REPEATED LOADS ABOVE THE PROPORTIONAL LIMIT ON 24ST ALUMINUM ALLOY

Thesis by

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REPEATED LOADS ABOVE THE PROPORTIONAL LIMIT ON 24ST ALUMINUM ALLOY

Summary

The purpose of this investigation is to study the effect of repeated tensile stresses above the proportional limit on 24ST Aluminum Alloy.

The investigation consisted of two parts: the design and building of testing apparatus which would provide a pure tension stress capable of being repeated many times a minute without shock but with a high rate of loading, and to obtain data by means of runs on prepared samples of the metal under study.

It was found that permanent deformation caused by overstress is not a useful factor in forecasting life expectancy.

It was also found that the effects of "aging" (elapsed time between overstresses), initial cold work, and magnitude of overstresses applied all have definite influence on the ability of 24ST Aluminum Alloy to withstand further overstressing and require more thorough investigation.

It is considered that this field offers attractive possibilities for further study of the behavior of aircraft materials above the proportional limit with an eye toward increasing accuracy of airplane design.

The investigation was carried out at the Daniel Guggenheim Aeronautical Laboratory, California Institute of Technology, Pasadena, California.

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REPEATED LOADS ABOVE THE PROPORTIONAL LIMIT ON 24ST ALUMINUM ALLOY

Introduction

The purpose of this investigation is to study the effect of repeated tensile stresses with a high rate of loading above the proportional limit on 24 ST Aluminum Alloy. An attempt has been made to correlate deformation with frequency of loading at various stresses above the proportional limit of 24ST Aluminum Alloy up to the ultimate strength. It was undertaken with two purposes in mind: first, to obtain general information on the behavior of the aluminum alloys in the plastic region when subjected to repeated stresses, and second, in the hope of providing the aircraft industry with means to determine when an important member of the structure which is suspected of having suffered repeated stresses of that nature should be retired from service by showing that measured permanent deflection could be used to forecast probable remaining life.

Little experimental data has been made available in the past covering this phase of structural research. The problem is vast, including, as it does, an almost infinite number of combinations of metals, their alloys, structural shapes, and types of loading, so that this investigation can attempt to cover only a small range of conditions and indicate the direction in which further investigations might be profitable.

Several closely allied problems have been investigated at the California Institute of Technology during the past few years. All of them however, have dealt with an almost instantaneous impact type of loading supplied by a falling weight or similar arrangement. Great difficulty was experienced by most of these earlier investigators in isolating the characteristics they desired to study from the introduction of undesirable paramaters in their methods of testing.

When it is realized that any load applied to an aircraft cannot be of the shock, or impact type, due to the inherently elastic nature of an aircraft structure itself, we see at once that what actually happens is a high, but quite finite, rate of loading even with the most suddenly applied loads.

Hence, the decision was made very early to abandon the techniques used in previous investigations and to design and build a testing machine of the hydraulic type. Hydraulic loading of a test specimen offers the following advantages:

1. Accurate control of the magnitude of applied stresses.
2. Accurate control of the rate of loading.
3. Ability to apply a pure tension load, repeated at will, with no motion of the specimen or adjacent parts of the machine which might introduce unknown effects.
4. Adaptability to measuring results accurately and continuously by electrical means.

This investigation was carried out at the Daniel Guggenheim Aeronautical Laboratory, California Institute of Technology, Pasadena, California.

Equipment

Test specimens:

The material used in the test was standard bar stock 24ST Aluminum Alloy. Test specimens were machined to the shape and dimensions as shown in Fig. 1. Each specimen was carefully made in accordance with the customary high standards of experimental work to eliminate residual stresses from machining and with a high polish on the test section to avoid minute scratches and nicks. Fig. 3 is a photograph of one of the specimens.

Testing machine:

To achieve the high rate of loading desired without subjecting the material to sudden shock, a hydraulic testing machine was designed and built by the writers in conjunction with Lt. Comdr. O. A. Soli, U.S.N. and Lieut. W. E. Ditch, U.S.N. who desired a similar type of loading for a project involving rivet assemblies.

The machine consists essentially of a hydraulic cylinder which exerts a pure tensile stress on the specimen which is anchored at one end and fastened at the other to the piston of the cylinder. Hydraulic pressure is supplied to the cylinder by an aircraft-type hydraulic system consisting of a positive displacement gear pump driven by a five H.P. 220-volt a.c. electric motor. As the pump runs at constant speed, a pressure regulating valve is installed in the system to vary the hydraulic pressure applied up to 1000 psi. A pressure-relief valve is installed as a safety measure to lift at 1250 psi. To alternately apply the stress and relieve it without tedious manual operation, a Vickers pilot control valve is used. This valve is solenoid-operated, the solenoid in turn being triggered by contact points which are opened and closed by a cam driven by a 1/20 H.P. universal wound a.c. motor operating on 110 volts. This motor also operates a mechanical counter to record the number of cycles. Since there is little if any actual displacement of hydraulic fluid in the system during operation, any size cylinder within reason can be used which will give loads varying with the cylinder diameter. For this investigation a standard aircraft-type hydraulic cylinder, five inches in diameter, was used which gave a maximum load (based on 1000 psi.) on the specimen of about 11,500 lbs. With the cross section area of the specimens equal to .0707 sq.in., this gives a maximum possible stress of about 162,800 psi.

Since it is undesirable to present here the details of construction of this machine, a complete description of its design and operation are presented in an Appendix with photographs and schematic drawings.

Load measuring coupon:

As a means of checking the load applied to the specimen against that indicated by the pressure gage and to provide a method of measuring the amount and rate of loading under dynamic conditions, a device hereafter called a "load coupon" was made. Fig. 2 is a drawing of the load coupon; Fig. 4 is a photograph of it, showing the position of the electrical strain gages used.

Mounted on the coupon were four SR-4 Type A-1 electric strain gages manufactured by the Baldwin-Southwark Company. These gages were connected in series to increase the sensitivity of the coupon and to remove any effects of bending. A description of the calibration of the load coupon follows later in this report.

Measuring apparatus:

Elongation of each specimen was measured using a traveling microscope capable of measuring to an accuracy of one ten-thousandth of an inch. Elongations were measured over an original gage length of two inches. Methyl violet was applied to the test area of the specimens and fine scratch marks made with dividers without scratching the surface of the metal itself.

It was originally planned to measure elongation of the specimens using electric strain gages. However, the specimens were subjected to such high stresses and deformations that the strain gages became inoperative. Therefore this method was abandoned in favor of mechanical measurement.

Dynamic load measuring equipment:

The electrical load measuring equipment has two purposes: first, that of determining the exact stress in the speciman and second, to measure the rate of loading applied on the specimen.

The equipment consists essentially of the load coupon on which four electric strain gages are mounted in series. The change of resistance of the gages with changes in load is measured by a Wheatstone Bridge. This signal is sent to an amplifier which in turn amplifies and sends the signal to a Heiland Recording Oscilloscope. The recording oscilloscope makes a photographic record of the load vs. time. Incorporated in the electrical system is a means of putting a known load line on the photographic record. This was accomplished by loading the coupon with known loads of 1000, 2000, and 3000 lbs. and finding experimentally the amount of resistance required to be connected in parallel with the gages in order to balance the bridge.

By incorporating these resistances in the electrical circuit and connecting to a selector switch, it was possible to select either 1000, 2000, or 3000 lbs. and then by pushing a button on the panel, a calibrating line for one of the three loads could be put on the recording tape. By comparing the load vs. time curve to the calibrating line the load on the specimen could be obtained and hence the stress. This calibration method eliminated errors due to changes in voltage of the power supply since all measurements could be referred to a calibrating line which was obtained as often as desired.

Fig. 21 is a circuit diagram of the dynamic load measuring equipment.

Fig. 22 is a series of photographic records of the time rate of loading at a high and low stress. Also included are the load calibration lines previously mentioned. The rate of loading, and time from no load to full load are noted on the records. Construction lines used in obtaining these rates are shown. The timing lines on these records are .01 seconds apart.

PROCEDURE

Pressure gage calibration:

The pressure gage used in the hydraulic system was a standard Bourdon type with a range from 0-1000 psi. It was used to set the pressure desired to give a certain stress, while the load coupon gave a much more accurate measurement, and each served as a check on the other within fairly close limits. The gage was calibrated against load in the cylinder, the curve for which appears in Fig. 5. By incorporating the cross sectional area of the specimen with the calibration, a second calibration of stress in the specimen versus gage reading was obtained and appears in Fig. 6.

Calibration was carried out on a Tinius-Olsen Hydraulic Testing Machine by connecting the gage to the cylinder, filling the cylinder with oil, and then applying a series of loads to the piston of the cylinder and recording the gage readings.

Calibration of the load coupon:

The calibration of the load coupon was carried out using the Riehle Bros. Testing Machine located in the structures laboratory of the Daniel Guggenheim Aeronautical Laboratory. Electrical measurements were made with a Wheatstone Bridge which had been constructed previously for electrical strain gage measurements.

Each gage was first checked separately, plotting load vs. millivolts. This plot is shown in Fig. 7. This calibration ascertained whether or not each gage was operative and whether its output was comparative to the other three gages. Since each gage plotted as a straight line over the load range, this indicated that they were satisfactory.

After connecting all four gages in series the above process was repeated, obtaining millivolt output versus load at each 100-lb increment of load. Due to the limitations of the Ruhle Testing Machine, the load could only be carried to 3000 lbs. Fig. 8 is a load versus millivolt curve plotted from the data obtained in this calibration. Since the coupon operates well below the proportional limit of the material from which it is made and the calibration to 3000 lbs. is a straight line, it was deemed satisfactory to extend the calibration curve to obtain readings for the higher loads.

Also, during the load calibration, the amount of resistance was determined which would be required in parallel with the set of four gages at loads of 1000 lbs., 2000 lbs., and 3000 lbs. in order to balance the electric bridge described earlier in this report. This information was required in order to put a load calibrating line on the rate of loading trace from the oscillograph. Details of this phase of the calibration is discussed in the section dealing with the equipment for measuring the rate of loading.

Test procedure:

A record of all runs made appears in Table V.

Prior to starting any repeated load tests, a static stress/strain curve was obtained on one of the specimens from the batch of material to be tested. This appears in Fig. 9 and gives an ultimate strength of 72,000 psi.

Next, an attempt was made to measure, electrically, the elongation of the test specimen by means of two B&S SR-4 Type A-7 electric strain gages mounted on the test section of a specimen. Due to the excessive deformation of aluminum above the proportional limit the strain gages broke loose from their bonding. Hence this method of measuring elongation was abandoned in favor of mechanical measurement by means of a traveling microscope as previously described.

Then a specimen was subjected to a repeated stress of 58,000 psi. for 4400 cycles after which a static stress/strain curve was run on it to determine the change in properties of the metal. The result appears in Fig. 10.

Three more specimens were subjected to runs at 68,100 psi. (just below the ultimate strength) and fractured at widely varying numbers of cycles. Photomicrographs of their fractures appear in Fig. 19.

One specimen was subjected to the ultimate strength, 72,000 psi., to check the static stress/strain curve and it failed as expected upon the first application of the load.

Next several specimens were subjected to different initial repeated stresses of 500 cycles each (as a sort of cold work) ranging from the proportional limit to just below the ultimate and then worked at a stress just under the ultimate up to about 5000 total cycles. If failure did not occur, the pieces were allowed to age varying amounts and then reworked at the same high stress until failure.

RESULTS AND DISCUSSION

Static tests:

The initial static stress/strain curve (Fig. 9) of the first batch of 24ST used gives the following values:

Proportional limit	37,500 psi.
* Defined yield stress	50,000 psi.
Ultimate strength	72,000 psi.
Per cent elongation	No Reading

The static stress/strain curve (Fig. 10) of the damaged specimen (Table V, No. 3) gives the following values:

Proportional limit	45,000 psi.
Defined yield stress	55,000 psi.
Ultimate strenght	69,500 psi.
Per cent elongation	19.4 %

Examination of Fig. 10 shows a much sharper break or "knee" in the curve than occurs in the undamaged material and indicates that, as one might expect, the cold work has reduced the ductility; the proportional limit and the yield stress have increased while the ultimate strength remains essentially unchanged.

A static stress/strain curve of the second batch of material appears in Fig. 11. A damaged specimen of the same batch was subjected to a stress/strain test, the result of which appears in Fig. 12. The following

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* Defined yield stress: determined from the stress/strain diagram by drawing a line parallel to the straight or elastic portion of the curve through a point representing zero stress and 0.002 strain. The yield stress is taken as the intersection of this line with the stress/strain curve.

results obtain:

	Undamaged	Damaged
Proportional limit	34,000 psi.	60,000 psi.
Defined yield stress	42,500 psi.	64,500 psi.
Ultimate strength	66,000 psi.	65,500 psi.
Per cent elongation	16.08 %	12.5 %

Surprisingly enough, batch number two, which was softer and more ductile than batch number one was much more affected by cold work and gave a stress/strain curve indicating extreme brittleness after being subjected to a repeated tensile stress of 55,000 psi. for 1000 cycles, then 64,500 psi. for 1500 more cycles.

Examination of the detailed tables (VI-VIII) and Fig. 15 shows that in this case of a stress well into the plastic region, almost all of the elongation takes place in the first few cycles. This fact is consistently true in the subsequent tests as well and seems definitely to preclude any chance of obtaining a useful relationship between elongation and cycles of stress.

Fig. 15 also shows a noticeable uniform increase of elongation at about 50 cycles after which the elongation again remains constant. Since this phenomenon did not re-appear in other tests of only slightly different character, it is difficult to speculate on its cause. Some evidence of similar results can be found in "A Study of the Effect of Repeated Loads on Countersunk Riveted Joints" by Lt.Comdr. O. A. Soli, USN and Lieut. W. C. Ditch, USN indicating that it might be worthy of further investigation.

Since the three specimens, Nos. 3, 4, and 5, fractured at widely varying values of stress cycles although they were from the same batch of material and were worked at the same stress, the question arose as to whether there might be internal evidence to indicate the reason. Hence photomicrographs were made of the fractured specimens. Fig. 19 shows the profiles of the fractures and the adjacent grain structure. As might be expected, the fracture profiles show the increase in brittleness with increase in number of applied cycles. However, the grain structures are essentially the same and yielded no clue beyond showing grain orientation in the direction of the applied stress which was to be expected. Fig. 20 is a photomicrograph of the same three specimens in a low stress region and here again is barren of results beyond showing that the grain structure of all are practically identical.

Repeated load tests involving initial cold work:

Specimens 7, 8, and 9, were subjected to 500 cycles each at stresses of 37,500, 43,750, and 50,000 psi. respectively, measuring permanent elongations with the load off as the test proceeded. A repeated stress was then applied at 68,750 psi. on each specimen and carried on until failure. Results of this procedure for these three specimens are plotted in Fig. 16. Examination of this figure shows that for each increment of load the major portion of the elongation is suffered in the first few cycles with gradually increasing elongation as the number of cycles increases. At the higher stress the elongation tends to level off after a few cycles and remain nearly constant until failure. The trend of the curves at the higher stress was obtained from tests 14 and 15 for which more complete data was obtained.

The procedure followed for this series of tests was chosen since it was felt that similar loads might be often encountered in actual aircraft operations, namely that of several application of stresses above but fairly near the proportional limit of the material followed by application of an occasional high stress near the ultimate strength.

The trend of these curves seems to indicate that a certain amount of cold work at a stress just above the proportional limit is beneficial because specimens 8 and 9 withstood many more repeated stresses at the higher stress level than did specimen No. 7.

The amount of initial working and stresses at which the cold working should be carried out to be most beneficial will require further investigation. The results here are analagous to the discussion in Reference 2, of the Bibliography, where it is shown how the endurance limit of a metal can be appreciably raised by cold working at that stress. This series of tests was intended to provide a framework upon which further investigation could be built.

Specimens 10, 11, and 12 were subjected to treatment similar to specimens 7, 8, and 9. Speciman No. 10 was cold worked at 60,000 psi. and then subjected to the same higher stress as that for Nos. 7, 8, and 9. Failure occurred at fewer cycles than either 8 or 9 further substantiating that there is a certain maximum stress level of cold work.

