REPEATED LOADS ABOVE THE PROPORTIONAL LIMIT ON 24ST ALUMINUM ALLOY

Thesis

by

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The author especially wishes to express his gratitude to Dr. E. E. Sechler, Dr. D. S. Clark, and Prof. F. J. Converse for their helpful advice and suggestions.

Acknowledgment is also made to Mr. M. E. Jessey for setting up the electrical measuring apparatus.

SUMMARY

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

The investigation consisted of three parts:

1. An investigation of the effects of the application of repeated tensile stress above the proportional limit for 500 cycles followed by a higher repeated tensile stress up to 5,000 cycles.
2. An investigation of the effects of changing the number of cycles of pre-stress.
3. An investigation of the effects of aging.

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, 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 considerably more thorough investigation.

It is considered that this field offers attractive possibilities for further study of the behavior of aircraft materials with the objective of increased accuracy in airplane design.

The investigation was carried out in collaboration with Conrad N. Nelson, Captain, U. S. Air Force at the Daniel Guggenheim Aeronautical Laboratory, California Institute of Technology, Pasadena, California.

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I. INTRODUCTION

The purpose of this investigation was the study of the effects of repeated tensile stresses with a high rate of loading above the proportional limit on 24ST Aluminum Alloy. 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 a means of determining when an important member of the structure which is suspected of having repeated stresses of that nature should be retired from service.

Little experimental data has been made available in the past covering this phase of structural research. The problem is vast, as it includes 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 allied problems have been investigated at the California Institute of Technology during the past few years. Most of them dealt with an almost instantaneous impact type of loading supplied by a falling weight or similar arrangement. Considerable difficulty was experienced by most of these earlier investigators in isolating the characteristics they desired to study from the effects of undesirable parameters in their methods of testing.

When it is realized that any load applied to an airplane 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 suddenly applied loads. Hence the decision was made by Edward G. Bull and Robert L. Mastin to abandon the techniques used in previous investigations and to design and build a testing machine of the hydraulic type. Hydraulic loading of the 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.

The present investigation was essentially a continuation of the work started by Edward G. Bull and Robert L. Mastin at the Daniel Guggenheim Laboratory, California Institute of Technology, Pasadena, California.

II. EQUIPMENT

Test Specimens:

The material used in the tests 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.

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 Bull and Mastin in conjunction with Soli and Ditch.

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 5 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 1,000 psi. A pressure relief valve is installed as a safety measure to lift at 1,250 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 very little displacement of hydraulic fluid in the system during operation, a cylinder of any reasonable size which would give loads varying with the cylinder diameter could have been used. Actually a standard aircraft type hydraulic cylinder, five inches in diameter, was used, which gave a maximum load on the specimen of about 11,500 lbs. based on 1,000 psi oil pressure. With the cross-sectional area of the specimens equal to 0.0707 square inch, 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 on its design and operation are presented in an Appendix with schematic drawing in Fig. 22.

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.

Mounted on the coupon were four SR-4 Type A-1 electrical 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:

The 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. This method of measurement was used in preference to electric strain gages as the deformations were large enough to make the strain gages inoperative.

Dynamic Load Measuring Equipment:

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

The equipment consisted essentially of the load coupon on which four electric strain gages were mounted in series. The change of resistance of these gages with the changes in load was measured by a Wheatstone Bridge. The signal was sent to an amplifier, which in turn amplified and sent the signal to a Heiland Recording Oscillograph. The recording oscillograph made a record of the load applied vs. time. Incorporated in the electrical system was a means of putting a known load line on the photographic record for purposes of calibration. This was accomplished by loading the coupon with known loads of 1,000, 2,000, 3,000, and 4,000 lbs. and finding experimentally the amount of resistance required to be connected in parallel with the gages by means of a potentiometer 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 1,000, 2,000, 3,000, or 4,000 lbs. and then, by pushing a button on the panel, a calibrating line for one of the four 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.

The voltage of the battery connected to the Heiland was chosen to make use of the full width of the photographic paper to get the largest possible scale for the ordinate - the load.

Fig. 25 is a circuit diagram of the dynamic load measuring equipment.

Fig. 21 shows an oscillograph recording for Test 27 at 505 cycles. This recording is typical of those obtained on all tests. An analysis of Fig. 21 yields the following information:

Duration of Zero Load	0.630 sec.
Duration of Maximum Load	0.330 sec.
Time - No Load to Full Load	0.170 sec.

Time - Full Load to No Load	0.025 sec.
Time for One Complete Cycle	1.155 sec.
Number of Cycles Per Minute	52
Maximum Rate of Loading	41,700 #/sec.
Maximum Rate of Unloading	184,000 #/sec.

III. INITIAL CALIBRATIONS

Pressure Gage Calibration:

The pressure gage used in the hydraulic system was of standard Bourdon type with a range of 0-1,000 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 calibration curves of gage reading psi vs. load on specimen lb. and of gage reading psi vs. stress on specimen psi are shown in Fig. 3 and Fig. 4 respectively.

The calibration was carried out by Bull and Mastin 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 a standard testing machine in the Daniel Guggenheim Aeronautical Laboratory. Electrical measurements were made with a potentiometer constructed previously for electrical strain gage measurements. Each gage was first checked separately by plotting load vs. millivolts. This plot is shown in Fig. 5. This calibration ascertained whether or not each gage was operative and whether its output was comparable to that of the three other gages. Since each gage plotted as a straight line over the entire load range, this indicated that they were satisfactory. After connecting all four gages in series, the above procedure was repeated, obtaining increase in millivolt drop vs. load and this was also found to be a straight line as shown in Fig. 6.

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 1,000, 2,000, 3,000, and 4,000 lbs. in order to balance the electrical bridge described earlier in this report. This information was required in order to put a load calibrating line on the oscillograph film.

Dynamic Calibration of the Pressure Gage:

Early during the investigation it was decided that a calibration of the pressure gage should be taken under dynamic conditions to be able to set the pressure gage accurately to produce a required stress on the specimen. For this, an oscillograph reading was taken for loads of 1,000, 2,000, 3,000, and 4,000 lbs. Then oscillograph recordings were made for various pressure gage readings. The latter oscillograph readings were converted to loads on the basis of the calibrations for 1,000, 2,000, 3,000, and 4,000 lbs. and then to stresses on the specimen by dividing the loads by the cross-sectional area of the specimen. This curve is shown in Fig. 7.

IV. TEST PROCEDURE

A record of all runs made appears in the Tables S.1-32.

Prior to starting any repeated load tests, static tension tests were made on two specimens from the same bar stock of the material to be tested for fatigue. This appears in Fig. 8 and gives an ultimate strength of 66,500 psi and 66,400 psi respectively for the two specimens.

Specimens 1-18 were subjected to different initial repeated stresses for 500 cycles each as a sort of cold work ranging from the proportional limit to just below the ultimate and then worked at a higher or the same stress up to 5,000 total cycles.

