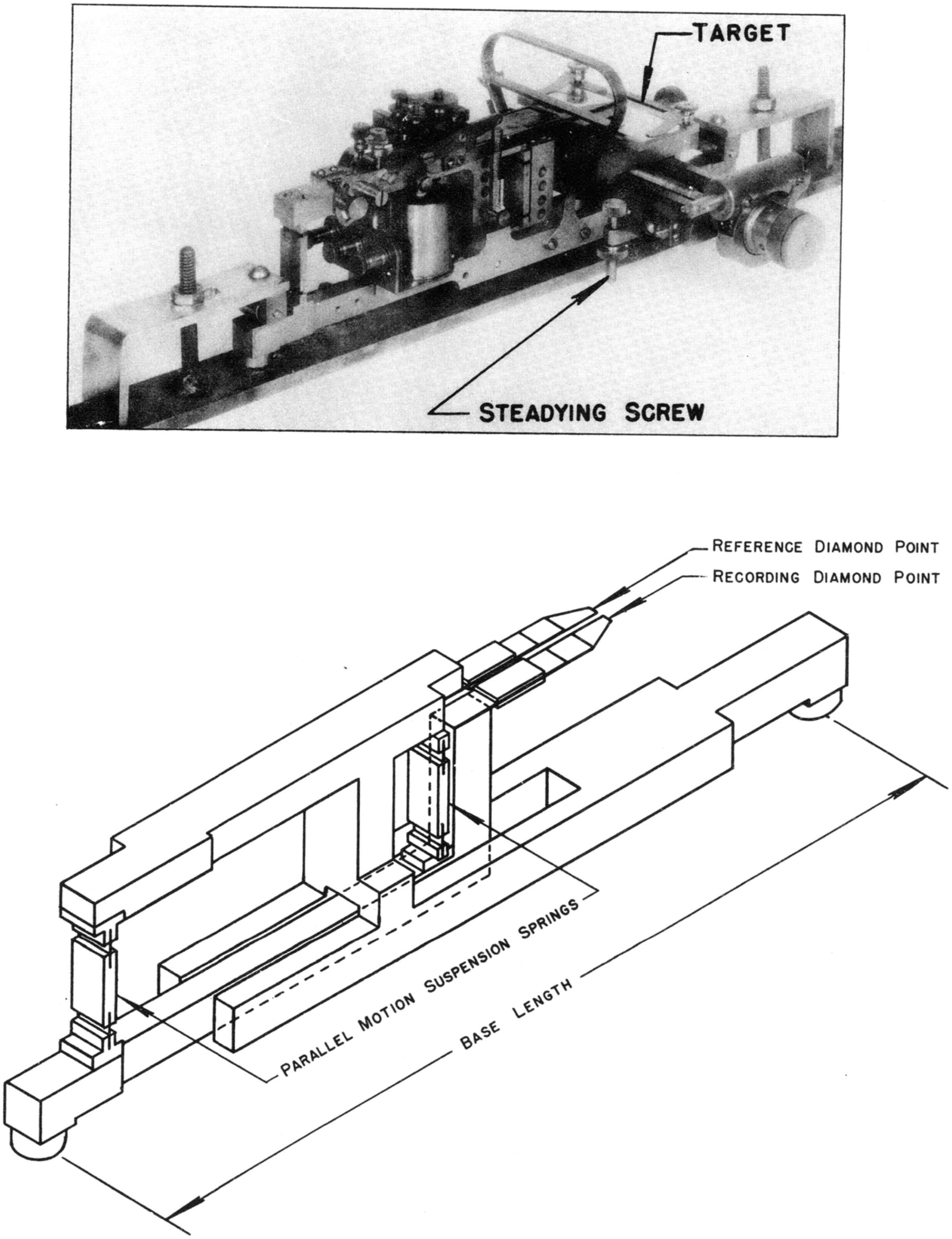


Figure 5 – EMB Rectangular Target Scratch Gage

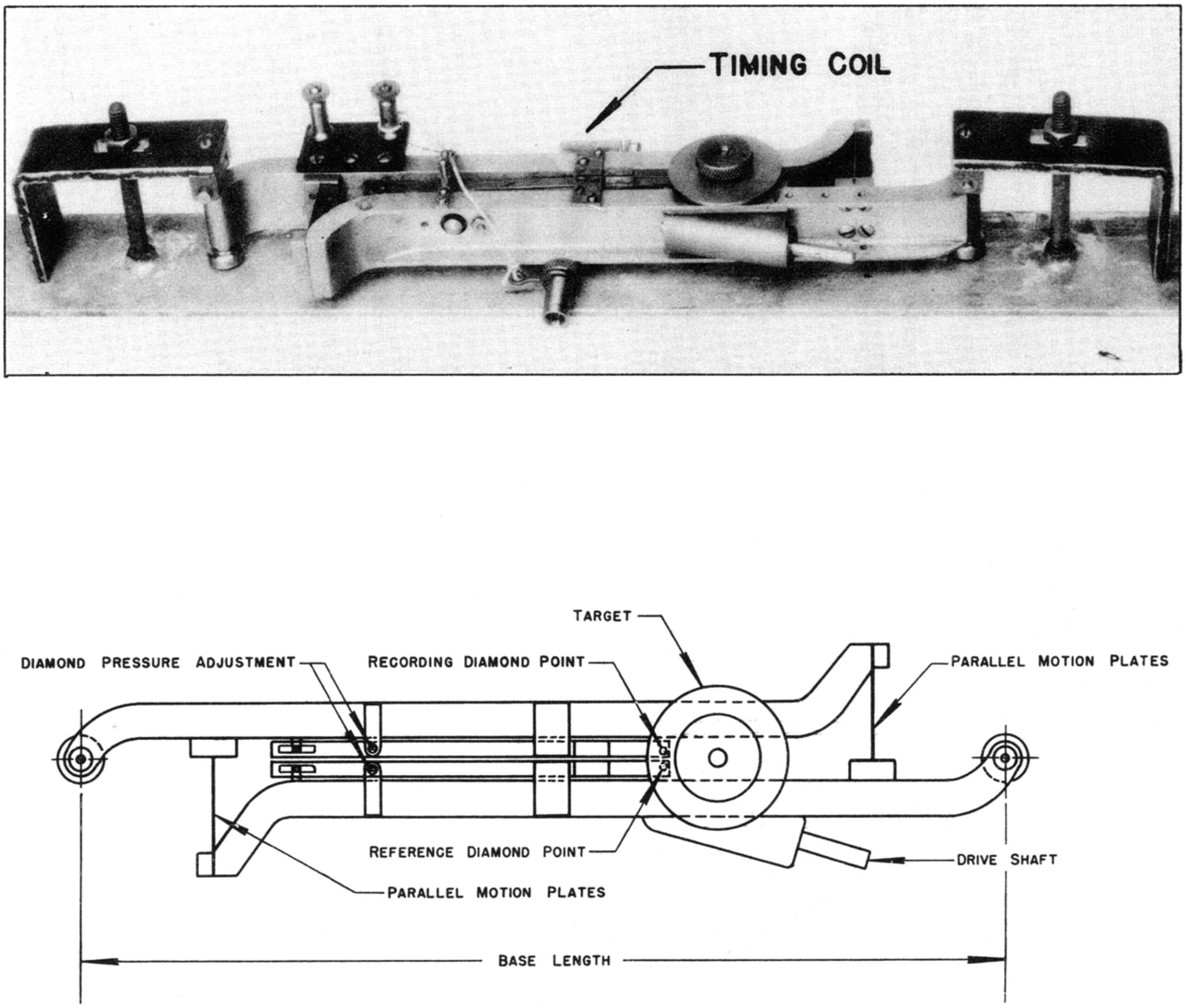
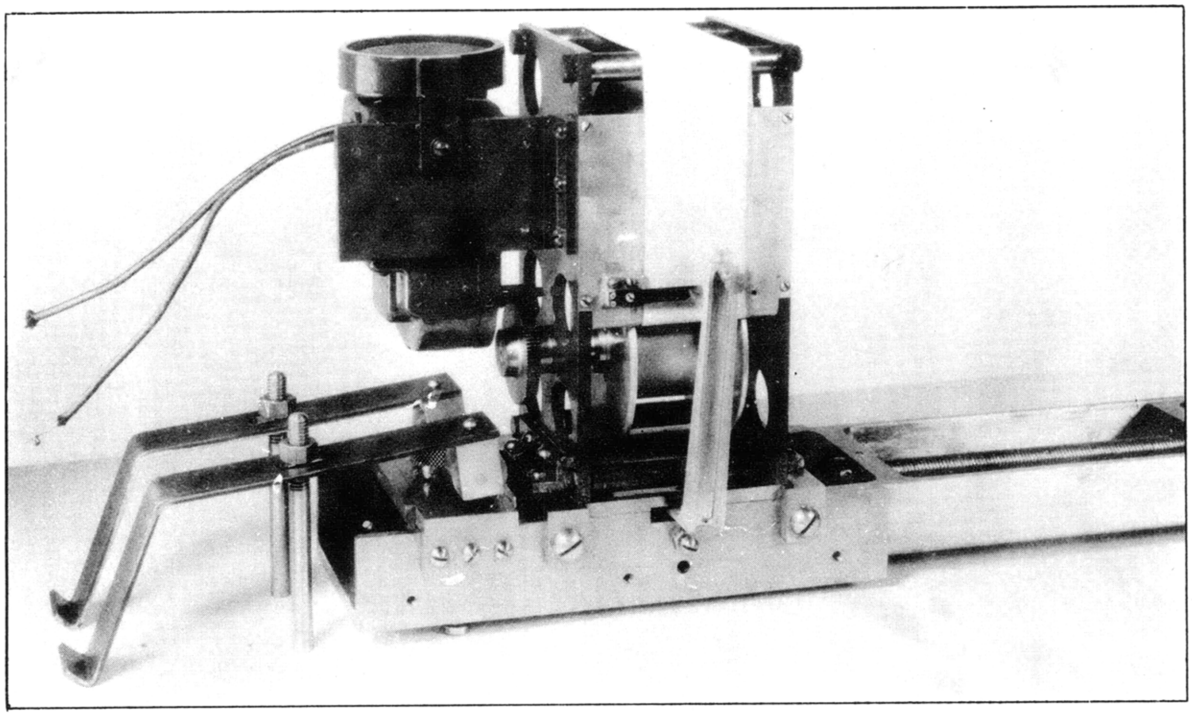


Figure 6 – EMB Circular Target Scratch Gage



Recording End of Gage

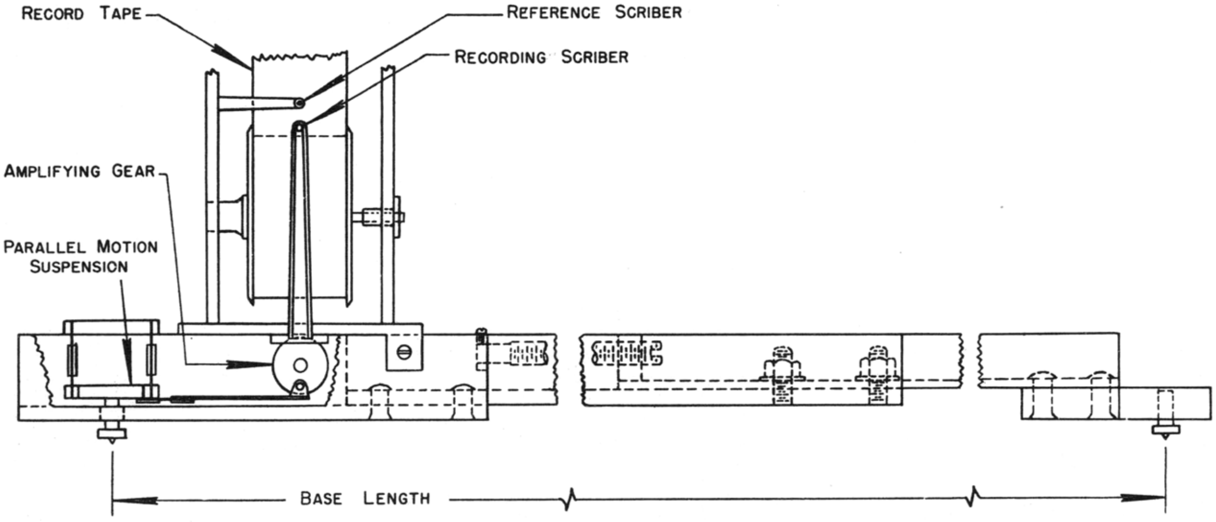


Figure 7 – EMB Long-Base Strain Gage

The gage is attached to the structure by clamps incorporating rollers. The movable gage points are carried on a parallel-motion member suspended from the frame by flexure springs. The total weight of the gage is about 50 pounds.

### Dial Gages

Photographic recording of dial-gage readings by motion picture cameras has been standard practice at the Experimental Model Basin for some time and a typical record is shown in Figure 8. Dial micrometers are used in a great variety of applications, such as in the Whittemore and EMB hand strain gages and in many types of deflection measuring equipment. The only recent development lies in the synchronization of the timing element.