Specimens 11 and 12 were a check on a parameter that was not anticipated but had been observed to have a definite effect during the investigation. This was the effect of "short duration aging" which can be defined as the length of time the material is allowed to rest between overstresses. It entered in the following typical manner: a specimen which was being worked at a high stress well above the proportional limit and having already suffered considerable elongation would withstand several thousand cycles with little or no further elongation and without failure. By interrupting the repeated loading and allowing the material to rest a short period, it invariably failed after reworking a small number of cycles.

With this in mind, specimens 11 and 12 were subjected to 55,500 psi. for 500 cycles. Specimen No. 11 was then immediately subjected to repeated stresses of 68,750 psi. for 5500 cycles without failure. Specimen No. 12 was allowed to age for four days and then subjected to the same repeated stress as No. 11. Failure occurred at 1124 additional cycles.

Future investigations should include a thorough study of this phenomenon of aging. It may also be significant that recovery of the metal in the form of decreasing elongation did not take place during the aging time.

Tests of specimens Nos. 14 and 15 consisted of cold working at stresses above the proportional limit for 1000 cycles instead of 500 cycles in order to investigate the effect of increasing the number of cycles of cold work as compared to specimens Nos. 8 and 9. Cold work was carried out at approximately the same stress as for Nos. 8 and 9 and repeated stress then increased to 64,500 psi. after the 1000 cycles. Specimens Nos. 14 and 15 were from the second batch of material whose ultimate strength was about 3000 psi. less than batch number one. Therefore the stress of 64,500 psi. was considered comparable to the stress of 68,750 psi. used on Nos. 8 and 9. Failure for specimen No. 14 occurred after 4640 total cycles. No. 15 was subjected to a total of 2500 cycles without failure after which a static stress/strain curve was run on it. (Fig. 12). Fig. 18 is a plot showing elongation vs. cycles for specimens 14 and 15. This set of curves shows a trend which will bear further investigation. No. 15, which has a relatively higher elongation after initial cold work, obtained its final elongation upon application of the first few cycles at the higher stress. However, No. 14 which has a lower elongation after initial cold work, gradually obtains its final elongation at the higher stress. Both of these specimens had been aged after the initial cold work and were watched for the effect previously encountered. For these two specimens the detrimental effect was not noticeable.

The authors realize that the test work to date is incomplete and that many blanks are unfilled. However, it is felt that with completion of the testing machine, the development of reliable measuring equipment, and the framework of investigation attempted, the direction in which further profitable investigation has been indicated.

CONCLUSIONS

The following conclusions are obtained from this investigation:

1. That at tensile stresses above the proportional limit on 24ST Aluminum Alloy practically all deformation takes place in the first few cycles of applied stress.

2. That there exists no reasonable relationship between elongation and frequency of stress above the proportional limit which could serve as a useful means of forecasting life of overstressed 24ST Aluminum Alloy as stated in the secondary object of the investigation.

3. That repeated overstressing of 24ST Aluminum Alloy well above the proportional limit causes a change in its properties toward increasing brittleness accompanied at the same time by a raising of the proportional limit and yield stress.

4. That repeated stressing of 24ST Aluminum Alloy at and slightly above the proportional limit increases its life expectancy at repeated loads at higher stresses.

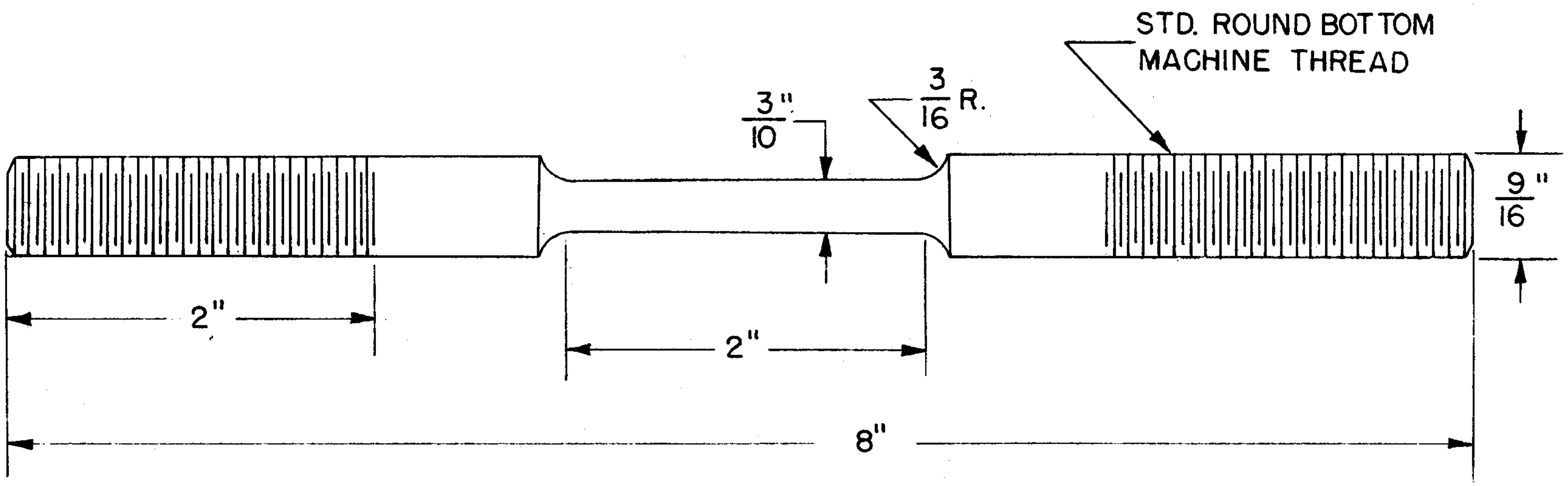
5. That the effects of aging, initial cold work, and magnitude of overstresses applied all have definite influence on the ability of 24ST Aluminum Alloy to withstand further overstressing and should be more fully investigated.

6. That the study of the fatigue of aluminum alloys when worked above the proportional limit, even if only occasionally, is a large and complicated field which will require exhaustive investigation before it can be hoped to use life expectancy as a criterion in airplane design.

BIBLIOGRAPHY

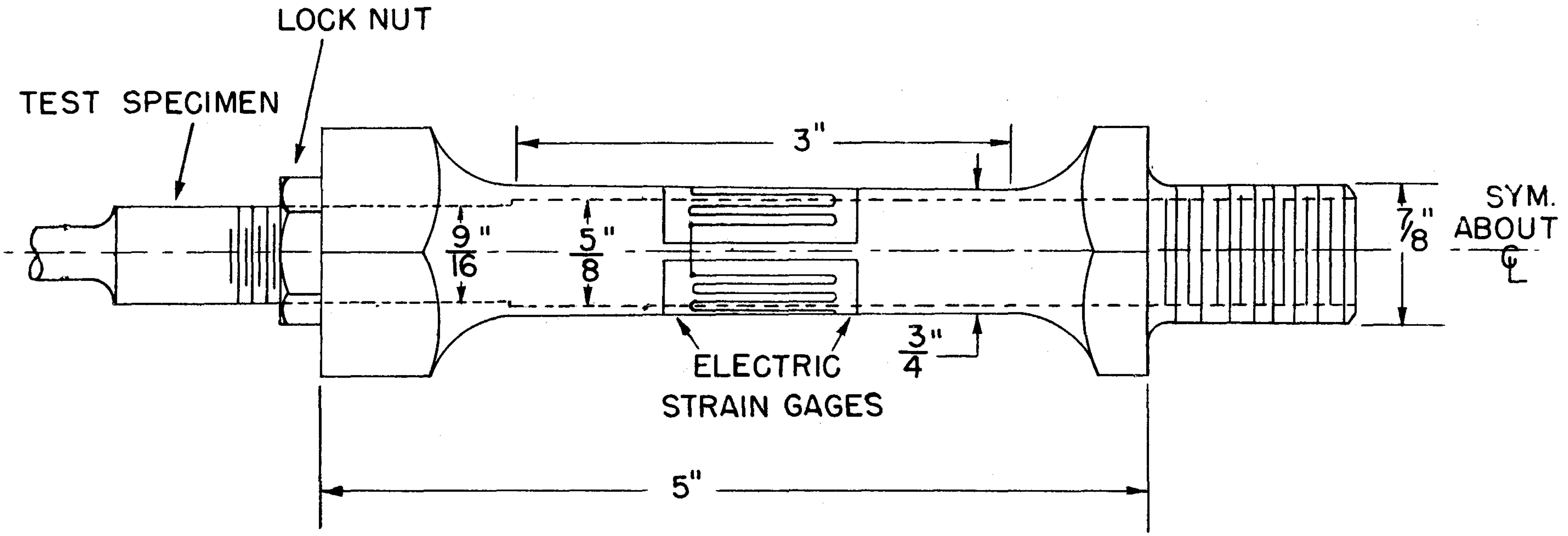
1. "The Deformation, Recovery and Recrystallization Behavior of Metals", Journal of the Aeronautical Sciences, Vol. 3, No. 6, April, 1936, by Dr. R. H. Hobrock, of the Daniel Guggenheim Airship Institute.
2. "Prevention of the Failure of Metals Under Repeated Stress", by the staff of Battelle Memorial Institute, 1941.
3. "Factors Influencing the Fatigue Strength of Materials", by F. Bollenrath, (N.A.C.A. Technical Memorandum No. 987).
4. "The Direct-Stress Fatigue Strength of 17S-T Aluminum Alloy", by E. C. Hartmann and G. W. Stickley, Aluminum Company of America, (N.A.C.A. Technical Note No. 865).
5. "Improvement of Fatigue Life of an Aluminum Alloy by Overstressing", by G. W. Stickley, Aluminum Company of America, (N.A.C.A. Technical Note No. 857).
6. "Evidence on the State of Fatigue of Metals Obtained from an Examination of the Surface Stresses by Means of X-Rays", by Glocker and Others, (R.T.P. Translation No. 1371).
7. "The Influence of Impact Velocity on the Tensile Characteristics of Some Aircraft Metals and Alloys", by Dr. D. S. Clark, California Institute of Technology, (N.A.C.A. Technical Note No. 868).
8. "Research on the Fatigue of Metals", by Dr. R. Cazaud, June 1930.
9. "A Correlation of Repeated Tension Impact Tests with Other Tension Tests of 17ST Duralumin", by Lt.Comdrs. E. S. Lee, Jr., and C. W. Stirling, U.S. Navy.
10. "A Study of the Effect of Repeated Tension Impact Loads upon Certain Metals Used in Aircraft Construction", by W. E. Gentner and J. O. Biglow.
11. "Some Fundamentals of the Flow and Rupture of Metals", by George Sachs.
12. "Effect of Alternately High and Low Repeated Stresses upon the Fatigue Strength of 24ST Aluminum Alloy", by G. W. Stickley, (N.A.C.A. Technical Note No. 792).
13. "Metal Fatigue and Methods for Its Measurement", by Dr. R. Cazaud, July 1934.
14. "A study of the Effects of Repeated Tension Impact Loads upon Certain Metals Used in Aircraft Construction", by Lt.Comdr. C. B. Olsen, U.S.C.G. and Lieut. S. W. Brown, U.S.N.