Specimen 19 was subjected to repeated stress just under the ultimate limit for 500 cycles to study the deformations in a greater detail than in Test 18.

Specimens 20-25 were subjected to initial repeated stress for 1,000 or 1,500 cycles before being worked at higher repeated stresses to study the effects of a change in the cycles of pre-stress.

Specimens 26-28 were subjected to a repeated stress just above the proportional limit for 500 cycles, then a higher repeated stress just below the ultimate strength up to 5,000 total cycles, and then allowed to age for different periods before being subjected to the high repeated stress until failure.

Specimens 29-31 were subjected to a repeated stress just above the proportional limit, for 500 cycles, then aged for different periods before being subjected to higher repeated stress until failure.

Specimen 32 was subjected to practically the same stresses and aging period as specimen 30 except for the fillets, the radius of which was doubled.

V. RESULTS AND DISCUSSION

(a) Static Tests:

The static stress strain curves of the two specimens from the same bar stock of 24ST give the following mean values:

Proportional limit	40,000 psi
Defined yield stress (0.02% offset)	43,700 psi
Ultimate strength	66,450 psi
Elongation	18.375%

(b) Fatigue Tests:

In the first few fatigue tests, in some cases it was found that there was a decrease in length after the repeated stress was removed. This effect was suspected to be due to the temperature rise caused by the setting up of the specimen and subsequent cooling with time due to conduction and radiation. This was eliminated by setting up the specimen and allowing it to reach an equilibrium temperature by standing overnight in the machine.

Also an increase in length was observed in several cases after the repeated stresses were removed; this effect was particularly noticeable between 10 and 500 cycles. Steady values of length could only be obtained at the end of 10 minutes. It may be due to plastic flow causing readjustment of crystals. However, it is felt that a more rational explanation might be possible through the physics of solids. This problem needs additional detailed study.

1. Tests 1-18. Repeated Load Tests Involving Initial Cold Work of 500 Cycles:

Examination of Tables 1-18 and Figs. 9-14 shows that, in the case of a stress well into the plastic region, almost all 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. 14, Test 18, shows a considerable increase of elongation between 15 and 100 cycles. The elongation remains constant after 100 cycles and is uniform up to 15 cycles. This phenomenon was also observed by Bull and Mastin when the repeated stress was just under the ultimate strength. Test 19 was run taking readings of elongations at close intervals and this effect of sudden increase of elongation between 15 and 100 cycles was not observed. This may be due to the repeated stress in Test 19 being a little lower. Several tests should be run with repeated stresses just under the ultimate stress to investigate this phenomenon.

2. Tests 20-25. Effect of Changing the Number of Cycles of Initial Cold Work:

Figs. 15-17 show the comparative effects of pre-stressing of 500, 1,000, and 1,500 cycles keeping the pre-stress and the higher stress approximately constant. With the pre-stress of about 40,000 psi, it was found that the maximum elongations occurred when subjected to 1,000 cycles of pre-stress, whereas for a pre-stress of about 60,000 psi maximum elongations occurred when subjected to 1,500 cycles of pre-stress. No definite conclusions can be drawn, however, without several more tests run up to failure, although it can be seen that the variation of the number of cycles of pre-stress has little effect on the elongations and life of the specimens.

3. Tests 26-28. Effects of Aging After a Fixed Pre-stress and Higher Stress:

Tests 26, 27, 28 were run under practically the same pre-stress of 40,000 psi, a higher stress of 65,000 psi, but aged for one hour, one day, and one week respectively before being subjected to the higher stress again until failure. It was found that the specimen subjected to one hour's aging failed earliest and that subjected to one week's aging failed last. Also for the specimens subjected to one hour's and one day's aging there was little elongation in the first ten cycles after aging, whereas for the specimen subjected to one week's aging the elongation in the first ten cycles after aging was considerable although it took the longest time to fail. This probably is due to the fact that the applied higher stress was a little lower. This again shows that no definite elongation failure correlation could be obtained.

4. Tests 29-31. Effects of Aging After a Fixed Pre-stress:

Tests 29, 30, 31 were subjected to practically the same initial stress, aged for one hour, one day, and one week respectively and then subjected approximately to the same stress again until failure. The elongations after aging were largest for one week's aging, although curiously smallest for one day's aging. In these tests, however, the number of cycles of life showed a decrease with increasing aging period.

Fig. 18 also shows comparison of these three tests with Test 2 where there was no aging at all. From this figure it is evident that the effect of aging is definitely to increase the elongations after the aging.

In all these tests, fracture, wherever it occurred, took place close to one of the two ends of the gage length near the fillet. As this failure close to the fillet is definitely due to the stress concentration, Test 32 was run with the radius of the fillets doubled to 3/8 inch under practically the same conditions as Test 30. The specimen failed in the gage length, and the elongation was much larger and the specimen 32 withstood more cycles of fatigue.

A study of the broken specimens definitely indicated a shear type of failure.

VI. SUGGESTED IMPROVEMENTS

1. A thermocouple could be mounted on the specimen to investigate quantitatively the effects of temperature throughout the test. However, fair accuracy was obtained by setting up the specimen sufficiently in advance of the tests. But for more accurate work it may be desirable to use some kind of temperature control such as blowing air of constant temperature over the specimen.

2. The motor and the solenoid valve which are the main sources of vibration should be vibration isolated.

3. Quicker and more accurate methods of length measurement should be used, as the traveling microscope takes considerable time to take readings of length during which the specimen is allowed to age.

4. A fillet radius of 3/8 inch should be used on the specimen as a smaller fillet radius such as 3/16 inch introduces higher stresses due to stress concentration, with the result that the specimens invariably fail very close to the fillet. A fillet radius of 3/8 inch lowers this stress concentration so that the specimens fail within the gage length due to shear fatigue.

5. A more accurate dynamic calibration curve of stress on the specimen vs. pressure gage reading should be drawn, taking the mean of several oscillograph recordings at every pressure gage reading along with calibration for 1,000, 2,000, 3,000, and 4,000 lbs., so that a more accurate control of applied stress could be obtained.

VII. CONCLUSIONS

The following conclusions are obtained from this investigation:

1. At repeated tensile stresses on 24ST above the proportional limit and well below the ultimate limit, practically all the deformation takes place within the first few cycles.

2. In the overstressed 24ST there exists no definite relationship between the elongation and the number of cycles, and as such this would not lead to any definite method of forecasting life expectancy.

3. Repeated pre-stressing of 24ST, above the proportional limit, increases its life expectancy at repeated loads at higher stresses.

4. Additional tests should be made before definite conclusions could be arrived at, on the effect of changing the number of cycles of pre-stress as to the most desirable number of cycles to be used in pre-stressing.

5. The effect of increasing the aging time seems to have a favorable effect when aging is done after a low pre-stress and higher later stress.

6. The effect of increasing the aging time seems to have an unfavorable effect when aging is done after a low pre-stress.