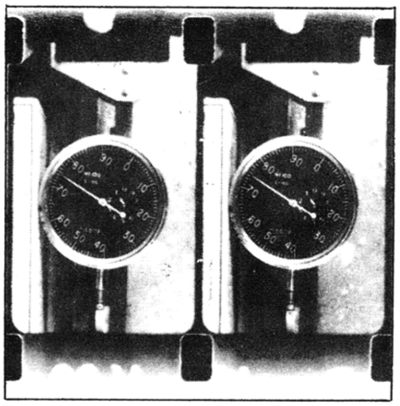


Figure 8 - Photographic Record of Dial-Gage Readings

### Electronic Gages

Application of thermionic tubes to the measurement of displacements becomes important as soon as dynamic loads are considered. Wire gages and indicating instruments for this purpose are in advanced stages of development at the Experimental Model Basin and will be fully described in a report of strain tests conducted on the U.S.S. WASP.

### Synchronization of Recordings

Centralized control of all the various gages used in a particular test is essential unless analysis is to be made by the much less direct method of cyclic averages discussed in a previous report (1). Gages here described are provided with electric control of the timing element. These electric controls are all operated simultaneously by one central unit, such as a chronometer. The time elements are thus synchronized, so that observation cycles on the various gages may be identified and correlated.