FIGURES



TEST SPECIMEN

FIG. 1



LOAD MEASURING COUPON

FIG. 2

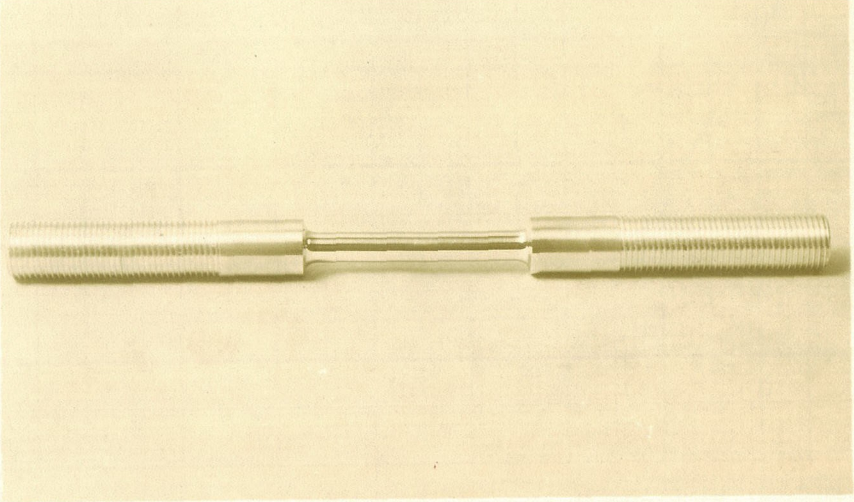


Fig. 3
Test Speciman

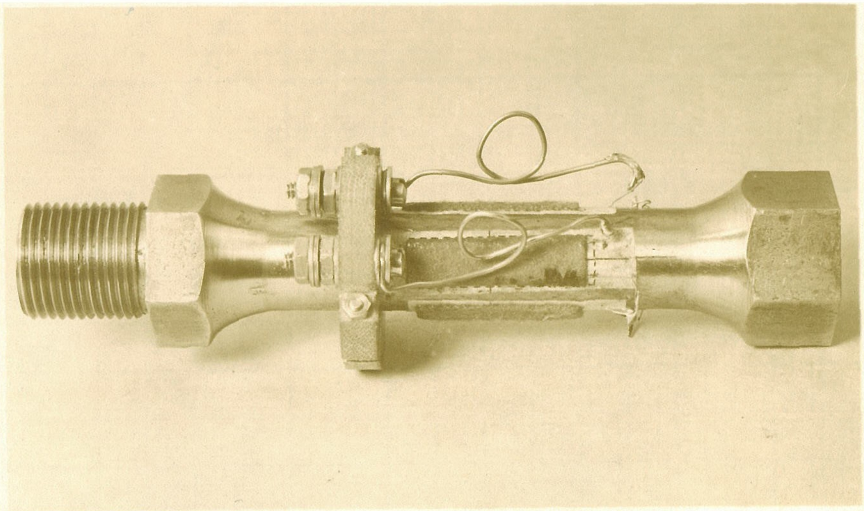
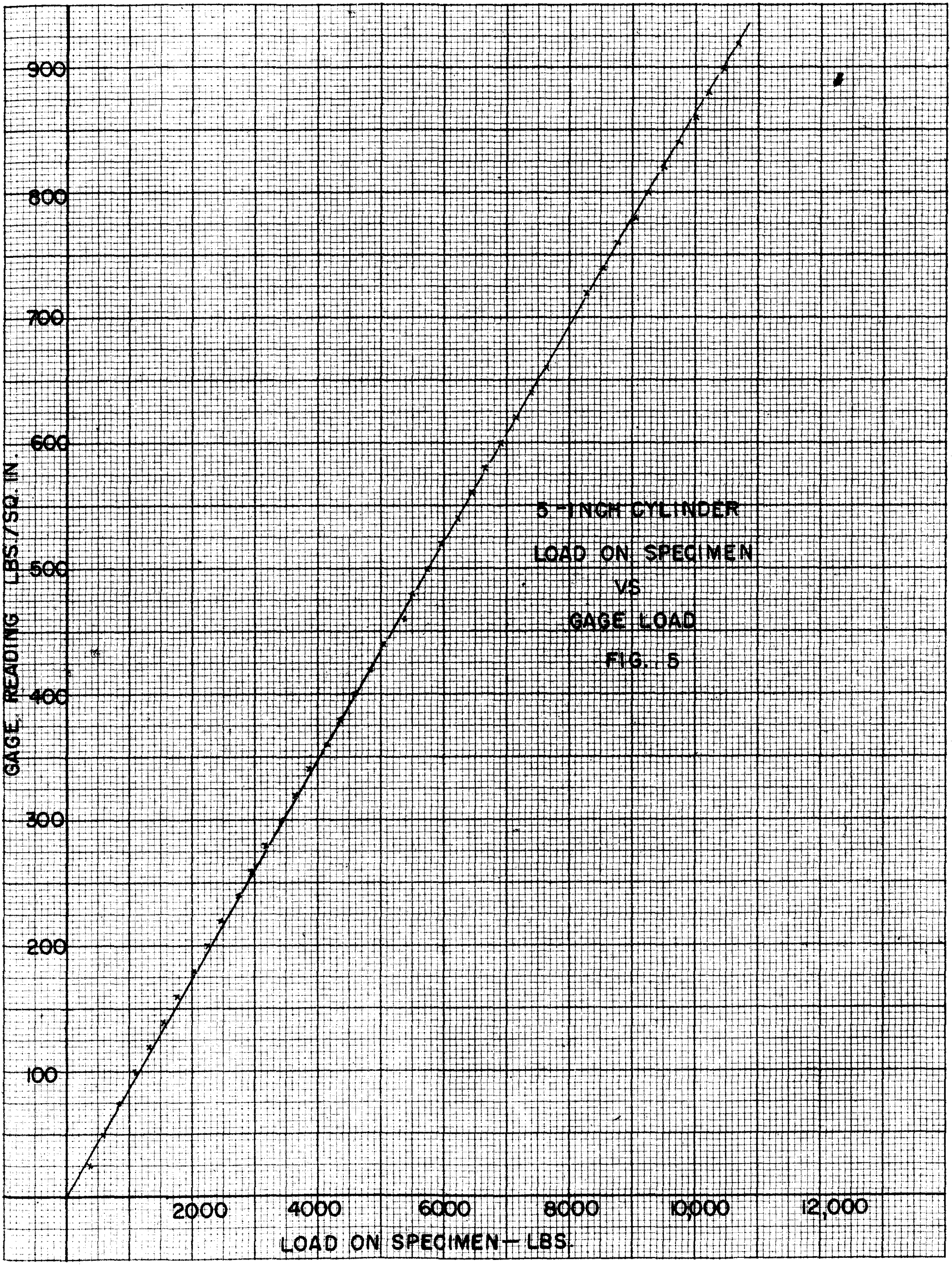
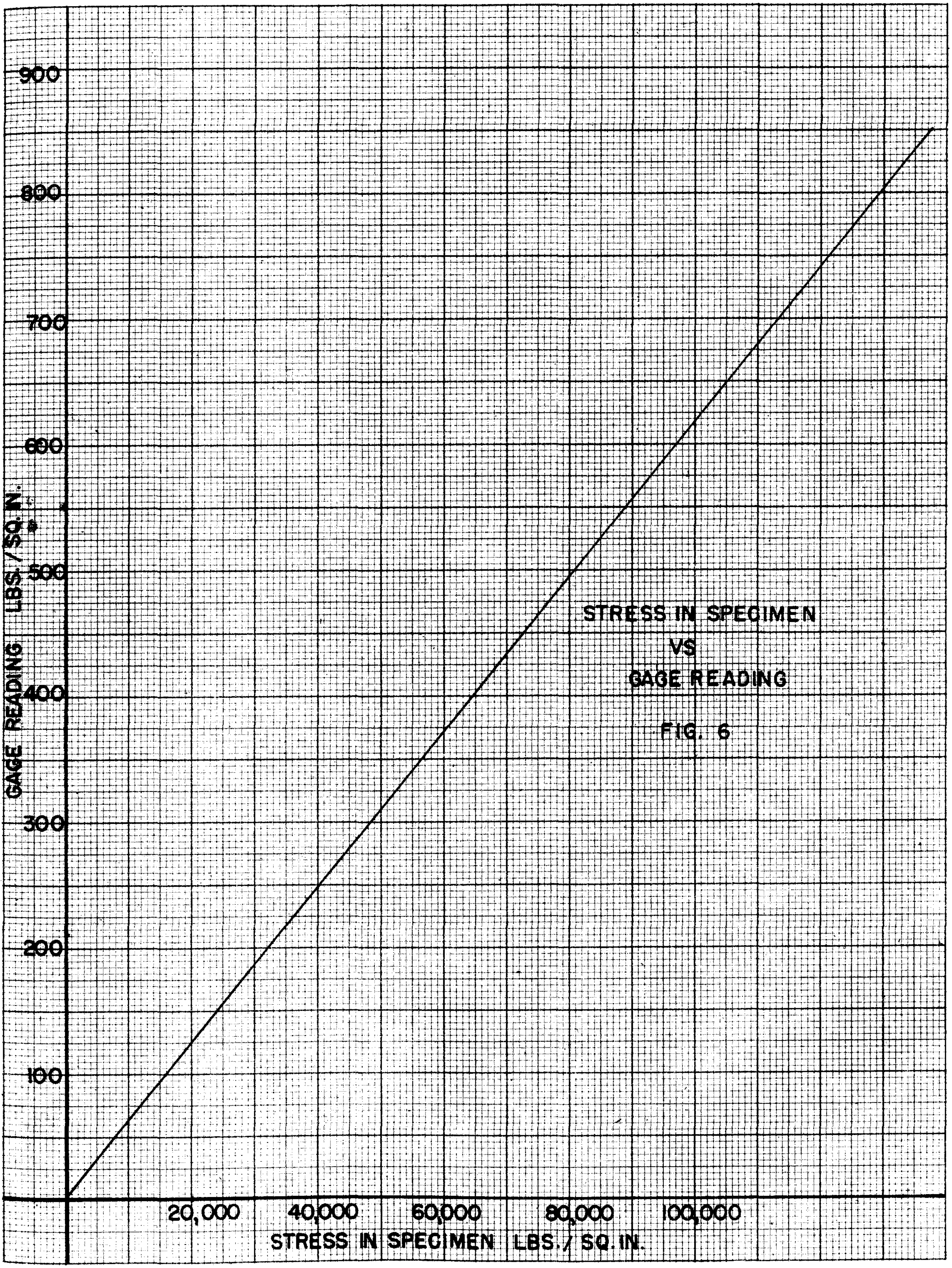


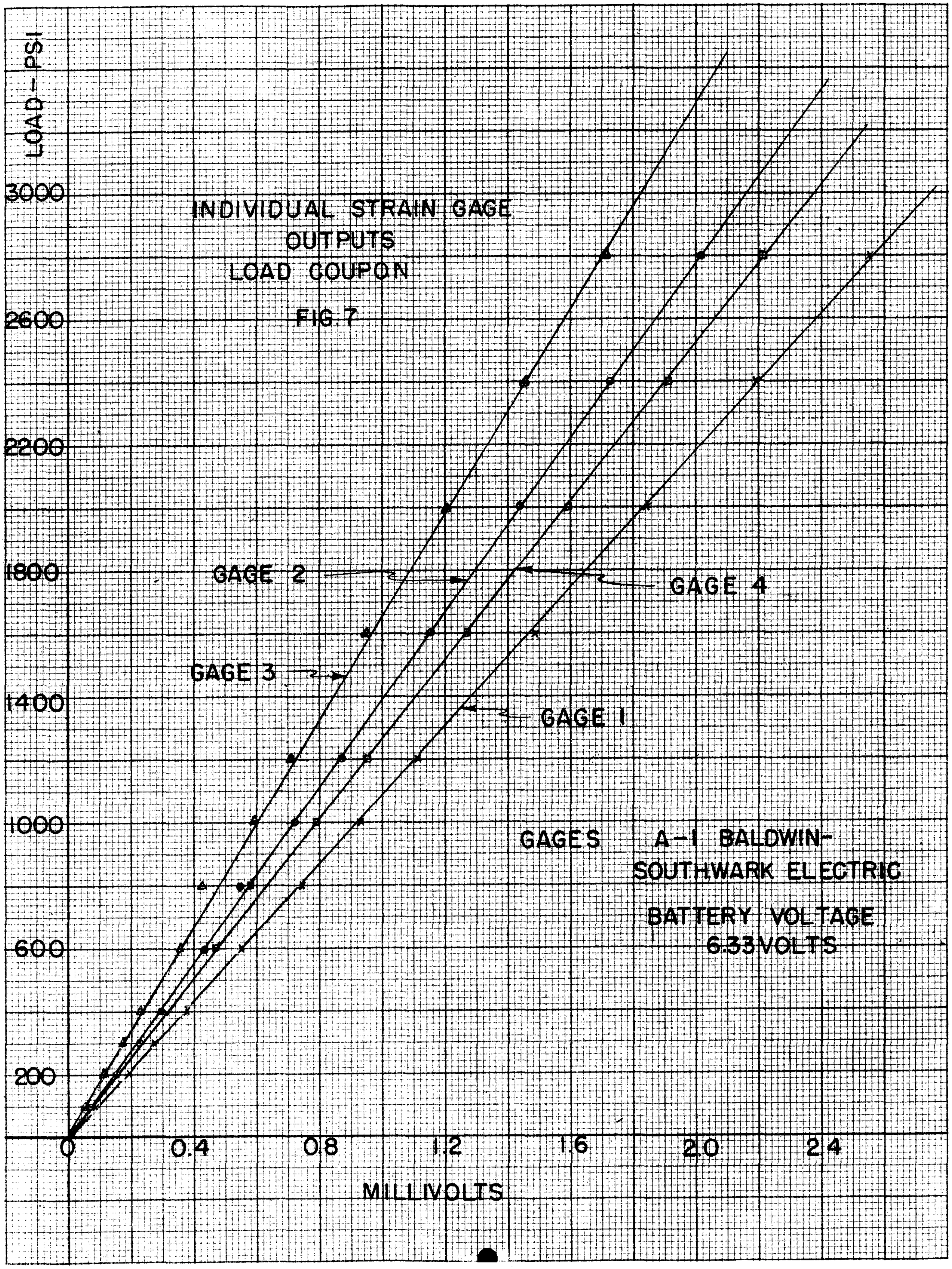
Fig. 4
Load Coupon


5-INCH CYLINDER
LOAD ON SPECIMEN
VS
GAGE LOAD
FIG. 5
GAGE READING LBS./SQ. IN.
900
800
700
600
500
400
300
200
100
2000
4000
6000
8000
10,000
12,000
LOAD ON SPECIMEN— LBS.



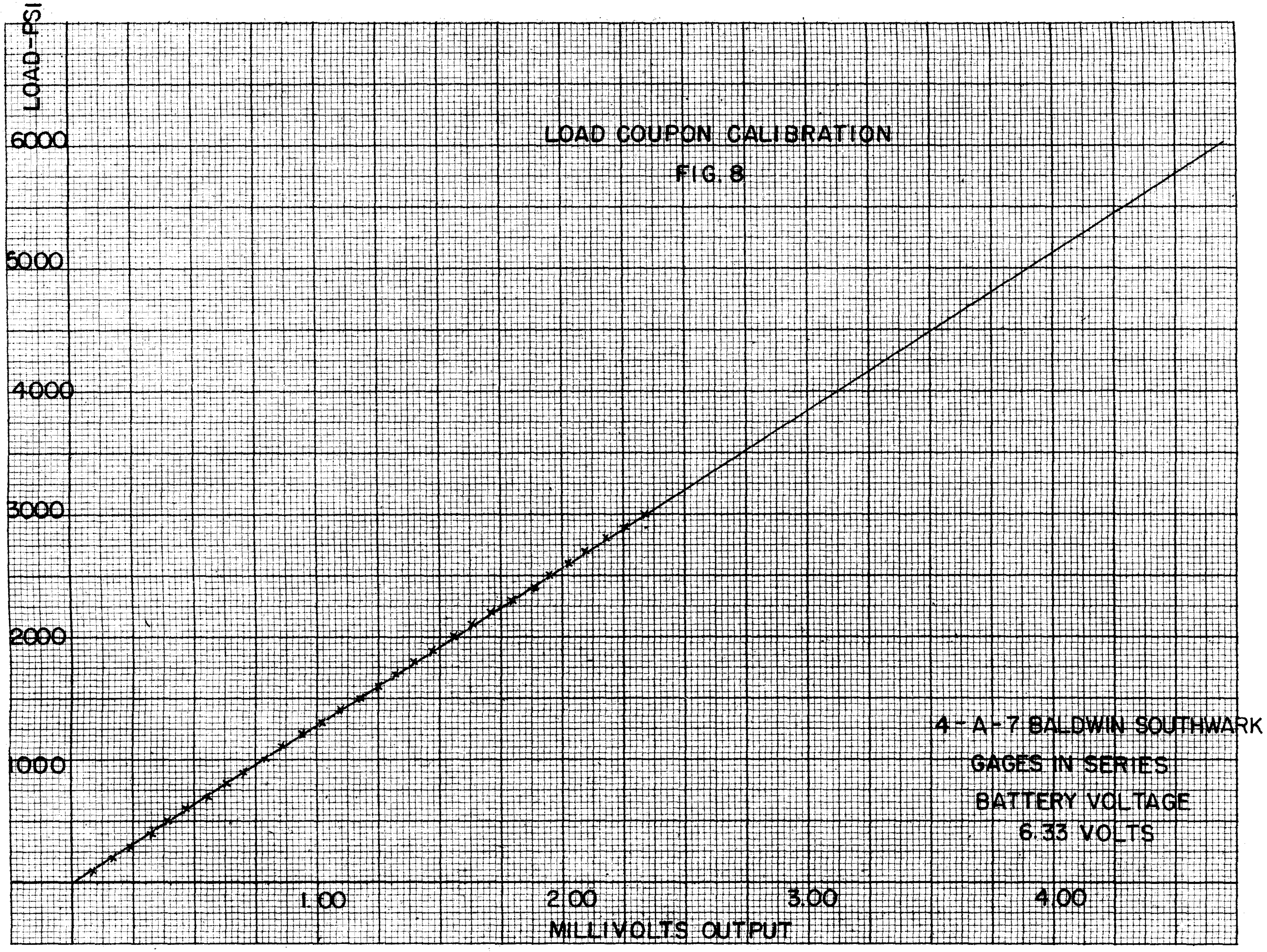
STRESS IN SPECIMEN
VS
GAGE READING

FIG. 6



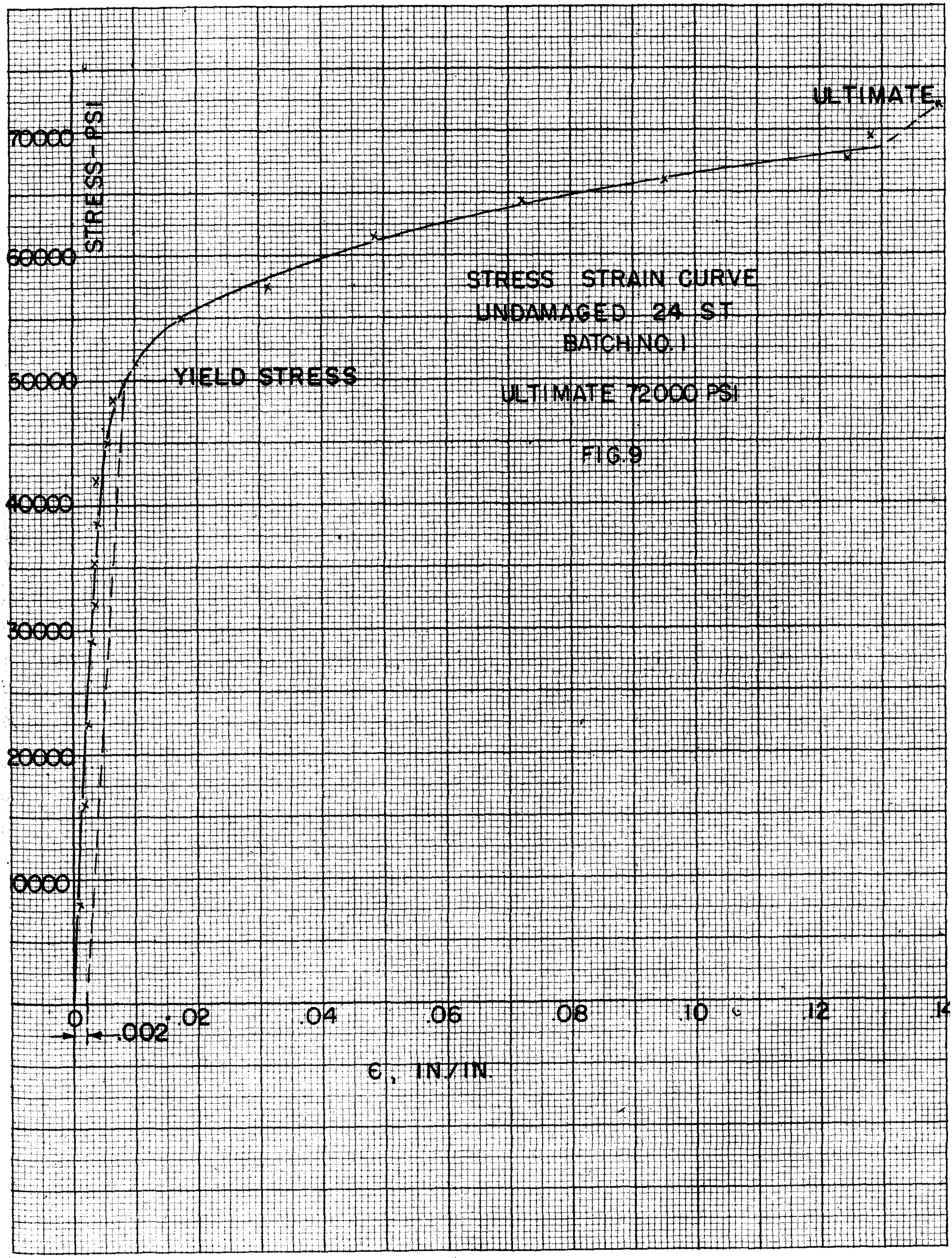
INDIVIDUAL STRAIN GAGE OUTPUTS
LOAD COUPON