7. 24ST Aluminum Alloy should be subjected to a complete statistical survey to determine definitely the effects of the various parameters as wide discrepancies were found between the results of the present investigation and those of Mastin and Bull.

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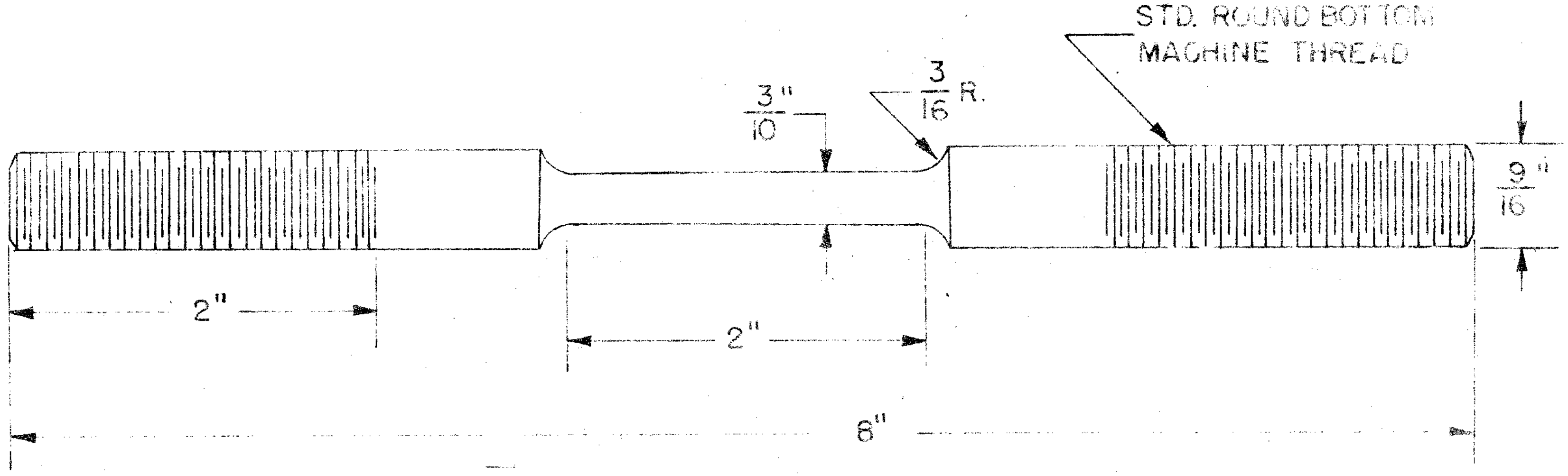
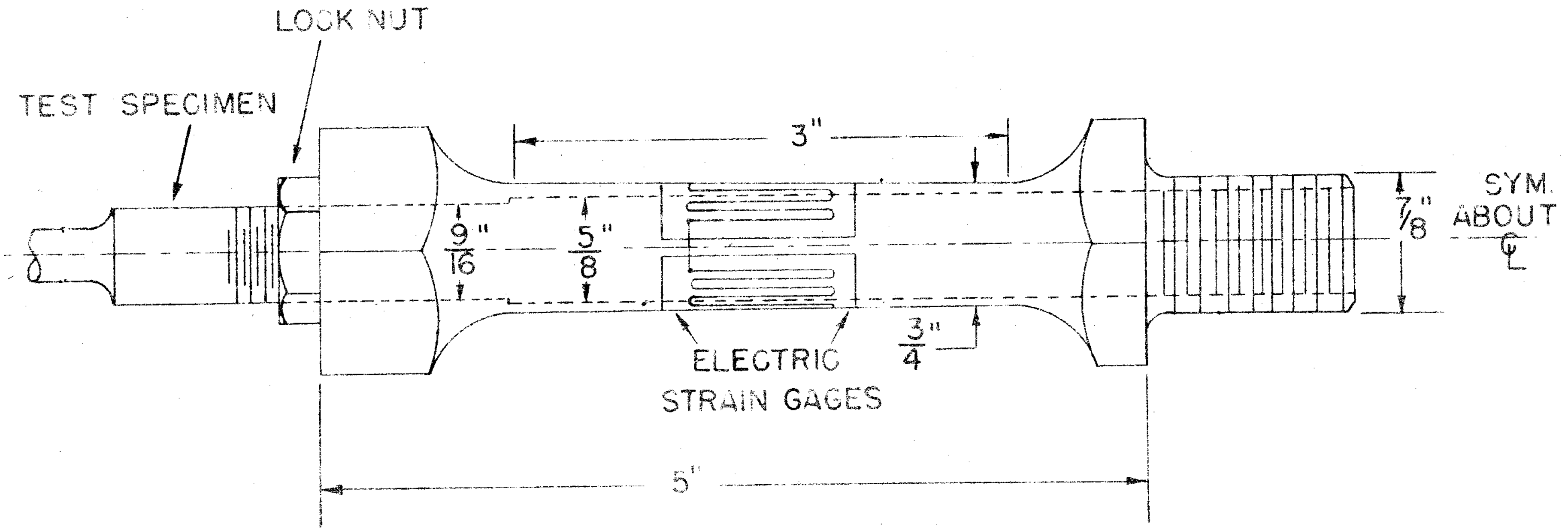
FIGURES