In the scratch gages, synchronization is accomplished either by the operation of electric hammers which produce a timing mark on the record, or by interruption of the drive.

Photographic records are obtained by the use of motion picture cameras electrically driven at slow speed (8 frames per second). The necessary timing is obtained by interruption of the lighting circuits, by placing time pieces in the field or by stopping the camera drive.

## Stress-Cycle Counters

Stress-cycle counters are different in principle from all other recorders. The type developed at the Experimental Model Basin is shown in Figure 9. A contactor attached to the amplifying lever of a 10-inch hand strain gage moves between two contact points mounted on a dynamically balanced rocker arm. Slight friction in its bearing prevents rotation of the rocker arm caused by vibration or by its own rotational inertia. When the stress range exceeds the gage setting, the contactor overcomes this friction and carries the rocker arm with it. On reversal of stress the rocker arm remains at rest unless the opposite point is contacted, when a cycle is recorded on the counter. The relay circuit is designed to require contact with each of the contact points in turn before the counter registers a count. Thus, oscillations smaller than the gap between the contactor and contact points are not recorded. The contact points can be set for any desired range of stress, and the counter records the number of cycles in which this range of stress is exceeded.

A similar type of instrument developed by the Goodyear Zeppelin Corporation for counting cycles of stress exceeding each of six fixed ranges is shown in Figure 10. A pivot arm rotated by the strain motion operates a series of ratchets which in turn rotate the counters. Variations in the dimensions of the ratchet teeth and their location on the arm determine the six fixed stress ranges counted.

The interpretation of data obtained from these counters is not yet wholly satisfactory. It is clear, however, that if permanently installed on a typical member of a vessel engaged in seagoing operations, such an instrument will give a direct summary of stresses in the form of a frequency distribution curve. For the service on which the ship is engaged it is then possible to estimate the probability of a stress cycle of any stated range. If the given service can be regarded as a representative sample of what may be expected in the future, definite predictions can then be made.

Three valuable features of such records deserve special mention:

1. Predictions as to future stress in the given member are independent of all considerations of structural detail, or of wave action, so long as the data on which the prediction is founded may be taken as a fair sample.

2. Application of considerations of probability is emphasized and the difference between complete certainty and a high degree of probability is clarified.

3. Emphasis on endurance of the structure under cyclic load is increased.

Additional phases of the information given by the counters will require much further study. Instruments of this type will be put in use at every opportunity so that comparisons between the results obtained from them and those obtained from more conventional methods can be extended.