FIG. 7



LOAD COUPON CALIBRATION

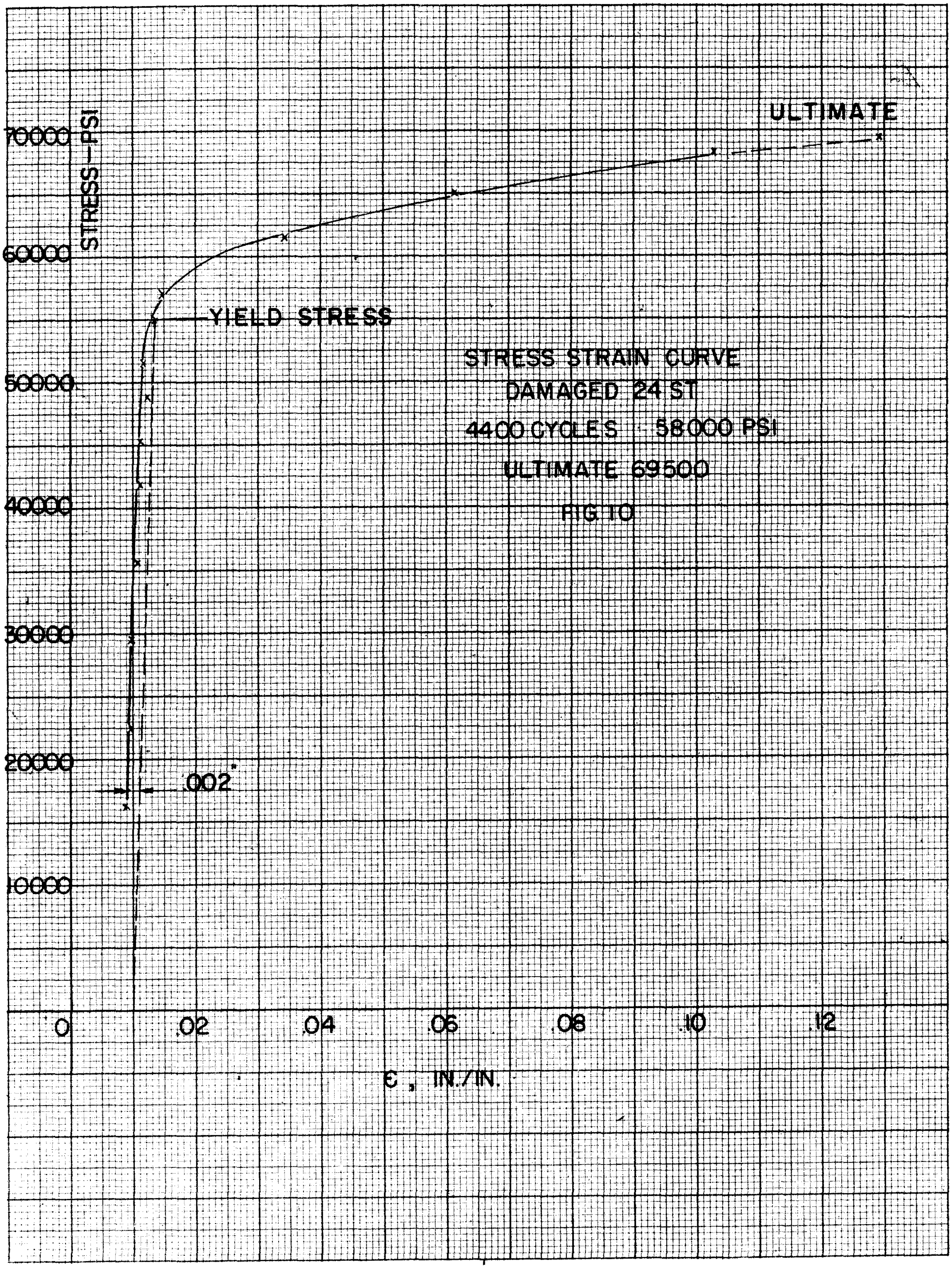
FIG. 8



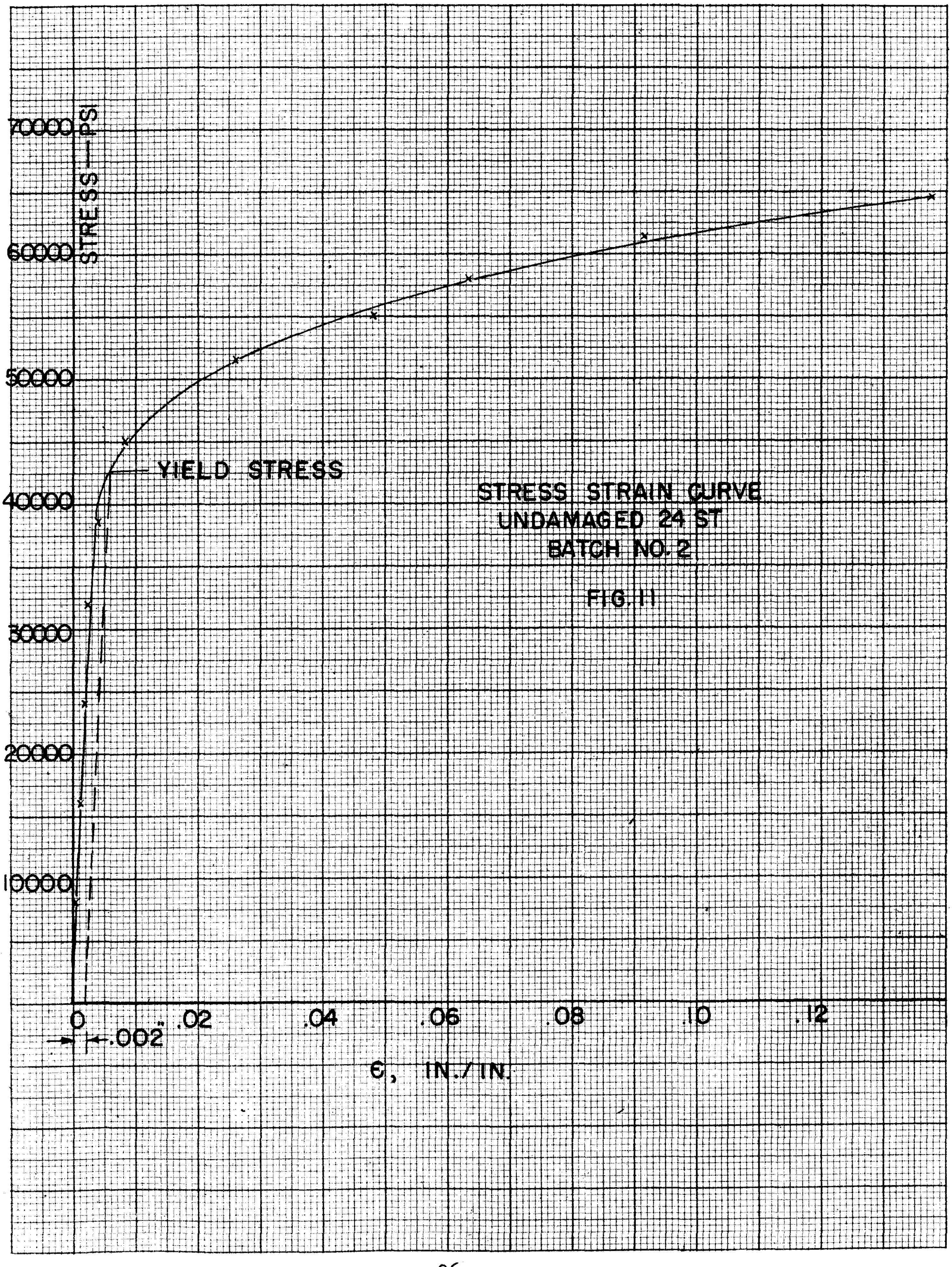
STRESS STRAIN CURVE
UNDAMAGED 24 ST
BATCH NO. 1

ULTIMATE 72000 PSI

FIG. 9

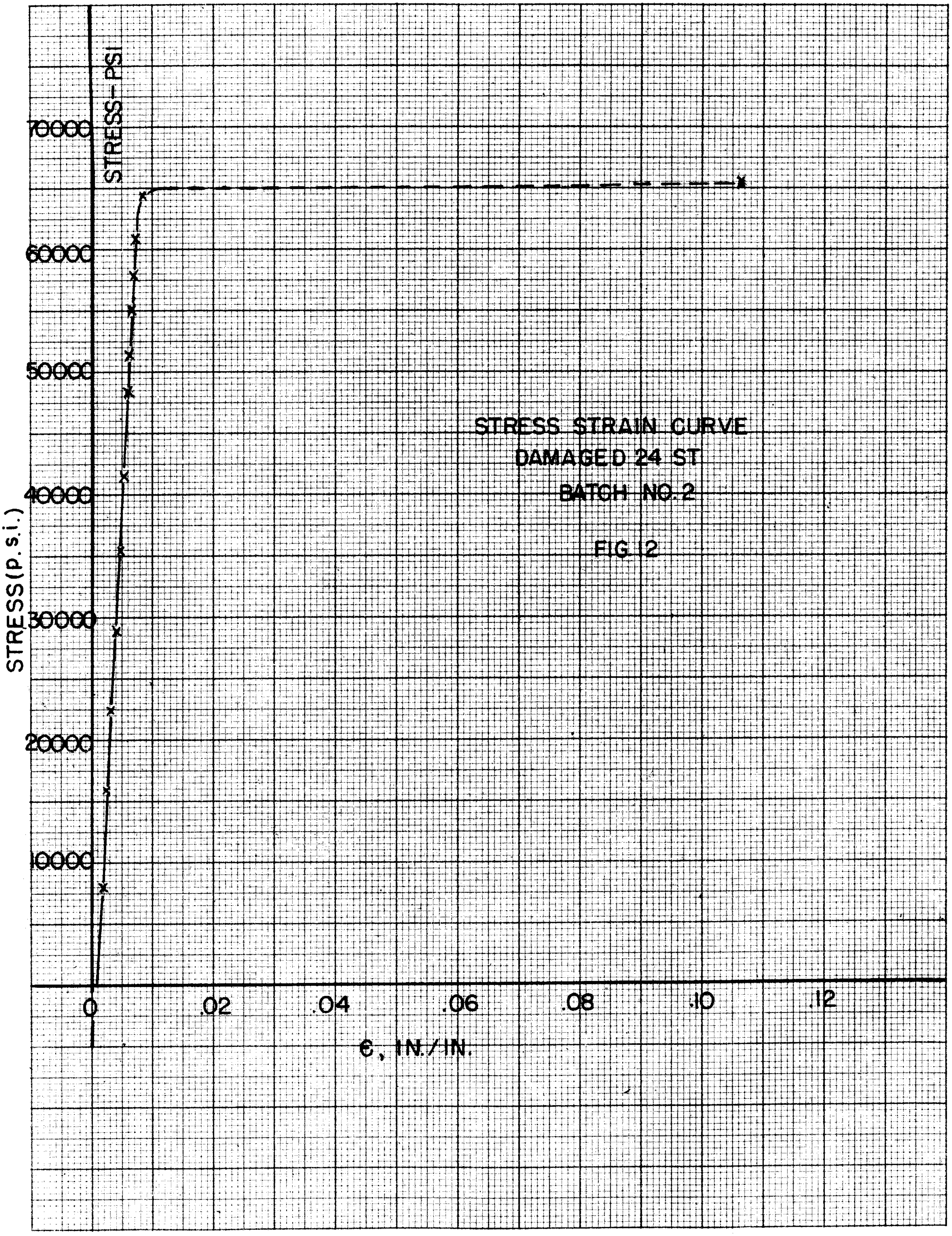


STRESS STRAIN CURVE
DAMAGED 24 ST
4400 CYCLES 58000 PSI
ULTIMATE 69500
FIG 10



STRESS STRAIN CURVE
UNDAMAGED 24 ST
BATCH NO. 2

FIG. 11



STRESS STRAIN CURVE
DAMAGED 24 ST
BATCH NO. 2

FIG 12

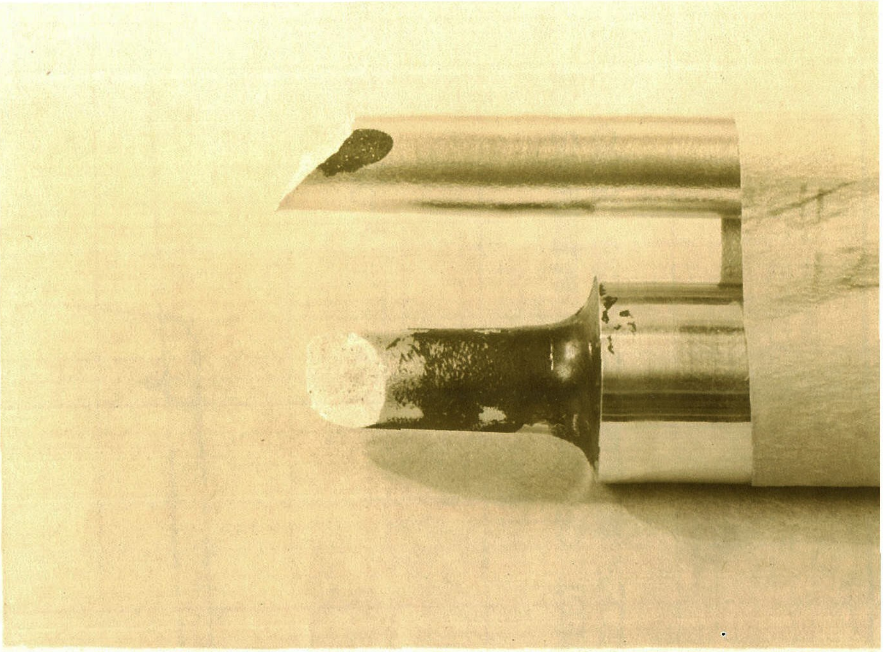


FIG. 13

Photograph of Fractured Speciman
No. 12 Showing Failure in Shear.