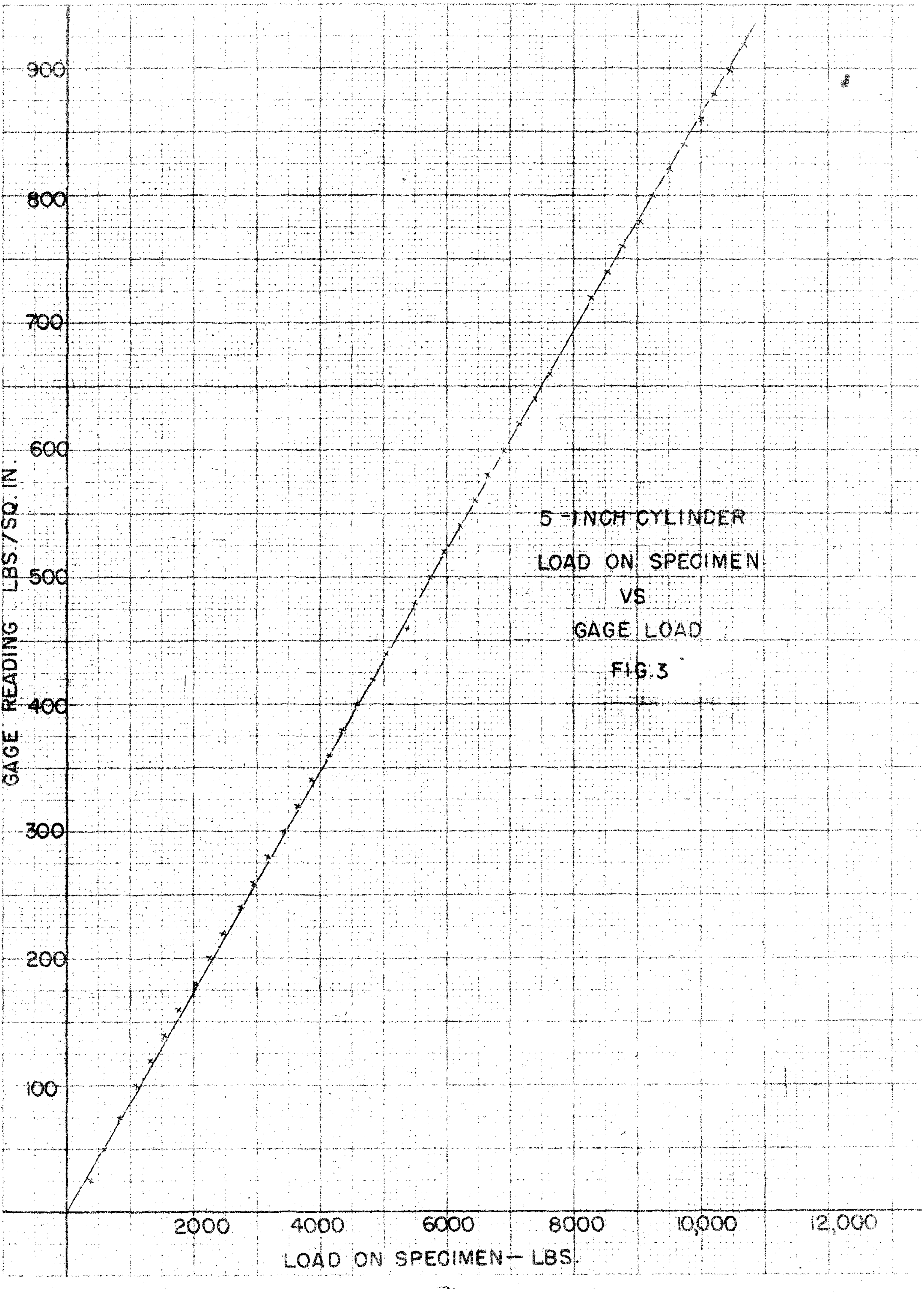
TEST SPECIMEN

FIG 1



LOAD MEASURING COUPON

FIG.2



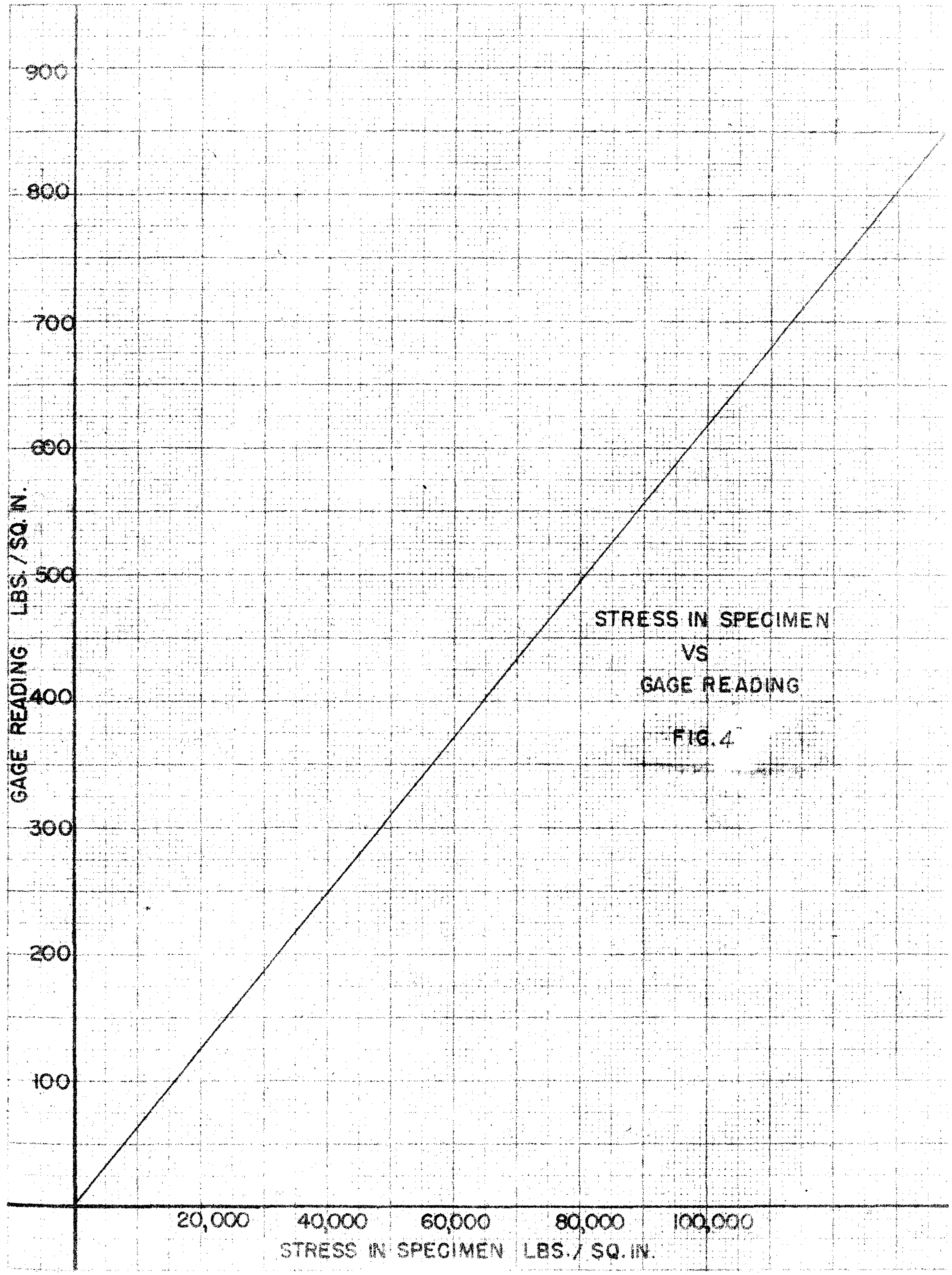
5-INCH CYLINDER

LOAD ON SPECIMEN

VS

GAGE LOAD

FIG.3



STRESS IN SPECIMEN
VS
GAGE READING

FIG. 4

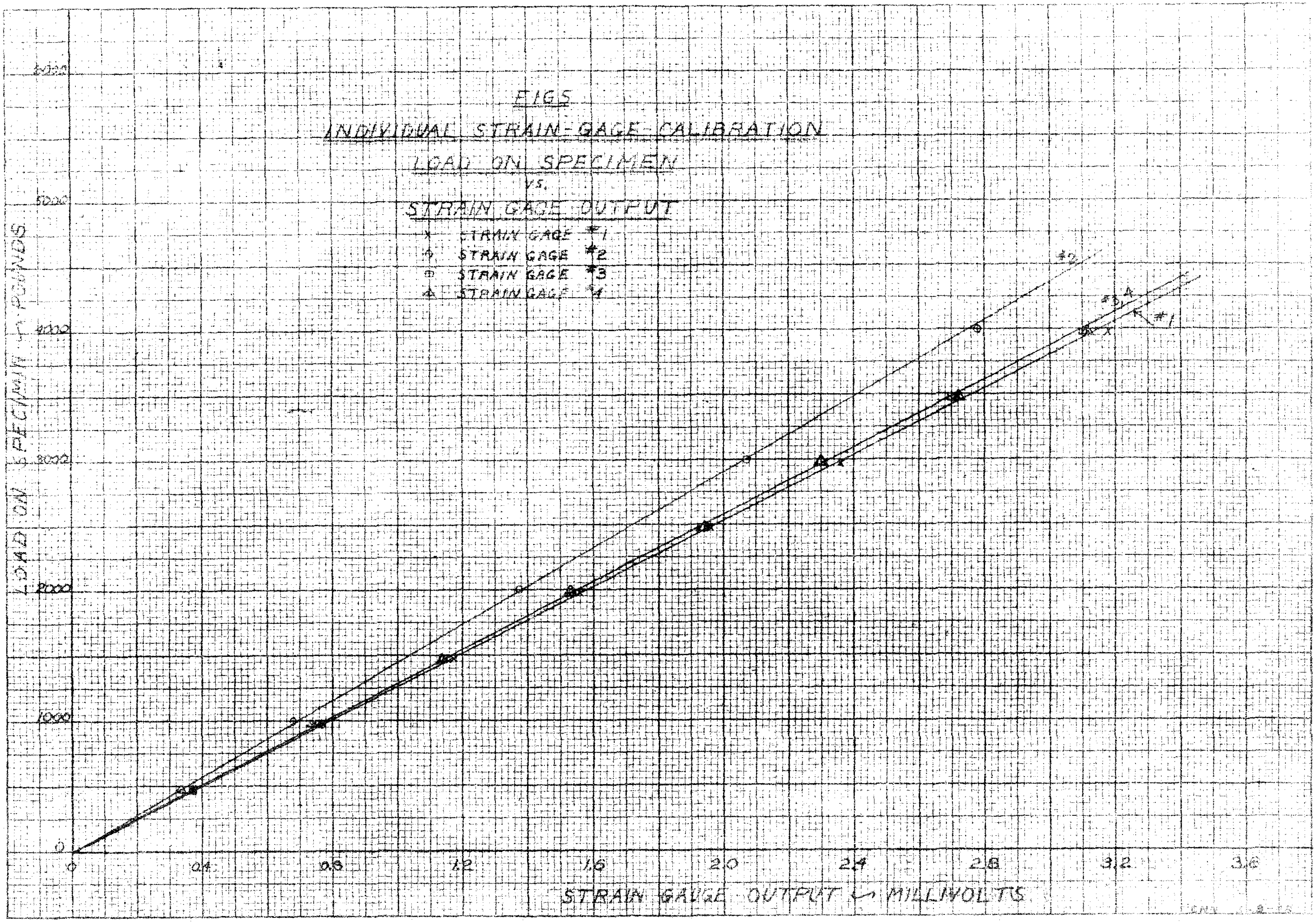


FIG 5

INDIVIDUAL STRAIN-GAGE CALIBRATION

LOAD ON SPECIMEN

VS.