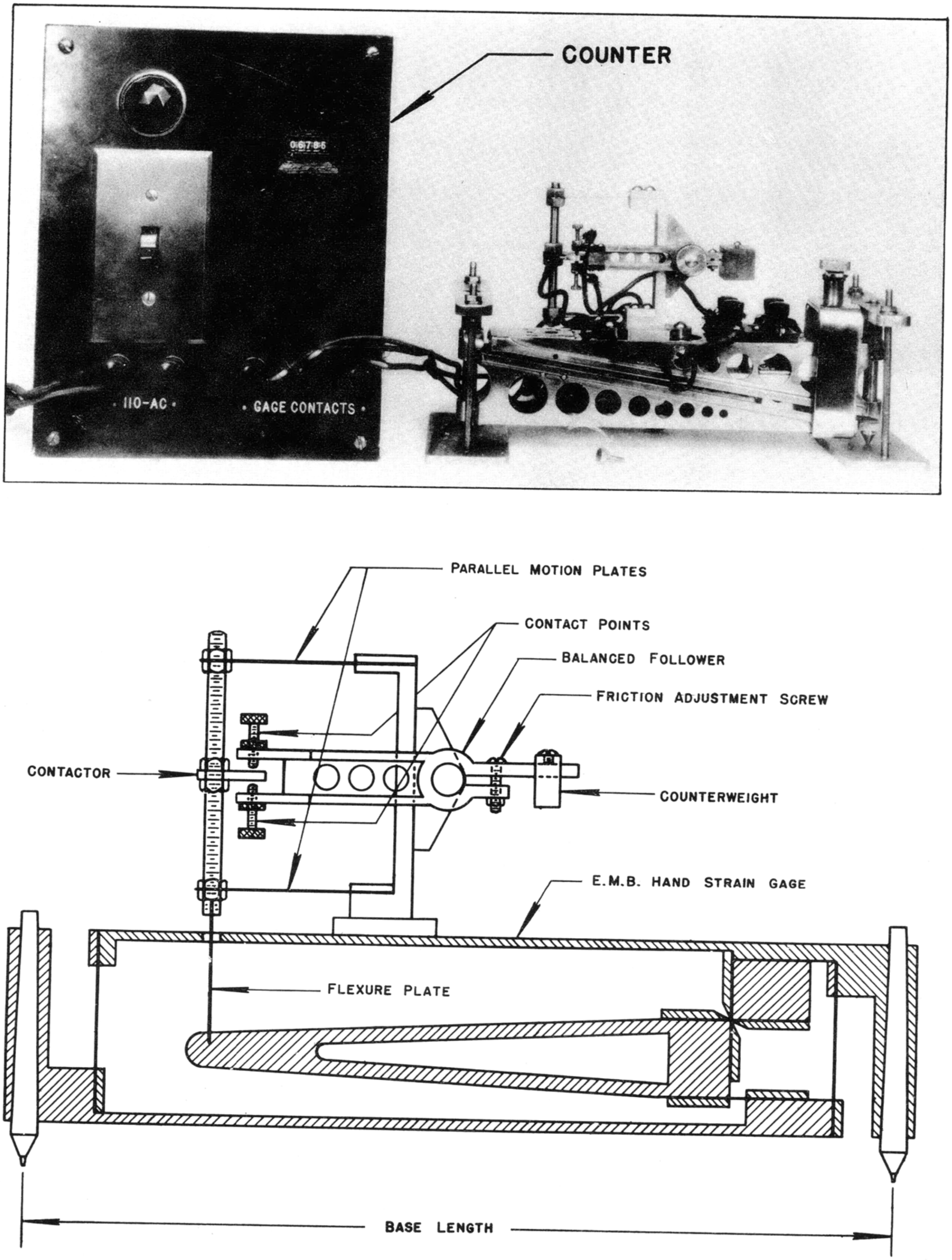


Figure 9 – EMB Stress-Cycle Counter

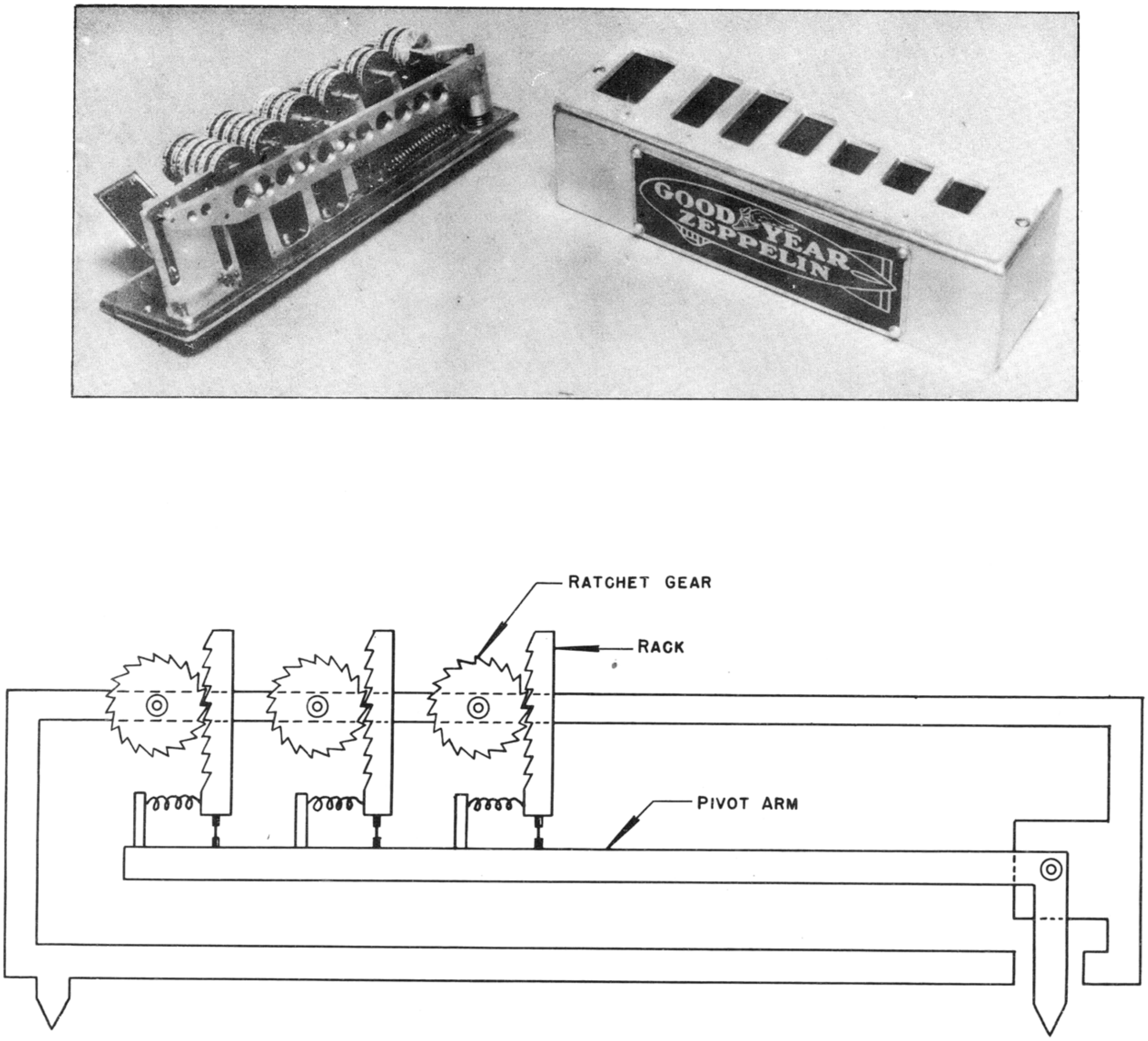


Figure 10 – Goodyear Zeppelin Stress-Cycle Counter

## APPLICATIONS TO U.S.S. PHOENIX

### General

In March 1939, gages of several of these types were installed on the U.S.S. PHOENIX, prior to the ship's final trials. The objects of this test were to observe the operation of the different gages under service conditions and to gain experience in their use.

### Location of Gages

The flag office of the ship was chosen as a gage station since it afforded a convenient place to set up the equipment; it was close to the midship section and distant from the neutral axis. Stress near the maximum occurring could be anticipated at this location.

Figure 11 shows the gages as mounted. One De Forest gage with 9-inch base, (Figure 4), the EMB scratch gages, and the EMB stress-cycle counter were located on the longitudinal between the main and second decks. An EMB hand gage, also mounted on this longitudinal, was used to check visually the order of magnitude of the strains encountered at any given time. By watching the oscillations of this gage the recording extensometers could be started at times when significant strains were taking place. The remaining De Forest gage and the long-base extensometer were located on the outboard longitudinal deck girder below the main deck. The gages were numbered from 1 to 7 as shown in the photograph.

### Installation of Gages

The gages were installed on the U.S.S. PHOENIX at the Navy Yard, Philadelphia. Studs were first welded to the longitudinals, using jigs for holding the studs during welding. The paint was removed and the surface metal smoothed at the gage point locations. Gage holes were drilled where necessary. To use gage points for making gage holes, the clamps were tightened with the locking pins in place, and then loosened and the locking pins removed. The remaining pressure of the clamps was sufficient only to hold the gage rigidly in position. For the EMB scratch gages the roller contact was made directly over the gage points. The De Forest gage was mounted with the roller contact between the gage points and the end steady screws.

Mounting the long-base strain gage was somewhat more difficult. Using the gage itself as a template for drilling the gage holes was first tried, but this was found impractical. Locating the holes by measurement and squaring with respect to the beam proved sufficiently accurate in view of the adjustability of the gage length. In future tests, a template will be provided for drilling the gage holes and locating the clamp studs.

All the electric gages were controlled from a single panel. A chronometer operated the timing hammers as well as the De Forest gage motors. The motors for the remaining gages were started by a second switch. The time required for the complete setup, including all wiring, was about four and one-half man days.

## Description of Test

Numerous records were taken during the ship's passage from Philadelphia to Boston, 18 March to 19 March, 1939, and during the final trials when enroute from Boston to Portland and return on 21 March 1939.

By closing the two controlling switches at the same time, simultaneous records from all the strain recorders were obtained. No chronometric time record was provided on the long-base gage, but by marking on the paper each time the gage was started and stopped the readings could be matched with those of other gages.

The sea was rather calm throughout the whole trip and the strains measured were consequently small. The stress-cycle counter, which had been originally set to count stress-range cycles exceeding 3000 pounds per square inch, had to be reset to a value of about 600 pounds per square inch. The gage mechanism worked satisfactorily, but the operation of the mechanical relays in the counter circuit was faulty, so that it has since been necessary to substitute more sturdy and reliable units.

## Data and Results

Photographs of simultaneous records for the different gages are shown in Figures 12 to 15. The scratch records are photomicrographs at 500 magnification. The record for the long-base gage has been magnified about 6 times. The beadlike time records can be seen on the EMB scratch gage records. Each step on the De Forest record represents a second.