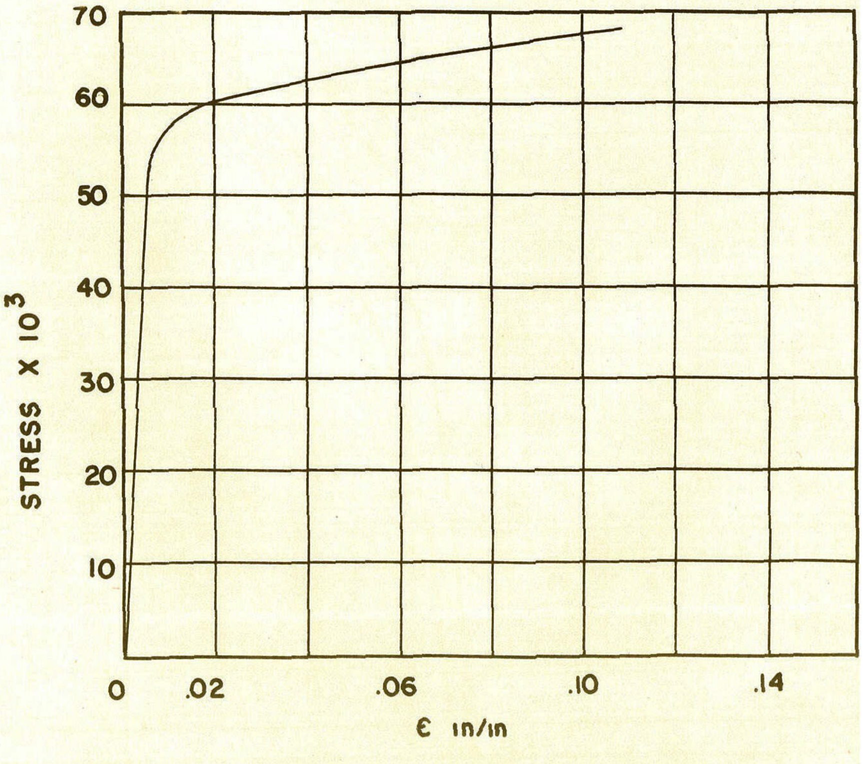


FIG. 14
DAMAGED 24 ST

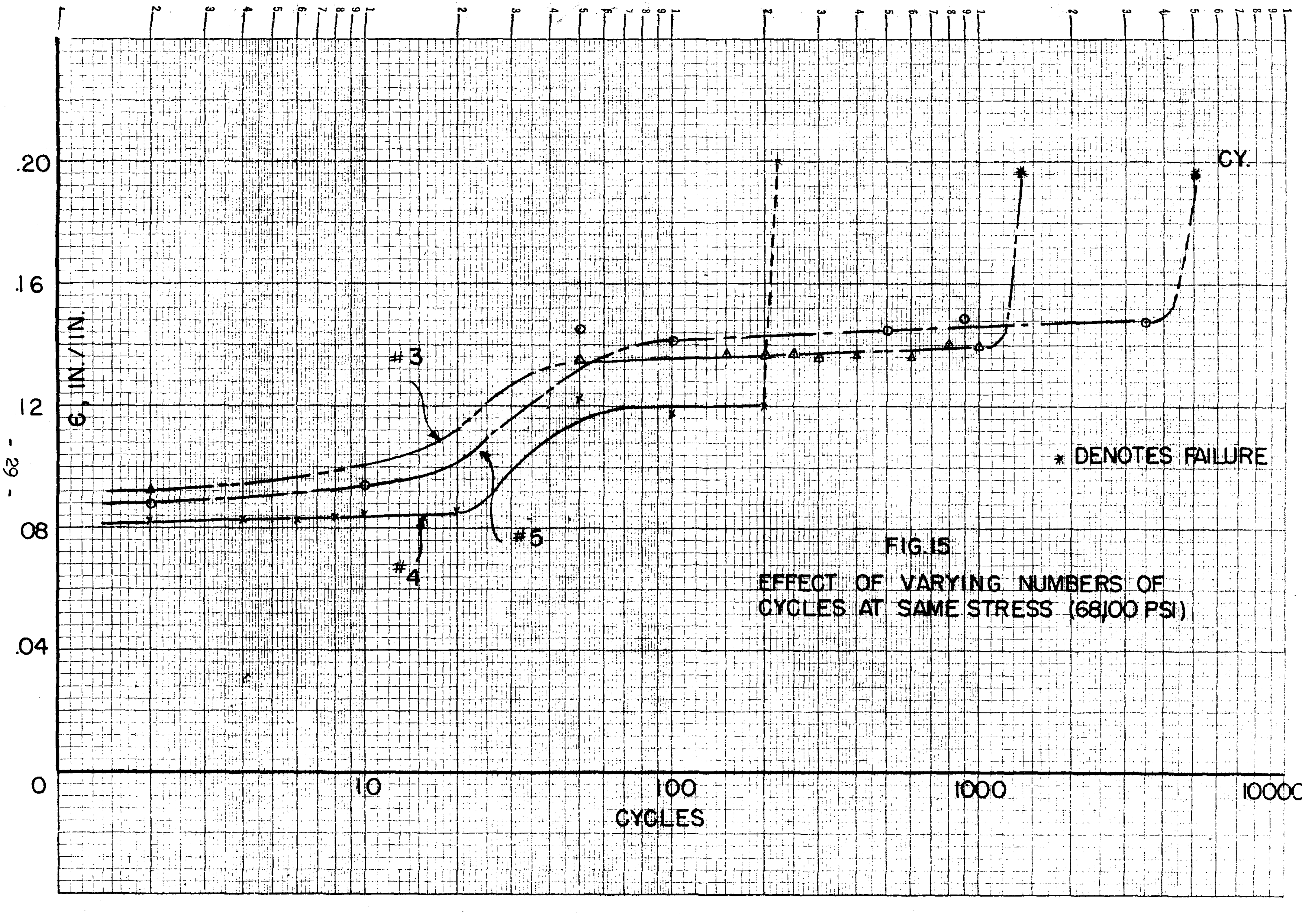


FIG.15

EFFECT OF VARYING NUMBERS OF CYCLES AT SAME STRESS (68,100 PSI)

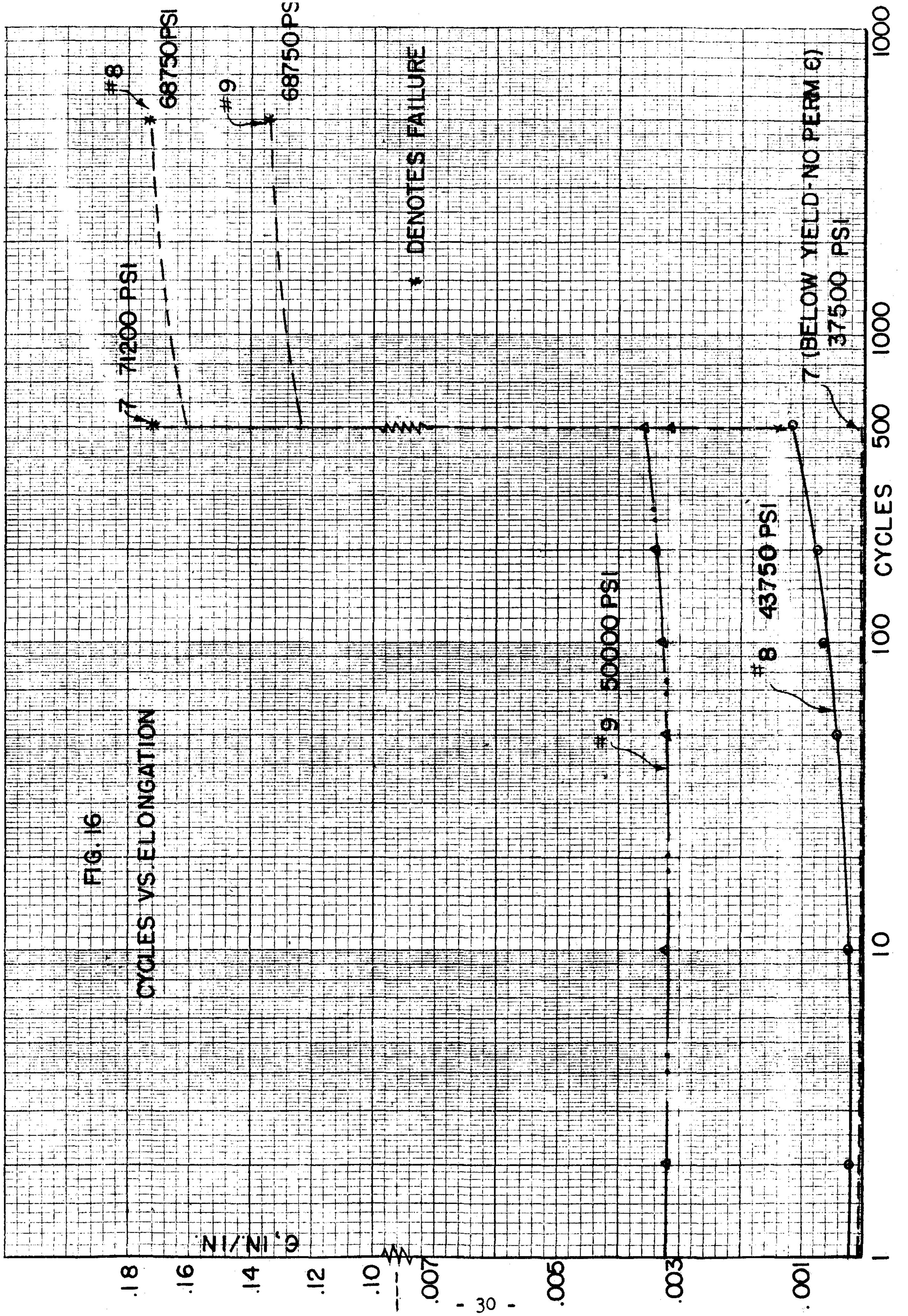
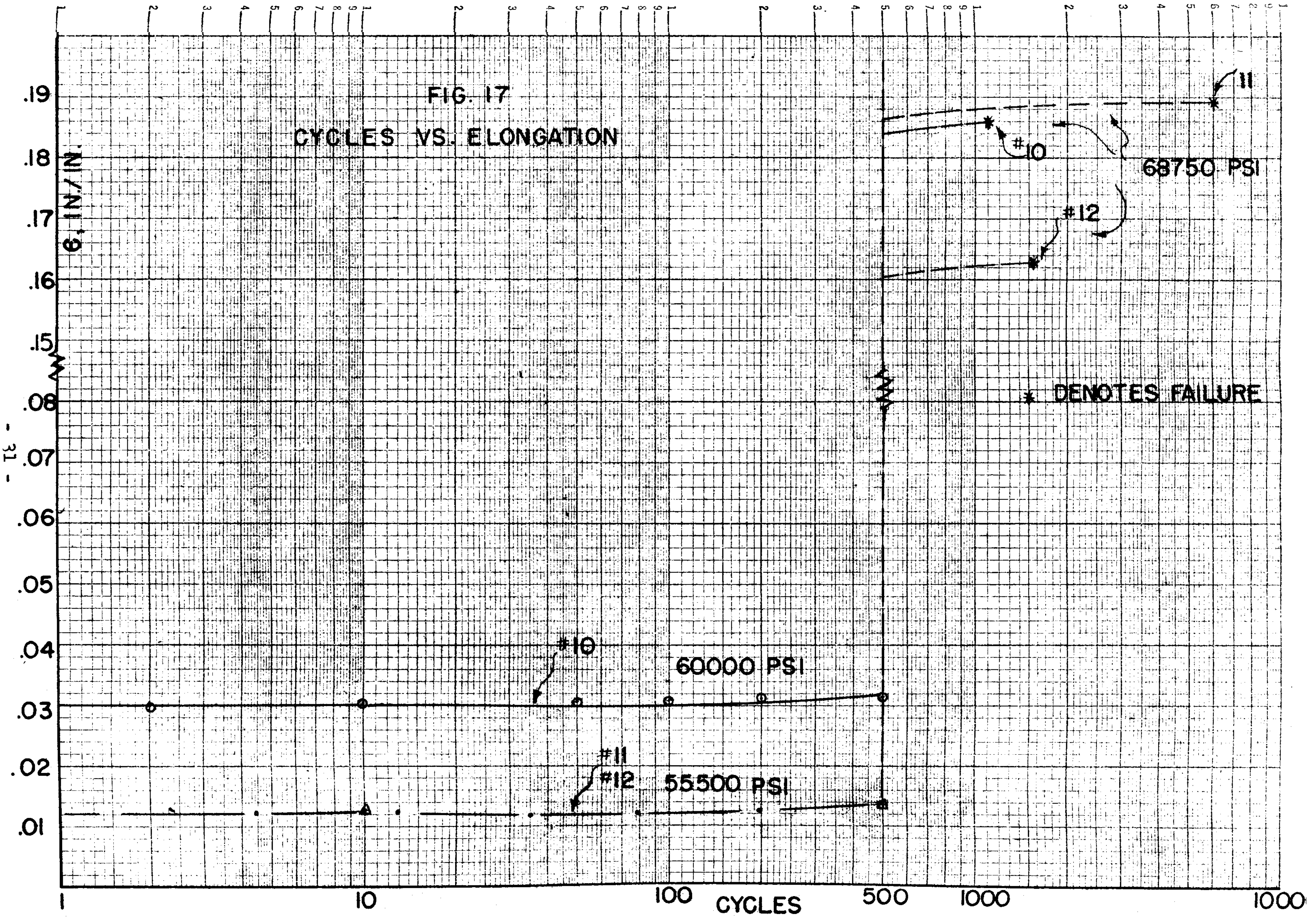


FIG. 16

CYCLES VS. ELONGATION

FIG. 17

CYCLES VS. ELONGATION



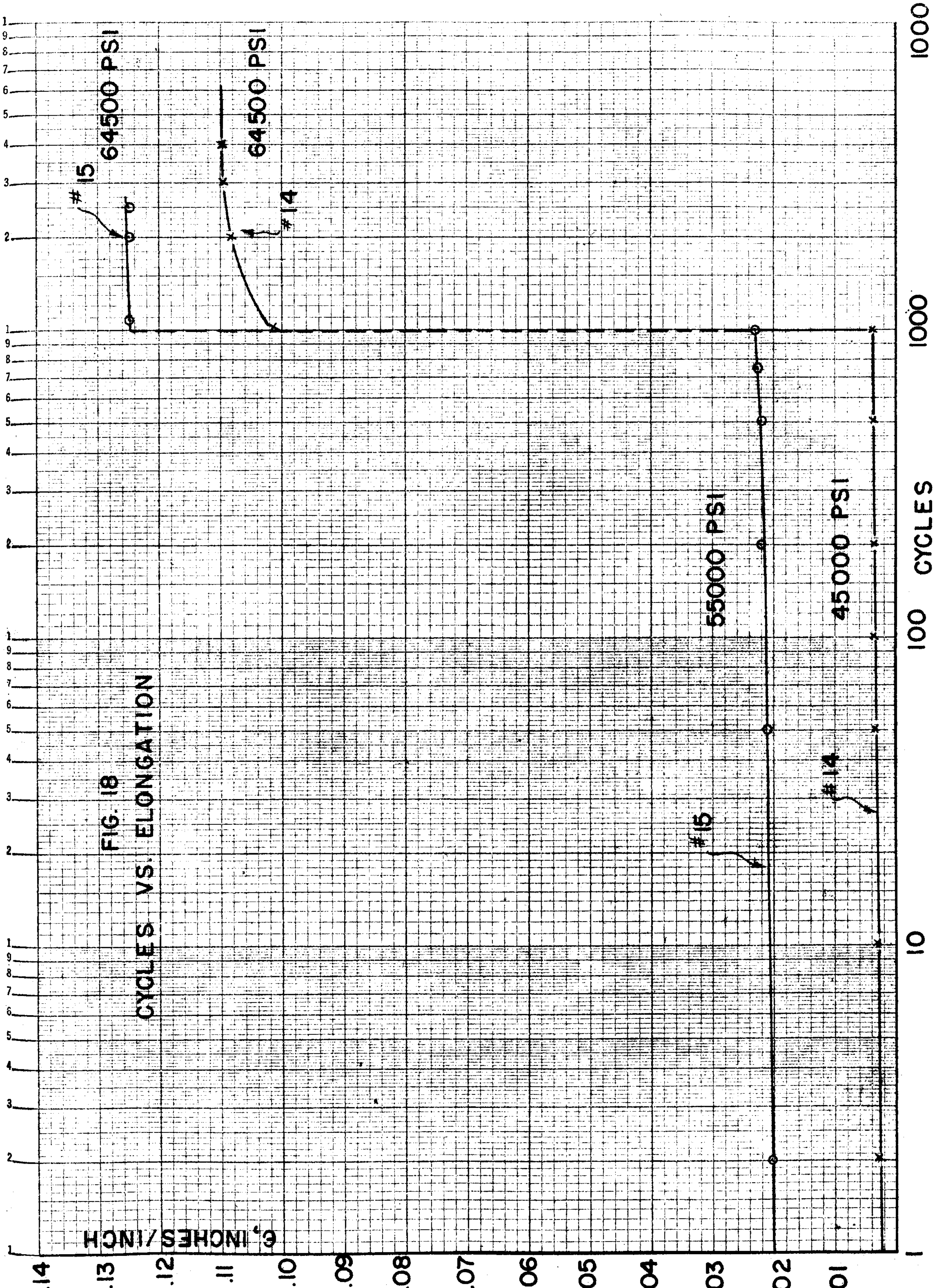
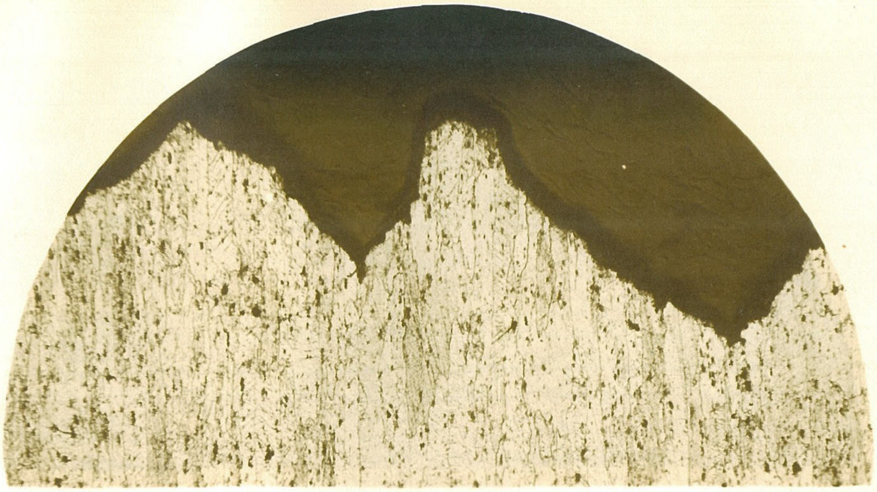
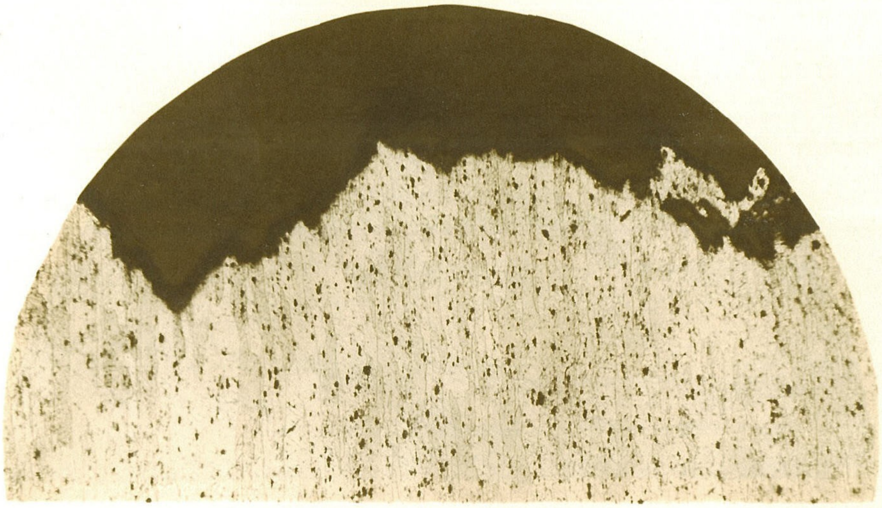