STRAIN GAGE OUTPUT

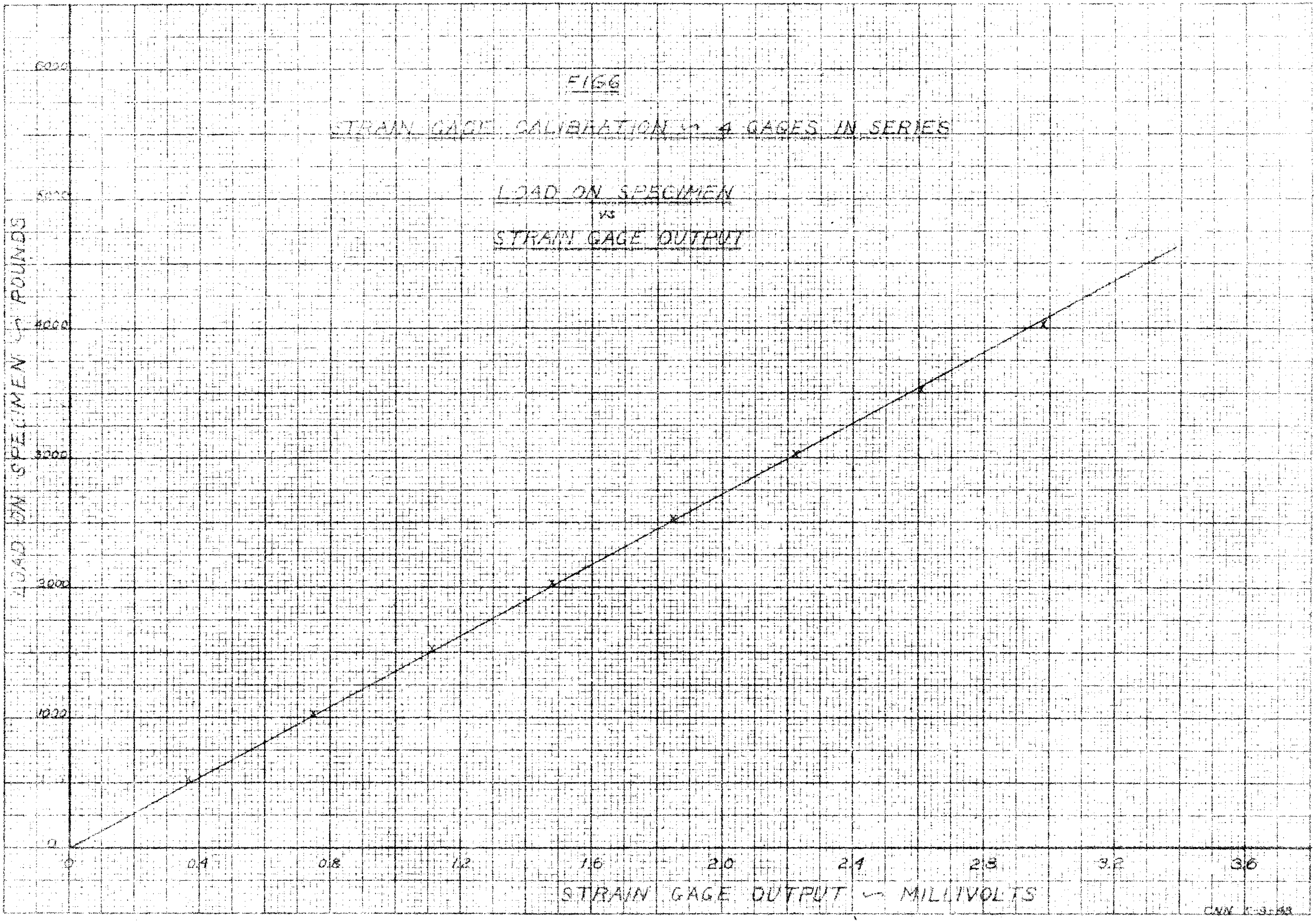
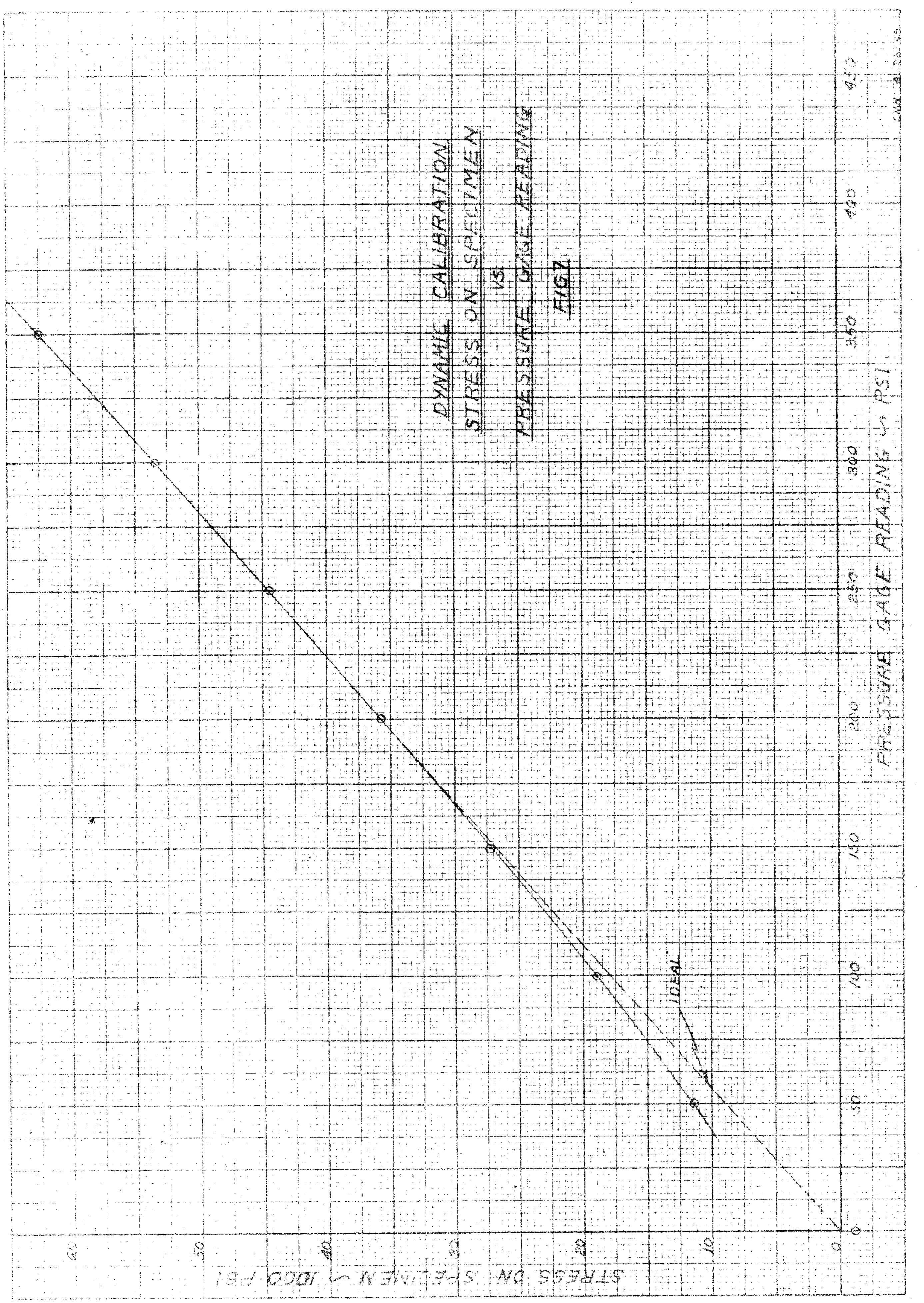