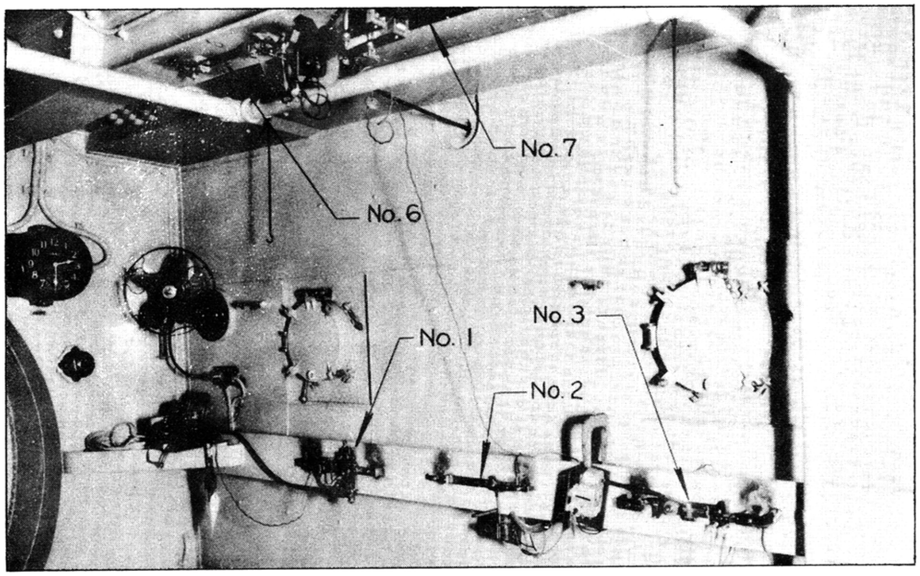
Comparative stress readings for the different gages are given in Table 1. Readings of the long-base and De Forest gages, corrected for distance from the neutral axis to make them comparable with those of the other two gages, are also tabulated.

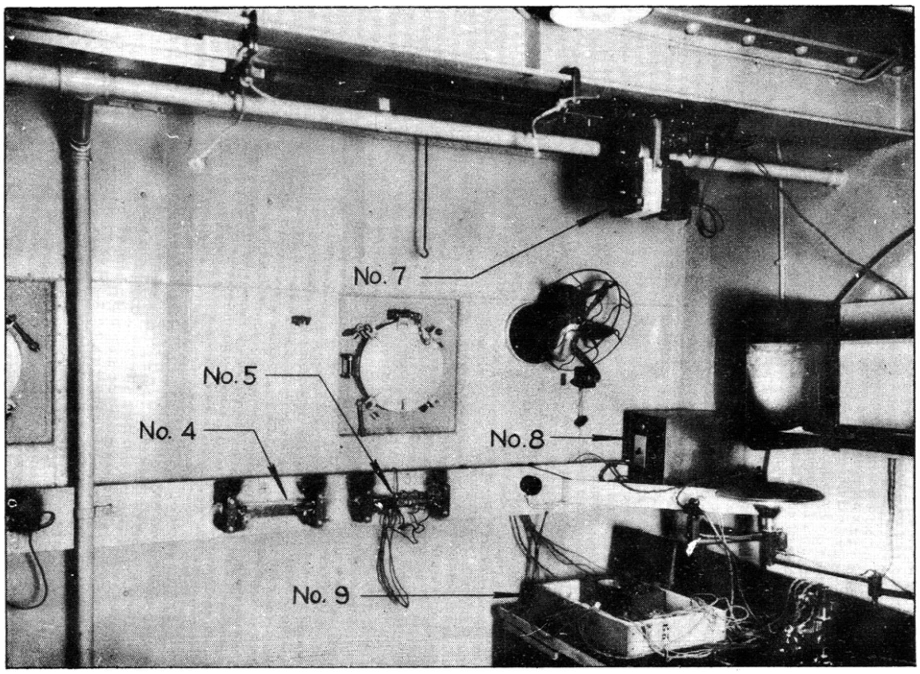
TABLE 1 - SIMULTANEOUS STRESS READINGS ON U.S.S. PHOENIX

Pounds per square inch

| Reading No. | On shell longitudinal between decks | | On main deck longitudinal girder | | | |
|---|---|---|---|---|---|---|
| | | | As observed | | Corrected to compare with gages on shell longitudinal | |
| | Rectangular Target Gage | Circular Target Gage | Long-Base Gage | De Forest *Gage No.6 | Long-Base Gage | De Forest *Gage No.6 |
| 1 | 2180 | 2130 | 2130 | 2110 | 1770 | 1760 |
| 2 | 3090 | 2910 | 3060 | 3000 | 2550 | 2500 |
| 3 | 2130 | 2100 | 2040 | 2190 | 1700 | 1820 |
| 4 | 2430 | 2310 | 2100 | 2370 | 1750 | 1970 |
| 5 | 4110 | 3780 | 3510 | 3960 | 2920 | 3300 |

* No. 6 in Figure 11.





No. 1. EMB Rectangular Target Scratch Gage
No. 2. De Forest Disk Scratch Gage
No. 3. EMB Circular Target Scratch Gage
No. 4. EMB Hand Strain Gage
No. 5. EMB Stress-Cycle Counter
No. 6. De Forest Disk Scratch Gage
No. 7. EMB Long-Base Strain Gage
No. 8. Stress-Cycle Counting Unit
No. 9. Control Panel and Chronometer

Figure 11 – Recording Strain Gages on U.S.S. PHOENIX

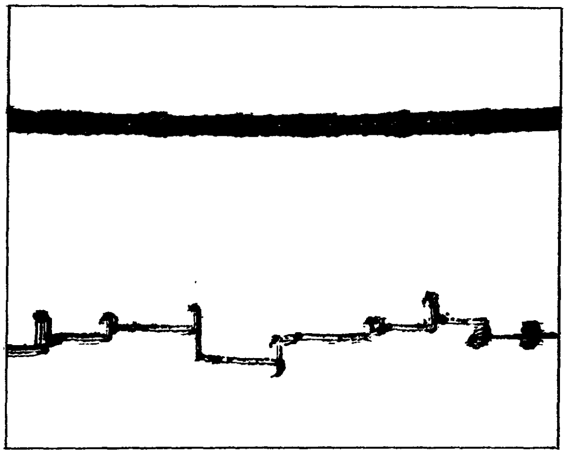


Figure 12 – De Forest Scratch Gage Record
Approximate Magnification 500x

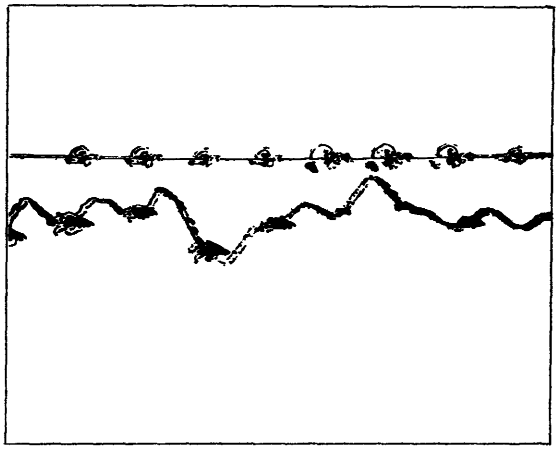


Figure 13 – EMB Rectangular Target Scratch Gage Record.
Approximate Magnification 500x