FIG. 18

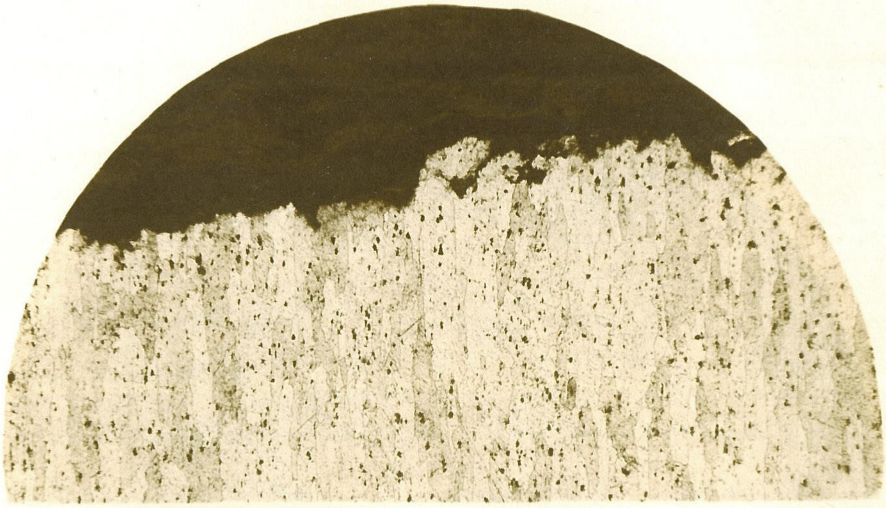
CYCLES VS. ELONGATION



No. 4
(220 cycles)



No. 3
(1200 cycles)



No. 5
(4050 cycles)

Fig. 19
Effect of Varying Numbers of Cycles
at Same Stress (68,100 p.s.i.)
Mag. 50 dia. Etch: Keller

FIG. 21

SCHEMATIC DIAGRAM OF ELECTRICAL LOAD MEASURING APPARATUS

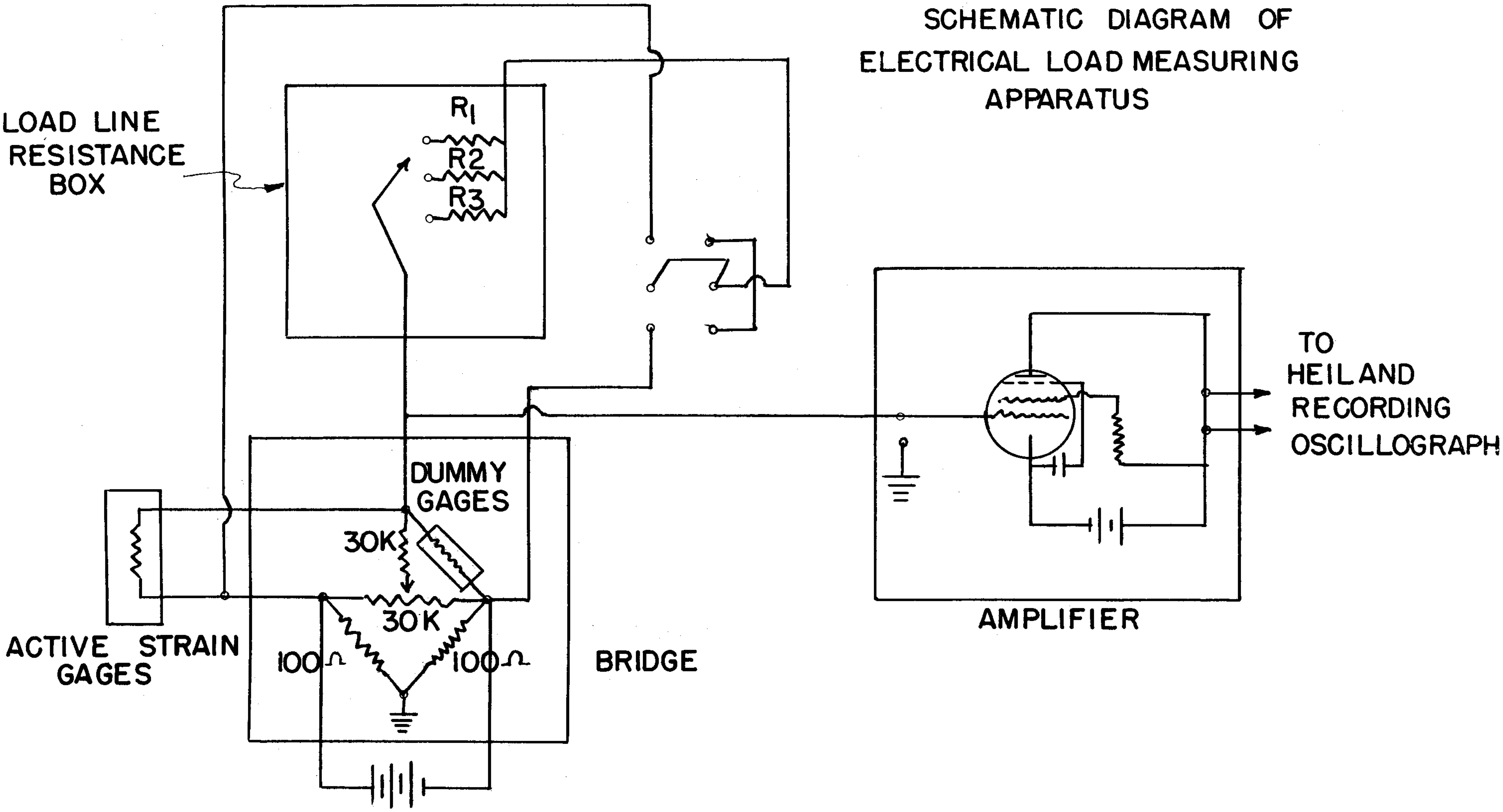
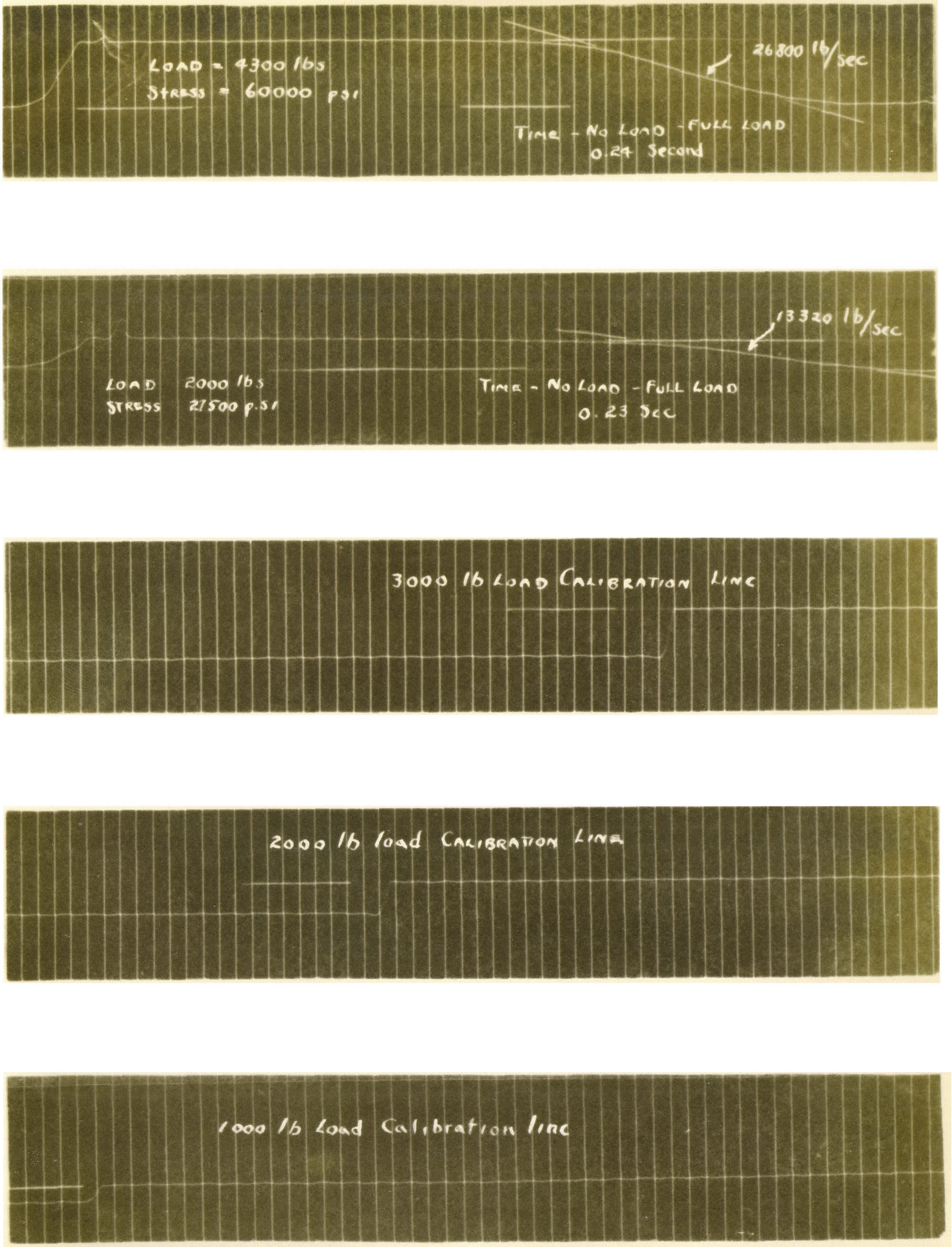


FIG. 22


LOAD = 4300 lbs
STRESS = 60000 psi
26800 lb/sec
TIME - NO LOAD - FULL LOAD
0.24 Second
LOAD 2000 lbs
STRESS 21500 p.s.i
13320 lb/sec
TIME - NO LOAD - FULL LOAD
0.23 Sec
3000 lb LOAD CALIBRATION LINE
2000 lb load CALIBRATION LINE
1000 lb Load Calibration line

TABLES

TABLE I

Calibration of Pressure Gage

Gage	Load	Gage	Load
0	0	520	5950
25	380	540	6210
50	590	560	6440
75	830	580	6660
100	1090	600	6900
120	1310	620	7140
140	1540	640	7390
160	1770	660	7620
180	2020	680	No reading
200	2260	700	No reading
220	2490	720	8290
240	2730	740	8520
260	2950	760	8770
280	3170	780	9030
300	3420	800	9250
320	3650	820	9500
340	3870	840	9710
360	4150	860	10,000
380	4350	880	10,200
400	4580	900	10,450
420	4820	920	10,670
440	5040	940	10,900
460	5380	960	11,150
480	5500	980	11,390
500	5740	.000	11,650

TABLE II

Static Stress Strain Test of Undamaged 24 ST

(First Batch)

Load (psi)	Stress (psi)	Length (In.)	Unit Elong. (in/in)
0	0	2.000	0
50	8,000	2.0021	.0010
100	16,000	2.0038	.0019
140	22,500	2.0045	.0022
180	29,000	2.0060	.0030
200	32,000	2.0071	.0035
220	35,500	2.0072	.0036
240	38,500	2.0081	.0040
260	42,000	2.0076	.0038
280	45,000	2.0115	.0057
300	48,500	2.0133	.0066
320	51,500	2.0202	.0101
340	55,000	2.0348	.0174
360	58,000	2.0622	.0311
380	61,400	2.0968	.0484
400	64,500	2.1444	.0722
410	66,000	2.1700	.0850
420	67,800	2.2493	.1246
430	69,500	2.2558	.1279
440	71,000	No Reading	Failure

TABLE III

Static Stress Strain Test of Damaged 24 ST
(First Batch)

Gage Read (psi)	Stress (psi.)	Length (In.)	Unit Elong.
0	0	1.9968	
100	16,230	2.0146	.0089
140	22,500	2.0155	.0094
180	29,400	2.0165	.0099
220	35,600	2.0178	.0105
260	41,900	2.0190	.0111
280	45,200	2.0189	.0111
300	48,800	2.0211	.0121
320	51,500	2.0201	.0117
340	55,000	2.0235	.0134
360	57,000	2.0258	.0145
380	61,500	2.0656	.0344
400	65,000	2.1195	.0614
420	68,200	2.2023	.1028
430	69,500	Failure	

TABLE IV

Static Stress Strain of Undamaged 24 ST

(New Batch)

Load (psi)	Stress (psi)	Length (in.)	Unit Elong. (in/in)
0	0	2.0008	0
50	8,000	2.0017	.0004
100	16,000	2.0033	.0012
150	24,000	2.0047	.0019
200	32,000	2.0055	.0023
240	38,500	2.0088	.0040
280	45,000	2.0176	.0084
320	51,500	2.0568	.0260
340	55,000	2.0973	.0482
360	58,000	2.1278	.0635
380	61,400	2.1841	.0916
400	64,500	2.2768	.1380
410	66,000	2.3225	.1608
Failure			

TABLE IVa

Static Stress Strain of Damaged 24 ST

(New Batch)