FIG 6

STRAIN GAGE CALIBRATION ~ 4 GAGES IN SERIES

LOAD ON SPECIMEN
vs
STRAIN GAGE OUTPUT



DYNAMIC CALIBRATION
STRESS ON SPECIMEN
VS
PRESSURE GAGE READING

FIG 7

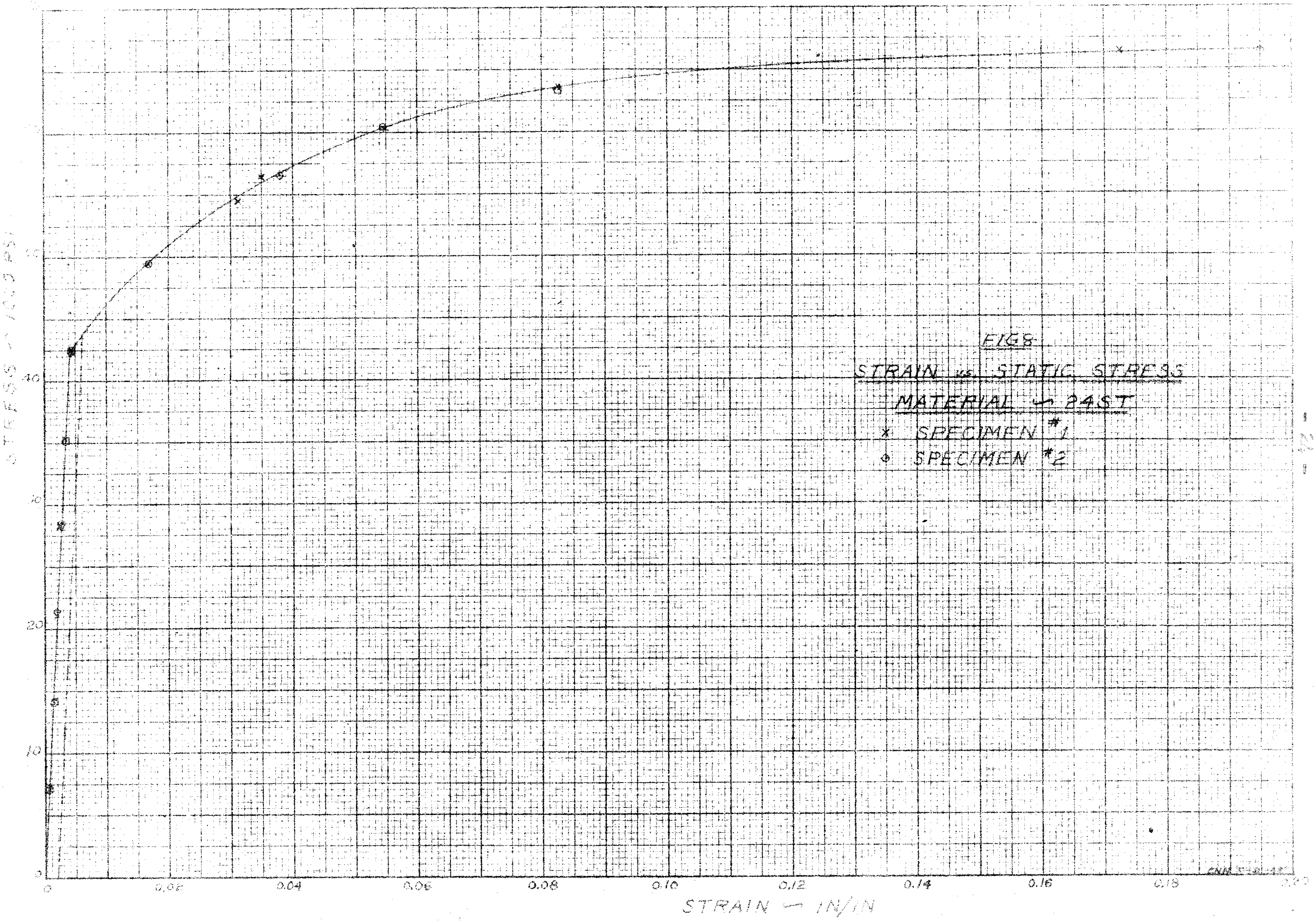


FIG 8

STRAIN vs. STATIC STRESS

MATERIAL — 24ST

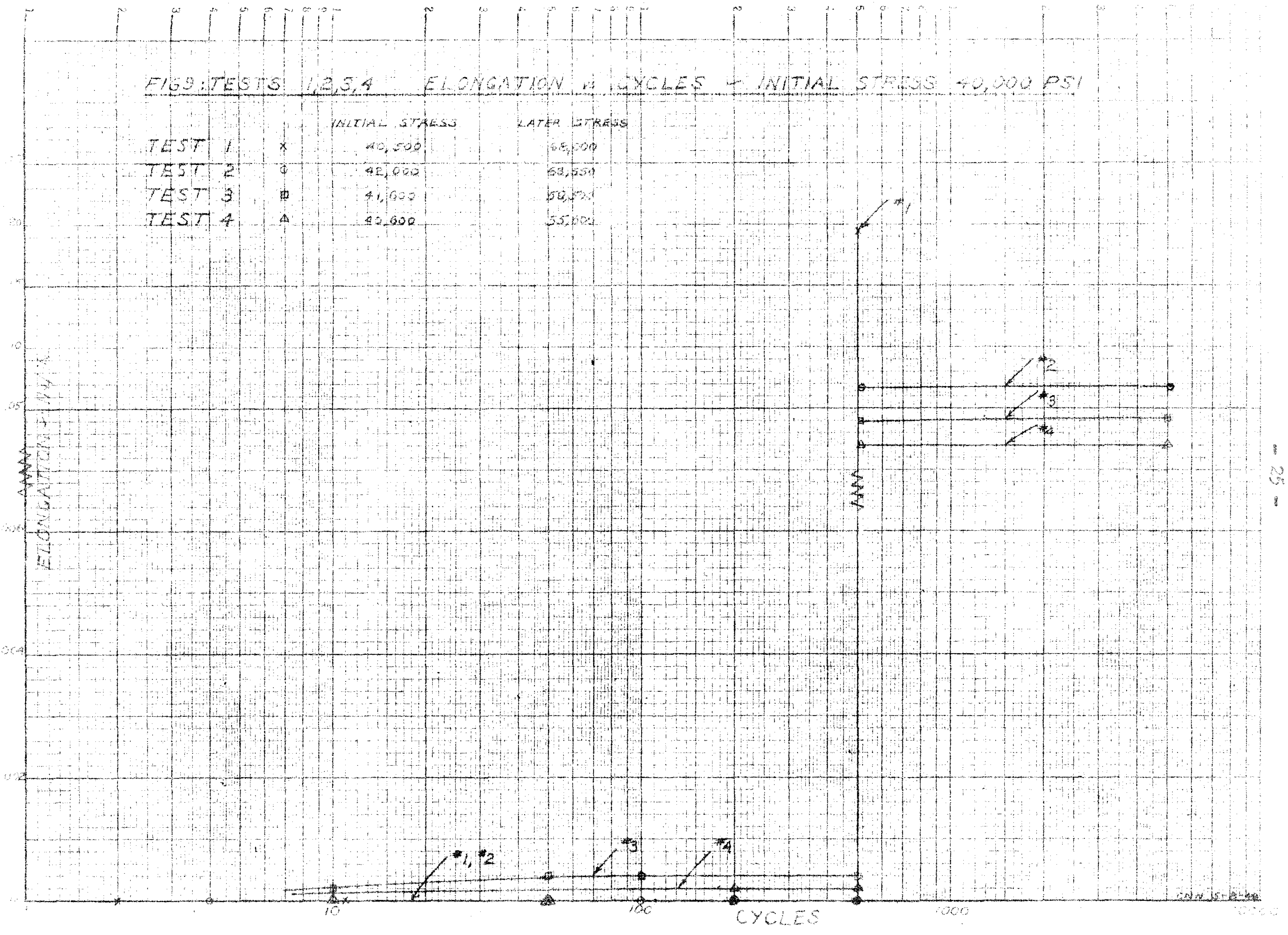
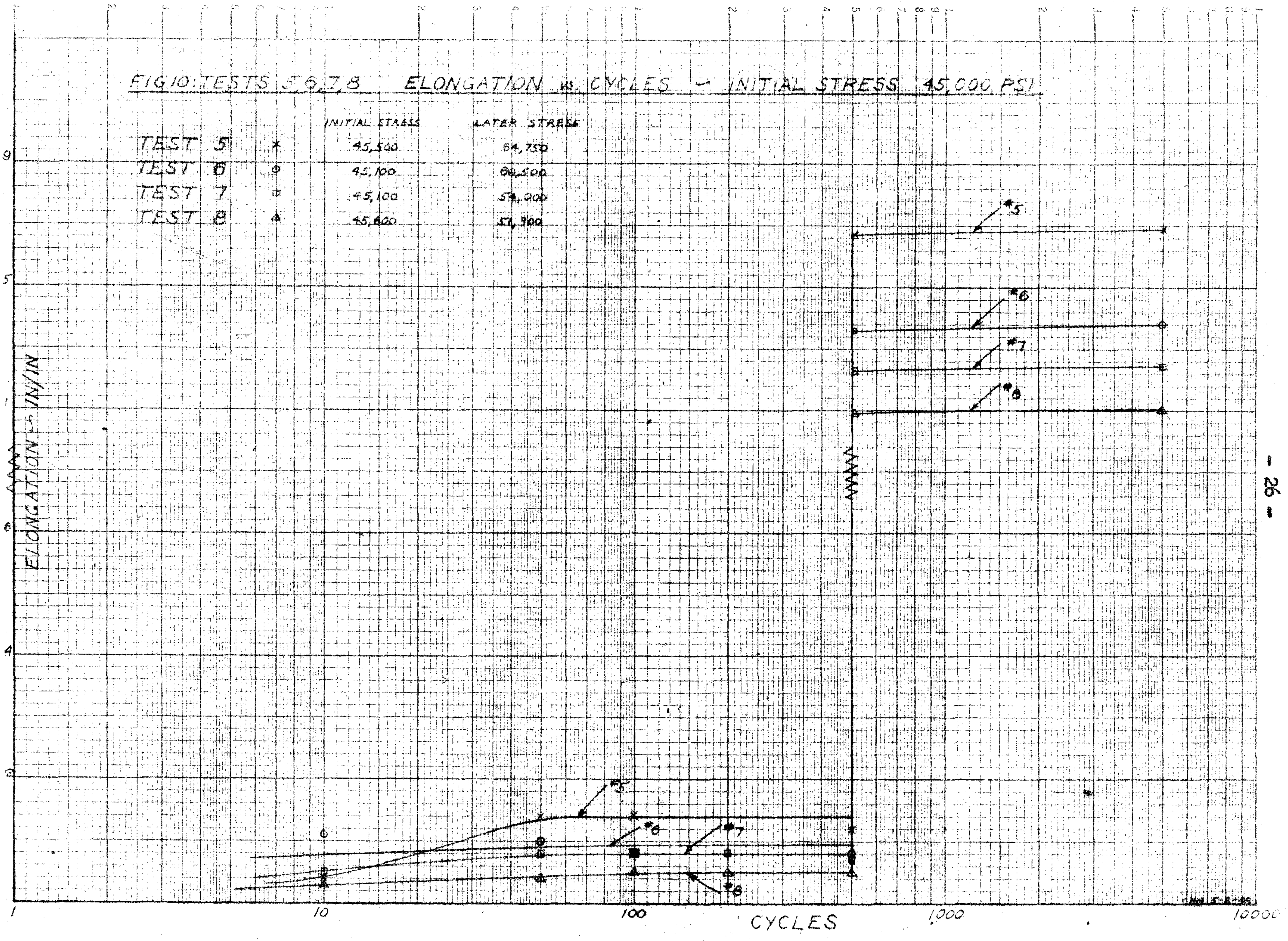