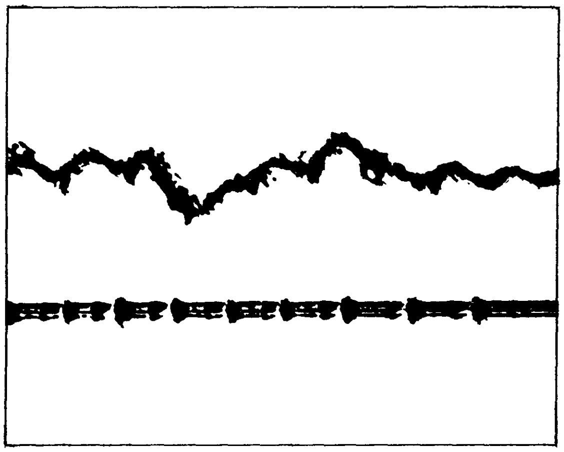


Figure 14 – EMB Circular Target Scratch Gage Record.
Approximate Magnification 500x

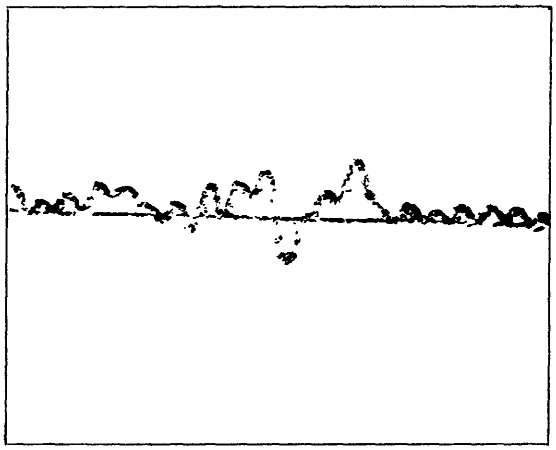


Figure 15 – Long-Base Strain Gage Record.
Approximate Magnification 6x

The two EMB scratch gages appear to agree within about 300 pounds per square inch; the lower readings are found on the circular target gage. The corrected readings for the remaining two gages are decidedly lower, with discrepancies from 400 to 1200 pounds per square inch. While the presence of an 18-inch I-beam adjacent to the deck girder on which these gages were attached may have reduced the strain in this member slightly, the laboratory calibration indicated that measurements with the long-base and the De Forest gages are less consistent than those of the EMB scratch gages.

## LABORATORY CALIBRATION OF GAGES

The gages, which had been checked on the calibration table at the Experimental Model Basin before installation on the U.S.S. PHOENIX, were calibrated more throughly later. The top of this calibration table is made in two parts, one stationary and the other movable. The relative motion of the two parts can be measured by a calibrated micrometer.

The stress-cycle counter was checked against a Huggenberger extensometer. Numerous trials showed that the stress range counted did not vary more than the equivalent of 150 pounds per square inch for steel. The factor of the multiplying linkage on the long-base gage was determined by means of an accurate dial micrometer attached to the table. Repeated checks gave a ratio of 10.1 to 1.

The EMB scratch gages were checked against the eyepiece micrometer of a 500 magnification microscope. As used on the U.S.S. PHOENIX, the circular target gage read about 3 per cent low. Improvement in the diamond support has subsequently brought this down to 1 per cent, and by the use of thinner flexure plates and heavier gage points in drilled holes, the error was reduced to approximately 3/4 of 1 per cent low. Observations for the rectangular target gage showed it to read 1.7 per cent low.

To determine the effect on gage readings of the roller clamps used for mounting the gages on board ship, the gages were mounted on test specimens set up in the testing machine. The scratch gages were calibrated with Tuckerman gages on 8-inch base length. The effect of the roller clamps was found to be an increase in the scratch gage readings of approximately 1 per cent. There was only a very slight variation in error depending upon clamping pressure. By using a different type of clamp in future tests this effect can be further reduced and known correction factors may then be applied. Since further development was found to be necessary on the De Forest scratch gages, they were not calibrated.

The long-base gage with base length at 48 inches was mounted on a tensile test specimen and checked, using the average of 10 local readings taken over the length of specimen covered by the gage. Records were made with the scriber always moving in one direction in order to eliminate the effect of any backlash in the gage. A check for backlash was then made by approaching a given load on the testing machine both by increasing and decreasing loads. Based on the 10 to 1 linkage ratio, the recording gage readings were 3 per cent higher than the average of the hand strain gage readings. However, when correction for bending in the specimen is made it can be concluded that the gage is as accurate as this method of calibration. Different clamping pressures did not affect the readings. A maximum backlash of 0.015 inch was observed on the record. This was reduced to about 0.005 inch by reducing the bearing pressure of the stylus on the paper.

## APPLICATIONS TO U.S.S. ST. LOUIS

### Description of Test

Four fully autographic instruments, the EMB recording scratch gage, the EMB long-base tape recording gage, and two stress-cycle counters, were installed on the U.S.S. ST. LOUIS for use on her shakedown cruise. During a period of the roughest weather encountered on the cruise the instruments were operated for a half-hour interval, during which the ship experienced 213 cycles of significant bending load. These offer the best examples of service strain data yet obtained. A sample of the tape record from the long-base gage is shown in Figure 16.

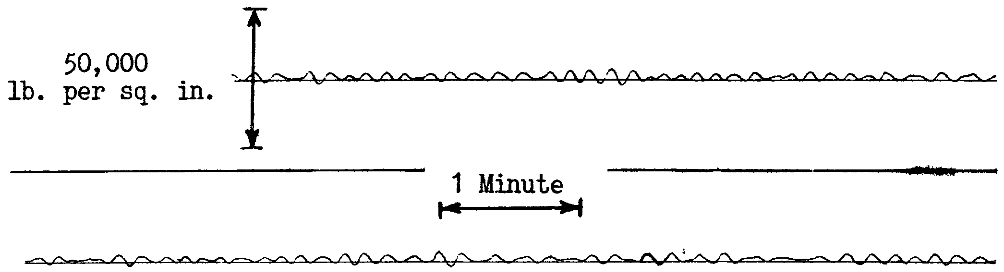


Figure 16 - Sample Tape Records from Long-Base Strain Gage, U.S.S. ST. LOUIS Test

Comparing the scratch record with the tape affords a check on both. It is found that the succession of varying strain amplitudes affords a positive identification of corresponding cycles on the two instruments, in addition to that of the time control.

### Data and Results

The ranges of strain measured on the records are from each maximum to the succeeding minimum. After applying the calibration factors (obtained in connection with the U.S.S. PHOENIX test) the average for the scratch record is about 150 pounds per square inch greater than the average for the tape record. This discrepancy is less than the least count on either instrument, and is probably caused by the backlash in the long-base gage, which has the effect of slightly reducing the amplitude recorded. This effect is apparently more pronounced at larger amplitudes; the stylus moves faster across the tape with resulting greater deformations in the stylus arm. Thus, in the 37 cycles in which the range exceeded 4000 pounds per square inch, the scratch gage readings exceeded tape gage readings by a greater amount than at lower stress ranges. A greater number of large amplitude cycles is necessary before this point can be clarified. It is not possible in any event to place two gages in precisely the same position, and the observed disparities may reflect actual differences in stress range at the two different, though adjoining stations.

Scatter in general is about what might be expected from a knowledge of the least counts of these instruments. Mean departure from the mean, of differences between scratch and tape values, is 210 pounds per square inch.