Load (psi)	Stress (psi)	Length (in.)	Unit Elong. (in/in)
0	0	2.2517	0
50	8,000	2.2569	.0021
100	16,000	2.2579	.0025
140	22,500	2.2596	.0031
180	28,800	2.2620	.0041
220	35,500	2.2637	.0048
260	41,700	2.2647	.0052
300	48,500	2.2678	.0064
320	51,500	2.2678	.0064
340	55,000	2.2685	.0067
360	58,000	2.2692	.0070
380	61,000	2.2697	.0072
400	64,500	2.2732	.0085
405*	65,300	2.3585	.1068

* Failure

TABLE NO V

RECORD OF TESTS

SPEC. NO.	INITIAL TREATMENT			STRESS PSI	CYCLES	FAILURE	ε IN./IN.	FURTHER TREATMENT					SUBSEQUENT TREATMENT	REMARKS
	INITIAL CYCLES	STRESS	PERM. ε IN./IN.					AGING TIME	CYCLES	STRESS PSI	FAILURE	ε IN./IN.		
1														STATIC STRESS STRAIN TEST (FIG. 9)
2														UNSUCCESSFUL ATTEMPT TO MEASURE ELONGATION ON SPECIMEN USING A-7 ELECTRIC STRAIN GAGES
2a	NONE			58000	4400	NO							AGED 7 DAYS	STATIC STRESS STRAIN (FIG. 10)
3	NONE			68100	1200	YES	.1937					.1937	PHOTO-MICROGRAPH	
4	NONE			68100	220	YES	.2019					.2019	"	
5	NONE			68100	4000	NO	.1470	1 DAY	50	68100	YES	.1942	"	
6	NONE			72750	1	YES	.1743					.1743		LOADED SLIGHTLY ABOVE ULTIMATE — FAILURE AT ONE CYCLE
7	500	37500	NONE	71200	2	YES	.1762							
8	500	43750	NONE	68750	4500	NO	.135	1 HOUR	8	68750	YES	NO READING		ONE HOUR ELAPSED TIME AFTER 5000 CYCLES BEFORE CONTINUING.
9	500	50000	.0036	68750	4500	NO	.132	2 DAYS	1	68750	YES	.2057		AGED 1 DAY AFTER 4000 CYCLES AGED 2 DAYS AFTER 5000 CYCLES
11	500	55500	.0142	68750	5500	NO	.189							CHECK OF STRESS AT 5000 CYCLES SHOWED A DROP OF APPROX. 1000 PSI, AFTER RESTORATION TO 68750, FAILURE ACCURED IMMEDIATELY
12	500	55500	.0146					4 DAYS	1124	68750	YES	.163		NO APPRECIABLE RECOVERY OF ELONGATION AFTER AGING
10	500	60000	.0317	68750	650	NO	.153	2 DAYS	1	68750	YES	.186		AGED 2 DAYS AFTER 1150 CYCLES
13														STRESS STRAIN TEST, SECOND BATCH UNDAMAGED
14	1000	45000	.0039					1 DAY	3640	64500	YES	.149		
15	1000	55000	.0328					2 DAYS	1500	64500	NO	.125	STRESS STRAIN CURVE	STRESS STRAIN CURVE OF DAMAGED MATERIAL (FIG. 12)

TABLE VI

SPEC. NO. 3 MATERIAL: 24 ST

Cycles	Stress (p.s.i.)	Length (in.)	Unit. Elong. in./in.
0	0	1.9981	0
50	68,100	2.2720	.1369
100	68,100	2.2695	.1357
150	68,100	2.2724	.1371
200	68,100	2.2716	.1368
250	68,100	2.2759	.1389
300	68,100	2.2733	.1376
400	68,100	2.2753	.1386
600	68,100	2.2754	.1387
800	68,100	2.2779	.1399
1000	68,100	2.2760	.1390
*1200	68,100	2.3855	.1937

Remarks: * Failure

TABLE VII

SPEC. NO. 4 MATERIAL: 24 ST

Cycles	Stress (p.s.i.)	Length (in.)	Unit Elong. in./in.
0	0	2.0040	0
2	54,500	2.1653	.0806
4	54,500	2.1692	.0826
6	54,500	2.1702	.0831
10	54,500	2.1726	.0843
20	54,500	2.1694	.0827
50	54,500	2.2464	.1212
100	54,500	2.2398	.1179
200	54,500	2.2452	.1206
*220	54,500	2.4038	.2019

Remarks: * Failure

TABLE VIII

SPEC. NO. 5 MATERIAL: 24 ST

Cycles	Stress (p.s.i.)	Length (in.)	Unit Elong. in./in.
0	0	1.9987	0
2	68,100	2.1761	.0887
10	68,100	2.1900	.0957
50	68,100	2.2905	.1459
100	68,100	2.2828	.1421
500	68,100	2.2880	.1447
924	68,100	2.2920	.1467
3500	68,100	2.2951	.1482
4000	68,100	2.2927	.1470
*4050	68,100	2.3871	.1942

Remarks: * Failure

TABLE IX

SPEC. NO. 6 MATERIAL: 24 ST

Cycles	Stress (p.s.i.)	Length (in.)	Unit Elong. in./in.
0	0	2.0041	0
1	72,800	2.3528	.1743

Remarks: Failure at first application of load. This run served only to re-check the ultimate strength of this material.

TABLE X

SPEC. NO. 7 MATERIAL: 24 ST

Cycles	Stress (p.s.i.)	Length (in.)	Unit Elong. in./in.
0	0	1.9959	0
2	37,500	1.9959	0
10	37,500	1.9959	0
50	37,500	1.9959	0
500	37,500	1.9959	0
*502	71,200	2.3485	.1678

Remarks: * Failure

TABLE XI

SPEC. NO. 8 MATERIAL: 24 ST

Cycles	Stress (p.s.i.)	Length (in.)	Unit Elong. in./in.
0	0	2.0021	0
2	43,750	2.0026	.00025
10	43,750	2.0027	.0003
50	43,750	2.0031	.0005
100	43,750	2.0034	.0007
200	43,750	2.0037	.0008
500	43,750	2.0045	.0012
5000	68,750	2.2719	.1349
*5008	68,750	No Reading	- -

Remarks: * Failure.
One hour elapsed time after 5000 cycles before continuing.

TABLE XII

SPEC. NO. 9 MATERIAL: 24 ST

Cycles	Stress (p.s.i.)	Length (in.)	Unit Elong. in./in.
0	0	2.0021	0
2	50,000	2.0085	.0032
10	50,000	2.0084	.0032
50	50,000	2.0085	.0032
100	50,000	2.0086	.0033
200	50,000	2.0088	.0034
500	50,000	2.0094	.0036
2464	68,750	2.2143	.1061
4000	68,750	2.2659	.1319
5000	68,750	2.2659	.1319
*5001	68,750	2.4136	.2057

Remarks: * Failure.
Aged 1 day after 4000 cycles.
Aged 2 days after 5000 cycles.

TABLE XIII

SPEC. NO. 10 MATERIAL: 24 ST

Cycles	Stress (p.s.i.)	Length (in.)	Unit Elong. in./in.
0	0	2.0005	0
2	60,000	2.0606	.0300
10	60,000	2.0621	.0308
50	60,000	2.0632	.0313
100	60,000	2.0633	.0314
200	60,000	2.0635	.0315
500	60,000	2.0639	.0317
1150	68,750	2.306	.1527
*1151	68,750	2.3707	.1851

Remarks: * Failure.
Aged 2 days at 1150 cycles.

TABLE XIV

SPEC. NO. 11 MATERIAL: 24 ST

Cycles	Stress (p.s.i.)	Length (in.)	Unit Elong. in./in.
0	0	1.9995	0
10	56,250	2.0268	.0134
500	56,250	2.0280	.0142
6000	68,750	2.2349	.1175
6500	68,750	2.3793	.1896
*6501	68,750	2.4198	.2101

Remarks: * Failure.
Check of stress at 5000 cycles showed it had dropped 1000 psi.
When raised back to 68,750 specimen failed immediately.

TABLE XV

SPEC. NO. 12 MATERIAL: 24 ST

Cycles	Stress (p.s.i.)	Length (in.)	Unit Elong. in./in.
0	0	2.0027	0
10	55,500	2.0295	.0134
500	55,500	2.0300	.0137
500	0	2.0307	.0140
*1624	68,750	2.3294	.1635

Remarks: * Failure.
Aged four days after 500 cycles. No appreciable recovery of elongation.

TABLE XVI

SPEC. NO. 14 MATERIAL: 24 ST

Cycles	Stress (p.s.i.)	Length (in.)	Unit Elong. in./in.
0	45,000	1.9993	0
2	45,000	2.0050	.0028
10	45,000	2.0055	.0031
50	45,000	2.0060	.0033
100	45,000	2.0061	.0034
200	45,000	2.0066	.0036
500	45,000	2.0066	.0037
1000	45,000	2.0070	.0038
1000	45,000	2.0074	.0040
1010	64,500	2.2022	.1015
2000	64,500	2.2159	.1083
3000	64,500	2.2183	.1095
4000	64,500	2.2183	.1095
*4640	64,500	2.2992	.1488

Remarks: * Failure

TABLE XVII

SPEC. NO. 15 MATERIAL: 24 ST

Cycles	Stress (p.s.i.)	Length (in.)	Unit Elong. in./in.
0	0	2.0013	0
2	55,000	2.0619	.0303
50	55,000	2.0634	.0310
200	55,000	2.0657	.0322
500	55,000	2.0654	.0320
750	55,000	2.0670	.0328
1000	55,000	2.0670	.0328
1000	55,000	2.0662	.0325
1100	55,000	2.2520	.1250
2000	55,000	2.2516	.1251
2500	55,000	2.2517	.1251

Remarks: No failure. Stress/strain curve run.

APPENDIX

DESCRIPTION OF REPEATED LOAD HYDRAULIC TESTING MACHINE

The machine consists essentially of an aircraft type hydraulic system which operates a cylinder, the piston of which is connected to the metal specimen undergoing test.

A 5 H.P. 220V D.C., electric motor rated at 1140 r.p.m. drives an aircraft hydraulic pump of the positive displacement type through a step-up reductor of 3.06 to 1 ratio, giving a pump r.p.m. of 3420. The path of the hydraulic oil is as follows: (Fig. 6A).

From the reservoir containing 4½ of gallons of standard Navy hydraulic oil, it passes through a strainer to the suction side of the pump. The pump delivers the oil through a pressure relief valve set to lift at 1250 psi. to a pressure regulating valve which is capable of controlling the pressure from 0 to 1000# accurately to within about 3 lb. of the desired setting. An accumulator is placed in the line between the relief valve and the regulating valve to smooth fluctuations in oil pressure. From the regulating valve, the oil flows to a solenoid-operated pilot control valve. A Bourdon hydraulic gauge is installed in the line just before the pilot valve to indicate pressure in the system. It is protected by a shut-off valve from shocks while the system is in operation under repeated loads. The pilot valve transmits oil pressure to the cylinder in cyclic intervals as controlled by the solenoid.

A low pressure return line to the reservoir is provided to which is connected the low pressure end of the cylinder, the discharge side of the pilot valve, the discharge side of the regulating valve and the discharge side of the relief valve. A check valve is provided in the discharge line from the pilot valve.

The reservoir is filled by means of a hand pump permanently located within the main frame of the machine.

The pilot valve is operated by a solenoid which is triggered from contact points operated by a circular cam driven by a 1/20 H.P. 110V A.C. universal wound motor. This motor also drives a mechanical counting device. The electrical diagram is shown in Fig. 7A.

All hydraulic lines and fittings, except the hydraulic cylinder are installed below the table top of the machine on which is mounted the testing section. The testing section itself consists primarily of a 5" H-beam 6' long upon which is mounted heavy steel fittings to anchor the cylinder and the far end of the test specimen. See Fig. 3A.

The test section which is located on the top of the H-beam is made of the following parts:

A hydraulic cylinder, 5" diameter, made of a steel jacket and forged aluminum alloy ends. The piston of this cylinder is attached to a universal joint which removes bending of the specimen due to small misalignments. The universal joint carries the load coupon, which is described in detail elsewhere in the report, but which is a device for measuring electrically, by strain gages, the load on the test specimen. One end of the test specimen is fastened into the load coupon and the other end is fastened into another universal joint which is in turn screwed on a fitting which bolts on a heavy metal tee-shaped anchor which in turn is bolted on the H-beam. Counter weights are mounted on the universal joints to balance their free ends.

The test machine can be readily adapted to apply compression loads as well as tension loads simply by interchanging the hydraulic lines to the cylinder.

The photographs and drawings accompaning this description should give the reader a fairly good idea of how it was made. However, since it was built without accurate plans or specifications, several improvements could be made should it be desirable to build a similar testing apparatus.

First, and most important, the fact that the machine is operated at repeated loads subjects all parts of the apparatus to severe vibrations. Special care should be given to the high pressure hydraulic fittings, constructing them of steel if possible, and using flexible hydraulic hose for the high pressure lines.

Second, all gages and measuring devices should be separated from the structure of the machine by vibration-proof leads or lines.

Third, the test section itself should be of extra heavy construction to minimize deflection. Even the 5 inch H-beam used in this apparatus deflected noticeably during operation.

Fourth, it would be more desirable to have a direct drive between the motor and hydraulic pump thereby eliminating the expense and a potential source of trouble of the reductor. In addition the reductor absorbs a considerable fraction of the motor's output.

Last, it might be desirable to incorporate in the electrical system a means to provide automatic shut-off when a specimen ruptures.

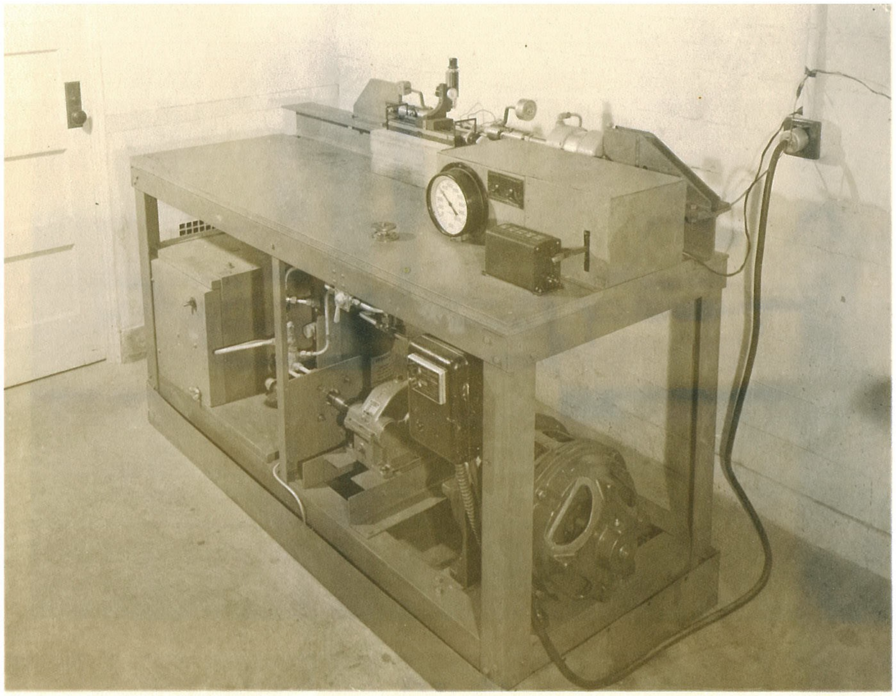


Fig. 1A

General View of Machine

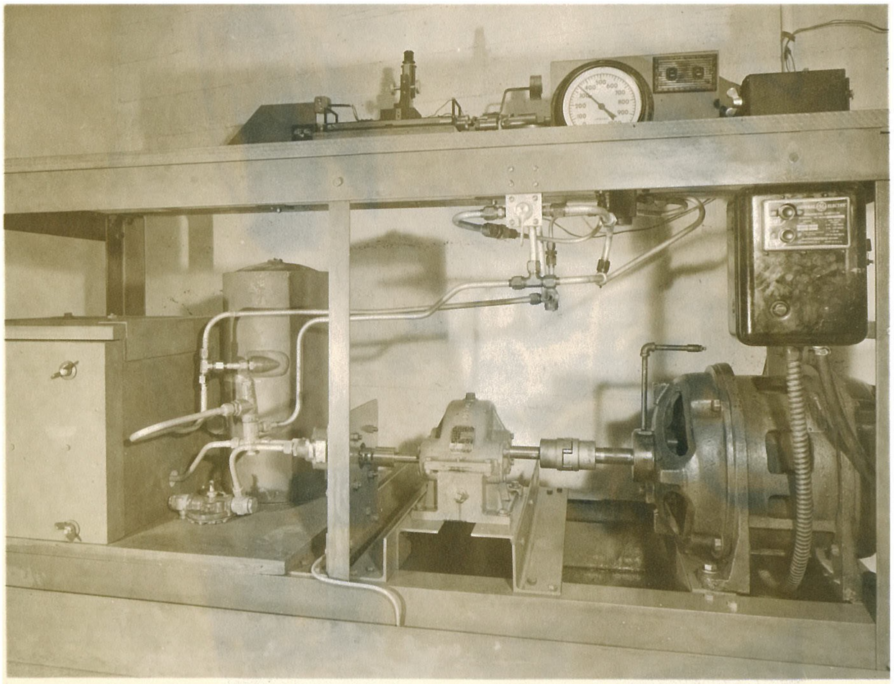


Fig. 2A

Hydraulic Section

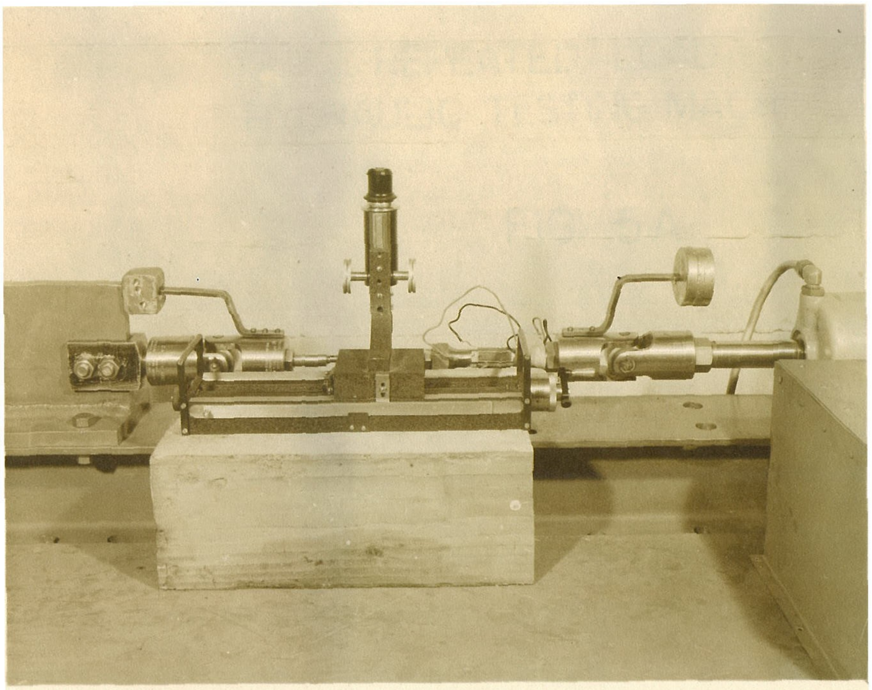


Fig. 3A
Test Section

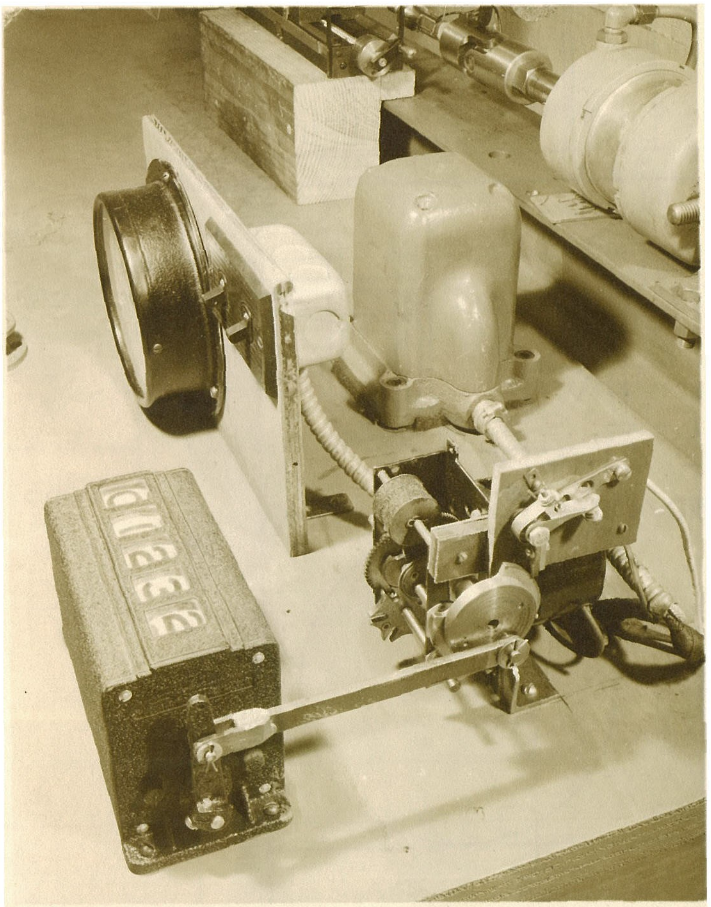
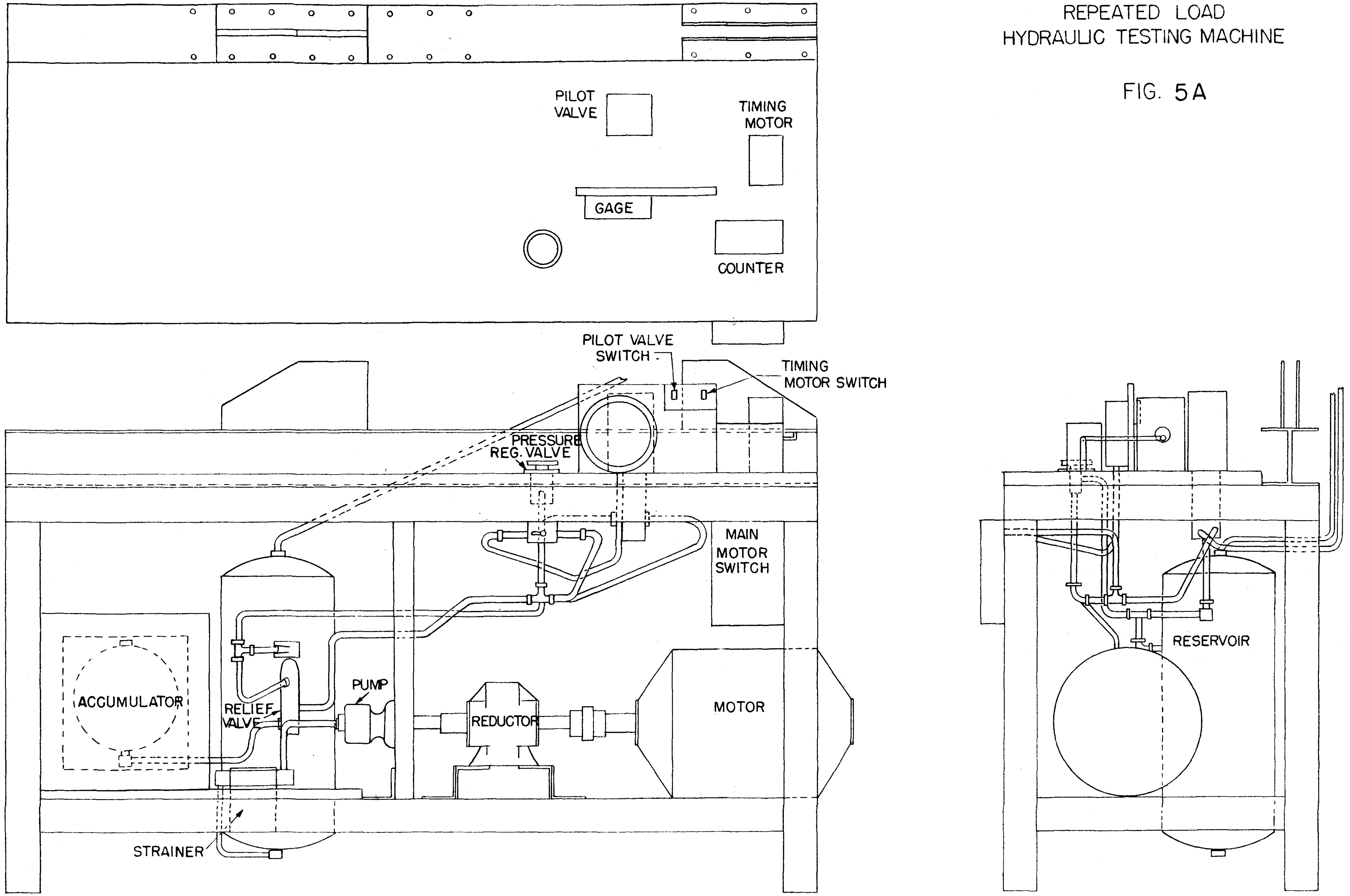
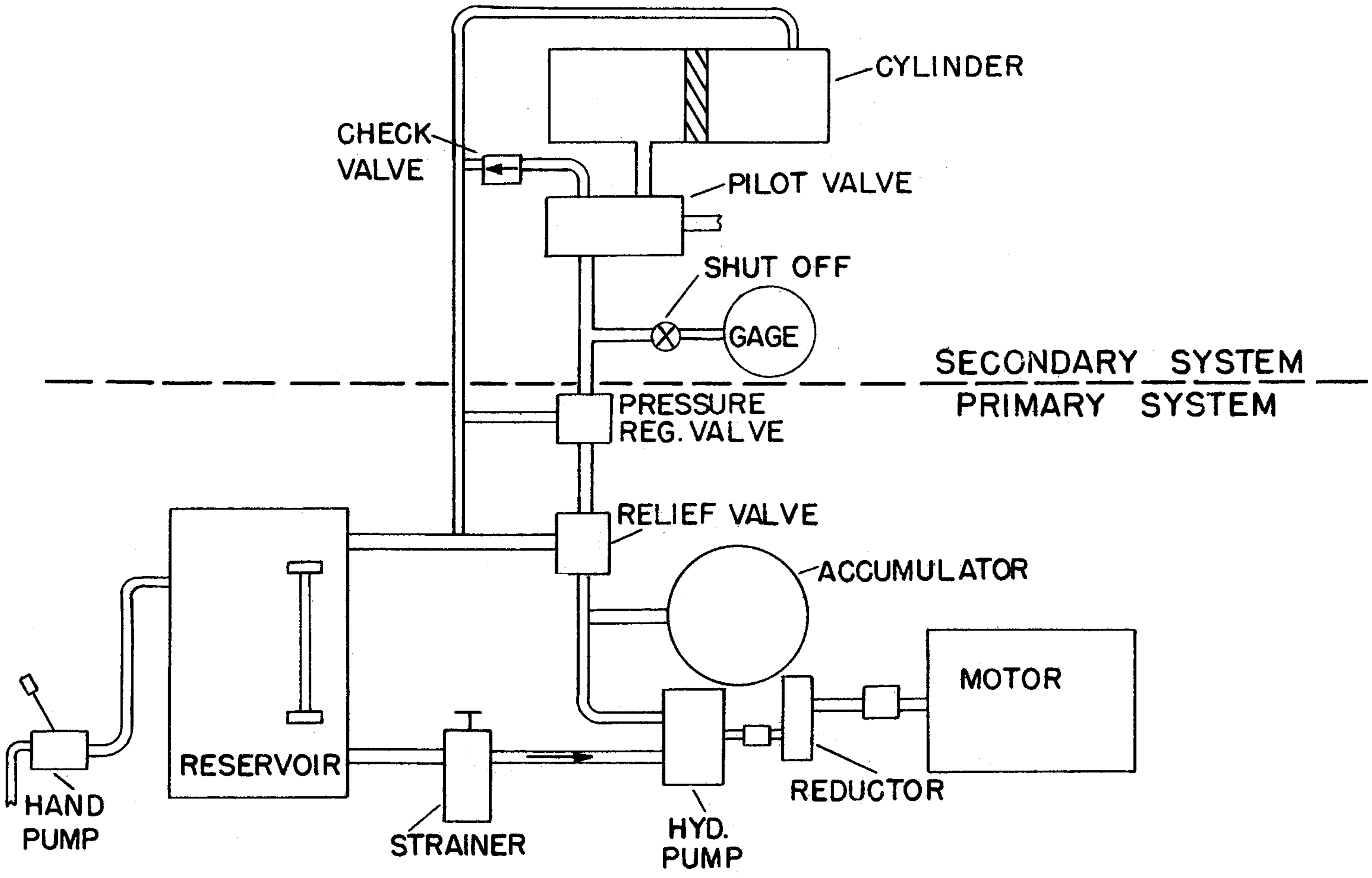


Fig. 4A
Timing Motor & Pilot Valve



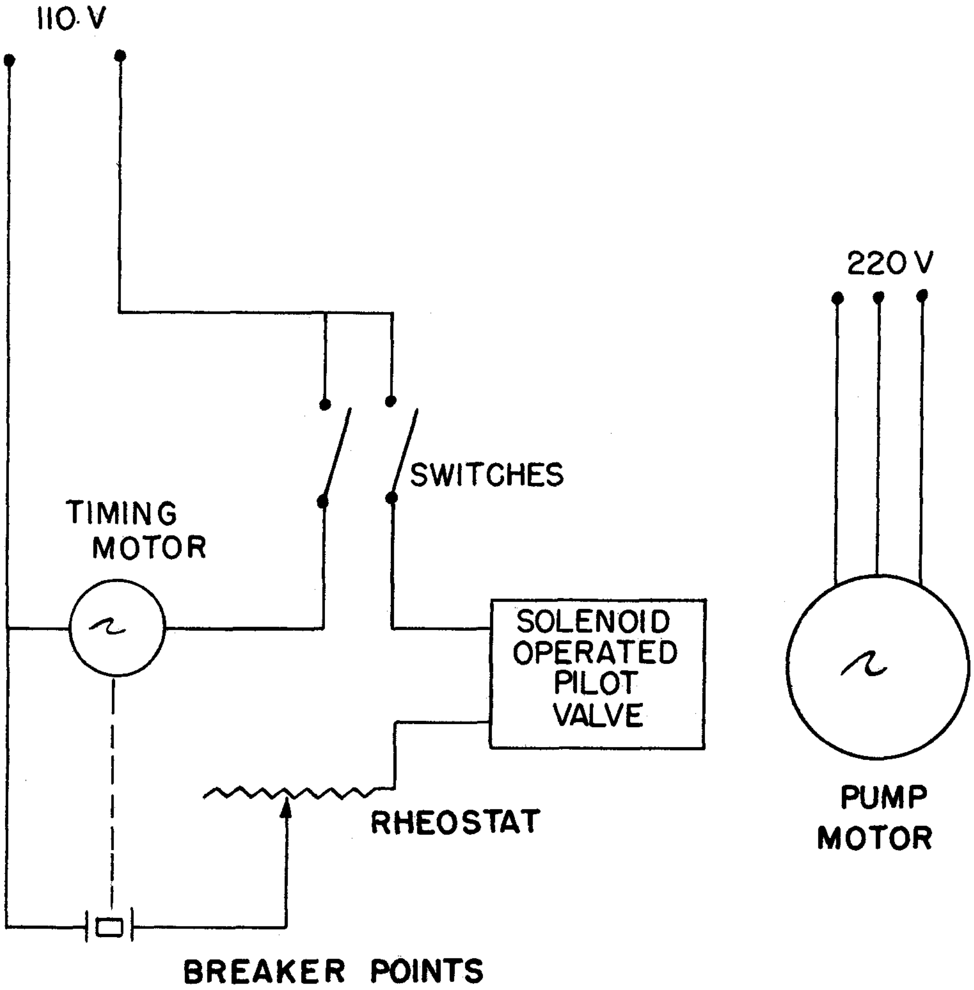
REPEATED LOAD
HYDRAULIC TESTING MACHINE

FIG. 5A



SCHEMATIC DRAWING OF HYDRAULIC SYSTEM

FIG. 6A



ELECTRICAL DIAGRAM
FOR
REPEATED LOADING
HYDRAULIC TESTING
MACHINE

FIG. 7 A