The most significant result obtainable from data of this nature refers to the distribution of the numbers of cycles among the various stress ranges occurring. If a ship were to move at uniform speed and on a steady course directly into the sea, among a completely uniform series of waves, the longitudinal bending stress would be expected to repeat exactly and the stress range would be subject to no variation from cycle to cycle. Of course this does not occur, and while it may be approximated under action of a very regular sea, a more confused sea may cause wide variation in stress range. Circumstances may combine to produce occasional very large stress ranges, even though the average may be moderate. It is important to be able to estimate the number and amplitude of such exceptional cycles, and data of the kind here obtained afford the information necessary for such estimates.

These data are in the form of a series of successive stress ranges as read from a record such as Figure 16. The number of cycles in which the stress range falls between given limits can be counted and expressed as a fraction of the whole number considered. The results can then be recorded in graphic or tabular form to show the distribution of the cycles among the various stress-range values occurring. The series of values obtained from the tape recorder on the ST. LOUIS are shown in Figure 17 as spots on the curve.

This curve is presented only to illustrate the form in which such data as these may be brought into the strength problem. This particular series is much too restricted to form the basis for any conclusions as to the strength of this particular ship.

## CONCLUSION

This report, combined with Experimental Model Basin Report 467, "Service Strain Tests of Hull Structures", presents an account of the state of the art of strain measurement on ships at sea, as practiced at the Experimental Model Basin up to the beginning of 1940.

It is expected that extended use will be made of these resources for increasing knowledge of the straining actions of the sea on ships, and that emphasis will come more and more to be placed on the statistical aspect of such actions.

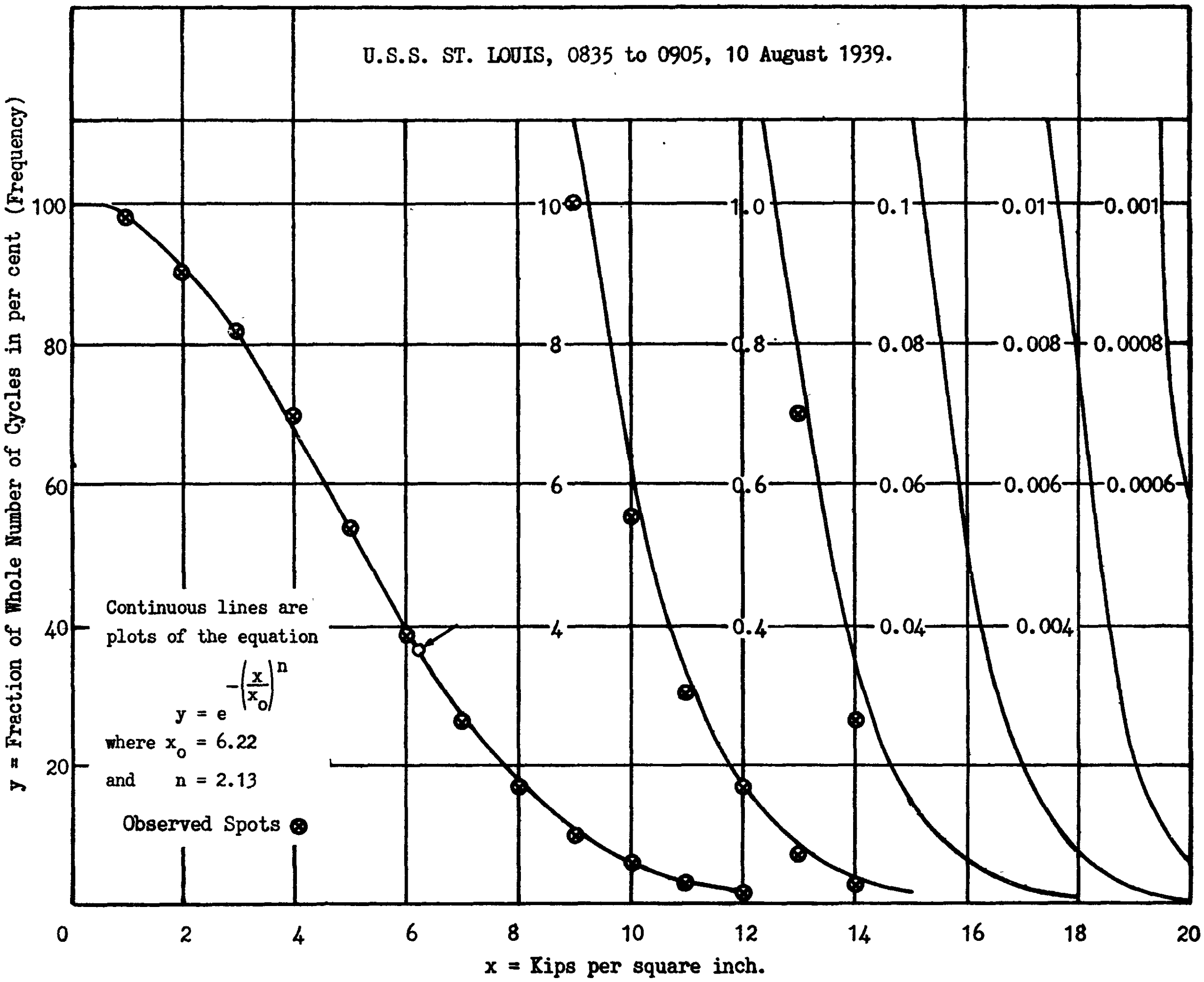


Figure 17 – Distribution of Cycles of Stress in Second Main Deck Longitudinal, Frame 71-1/2 starboard.

# APPENDIX ON STATISTICAL DESIGN

## STATISTICAL DESIGN

Figure 17 shows graphically the fraction of a total number of loading cycles in which given stress ranges are exceeded. The curve stands at unity for a zero stress value, since that range is exceeded in every cycle. As the stress value increases, however, it is more and more infrequently exceeded. For example, the value 6.22 kips per square inch is exceeded in 36.8 per cent of the total number of cycles, as shown by the point marked by the arrow. Beyond 10 kips per square inch the percentages become so small that they are shown separately on a tenfold scale, and at higher stress ranges there is still greater magnification of the percentage scale.

The observed data are shown as spots in Figure 17. By a process of "curve fitting" an analytical expression was chosen which gives rather accurate expression to the actual relation between the variables within the limits of observation. There is, of course, no assurance that this formula is valid beyond those limits. In fact, it seems reasonable to suppose that there must be an upper limit which might occur, and that very great loads under the conditions of service are actually impossible and not merely, as the curve would imply, highly improbable.

Thus, so far as length of wave is concerned, it is clear that bending loads become smaller when the wave length exceeds that of the ship. At the same time, under violent storm conditions the wave heights, the weight of deck loads of water, the severity of pounding of the forefoot, and similar irregular conditions all increase in severity, and to such actions as these no definite limit can be set.

The idea that there is a definite limit of required strength is, in practical fact, recognized as fiction. It is not true, short of grounding or collision or internal explosion, that ships come abruptly to the end of life. Rather, damage is progressive, more rapid as conditions are worse, but at such rates that the reduction of life to a single cycle would lie beyond the limits of actual experience. Recent developments confirm this view, which is implicit in the expression "Damage Control".

Of course, in situations of extreme emergency, the structure of a ship may not have opportunity to develop its expected resistance to load. Through casualty to equipment or personnel large or numerous compartments may be flooded, control of essential operations may be lost, excessive heel or trim may result, leading to loss of the ship. But complete rupture of the main strength members would hardly occur if some such circumstances had not intervened. In such a case no practicable amount of structural strength would be enough.

This progressive encroachment on resistance to very great loads, this reduced resistance to fatigue, is partly a matter of internal damage to the metal itself, which occurs not only at high stress intensities, but to some extent at moderate values, when long repeated. This will receive further attention in connection with the program of endurance testing. For the present it is enough to note that information of the sort here given, when available in a scope which truly represents service conditions, will furnish the base for estimates of service life of ships comparable with the actuarial tables of expectation of human life.

The curve as given applies only under the conditions existing when the data were taken. To make these data applicable under other conditions, it is necessary to establish a basis on which to account for the differences in the ship structure and in the action of the sea. These differences must be considered separately.

Structural analysis has as its objective the development of required values of section modulus, of stress per unit load. The determination of the value of section modulus to be required will be made in the light of the other requirements of the specified service, size and form of the ship, nature of its duty, and estimated working loads. But once the required values are stipulated, the rest is a matter only of structural design.

There is as yet no way of finding actual loads on a ship by calculation. Neither does Figure 17 show loads directly, but in order to pass from stress, which is directly observed, to load, it is necessary only to introduce a quantity having the dimensions of section modulus. For many purposes the nominal section modulus obtained by standard calculations may serve; for other purposes it may be necessary to introduce a "service section modulus" (1).

The essential point is to separate questions of structural design from questions of load determination. The main uncertainty in the whole process of design lies in the estimates of the action of the sea, and this is where data of the type here considered will have the greatest importance.

Two families of curves can be obtained by varying the denominator $x_0$ and the exponent n in the formula in Figure 17. These two parameters correspond to the chief variable features in the action of the sea on a ship, its intensity and its irregularity.

Figure 18 shows the results of introducing different values of these parameters into the formula.

The intensity of the action of the sea can be described in terms of stress on a given member, as directly observed, or of load on the whole ship, which can only be inferred. The frequency distribution would be of the same form in either case, and the exponent would have the same value; the only difference would be in a constant multiplier for the horizontal scale.

Without pausing now to ask whether height, length, or some other quality of the waves of a seaway determines load, it is clear that a heavy sea causes great loads. The greater the magnitude of these loads, the more our distribution curve will be stretched out toward high stress values. For mathematical convenience, the stress at which $x = x_0$ is taken as the reference point. The greater the effect of the sea, the greater $x_0$ will be. $x_0$ is thus the basic or reference value of x; it is the intensity parameter.

That, naturally, does not exhaust the matter. Through the point $x = x_0$,

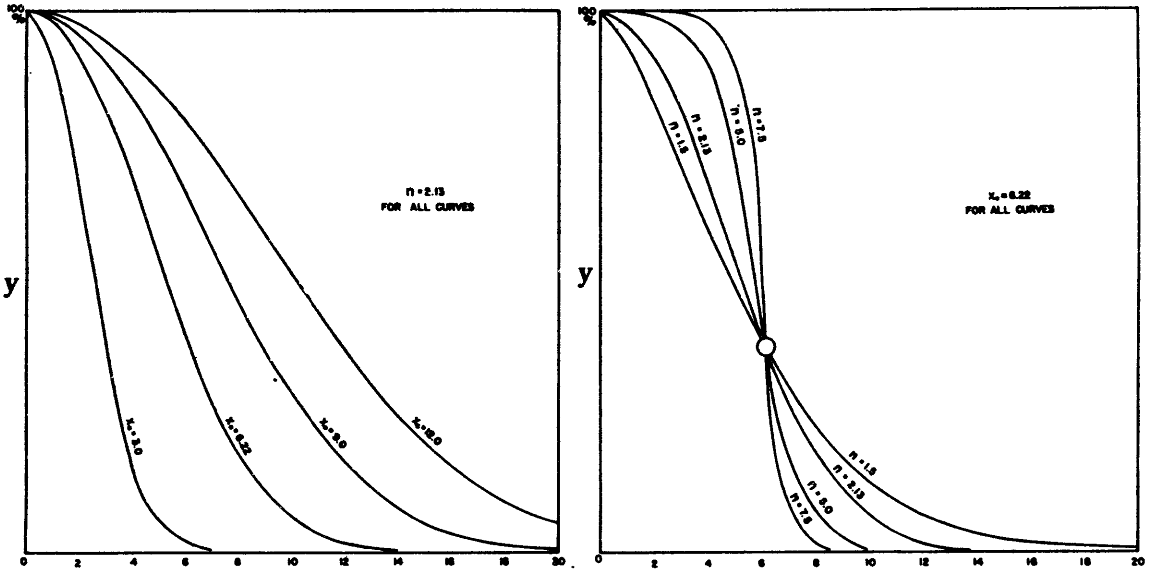


Figure 18 - Computed Curves Showing Effects of Variation of Parameters, $y = e^{-\left(\frac{x}{x_0}\right)^n}$

y = 1/e, in each case again a whole series of different curves may pass, varying with the exponent n. A high value of n corresponds to regular wave action, a nearly vertical drop of the frequency curve at $x = x_0$. A low value of n corresponds to irregular wave action, gradual decline of the curve to low frequencies at high stresses.

It is hoped that these two parameters, $x_0$ for intensity and n for regularity of wave action, may be found sufficient to characterize the main variations involved. If so, when values of these quantities are known for various conditions of weather, or, perhaps, even for various regions of the sea, the basic data for load specification, and so for rational solution of the problem of strength of ships, will be available.

The process of design will then become somewhat as follows:

(a) From consideration of the service for which the ship is intended, and from experimental records on actual ships in that service, assign for use in the design a frequency distribution curve for bending loads, as by choice of the two parameters for intensity and regularity of load.

(b) The desired life of the ship, in number of cycles endurance at the maximum stress range, is to be specified. A value of 50,000 cycles has been suggested. The conversion of life to terms of time rather than number of cycles would call for knowledge of a schedule of utilization of the ship. The permissible stress maximum and the specified life in cycles are related by laboratory endurance data on the material of construction.

(c) The total number of distributed cycles which will be equivalent in its encroachment on the reserve of endurance to the chosen number of maximum cycles must also be determined by laboratory tests. The life in distributed cycles will be related to the value of the intensity parameter much as the life in maximum cycles is related to the intensity of the maximum, so that when the desired value of life in distributed cycles is assigned, the permissible value of the intensity parameter $x_0$ for stress will become known.

(d) If both the load intensity parameter (Paragraph (a)) and the stress intensity parameter (Paragraph (c)) are now determined, their ratio, which has the dimensions of section modulus, provides the starting point for structural design.

When the procedure thus outlined becomes possible, a closer adaption of ship structure to its actual requirements will be achieved, yet without an abrupt break from present methods of design. The function of the gages in this process is to provide the necessary information.

## PERSONNEL

The development of the gages described has been shared by various members of the Applied Mechanics Section of the Experimental Model Basin. Detailed description of the gages is the work of E. E. Johnson. The discussion and assembly of the report is the work of Lieutenant Commander W. P. Roop, (CC), U.S.N.

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