FIG 9: TESTS 1,2,3,4 ELONGATION vs CYCLES – INITIAL STRESS 40,000 PSI

FIG 10: TESTS 5,6,7,8 ELONGATION vs. CYCLES – INITIAL STRESS 45,000 PSI



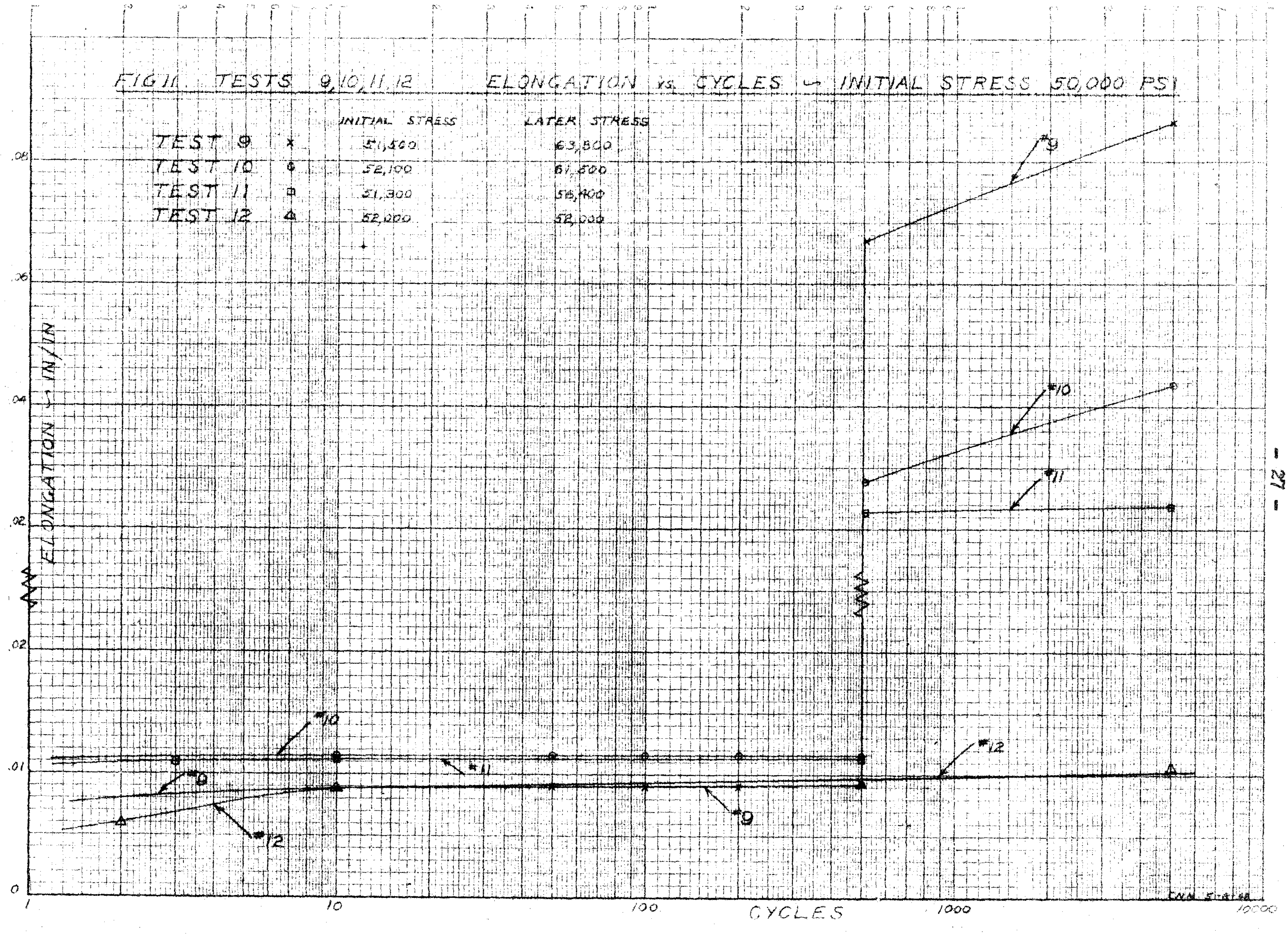
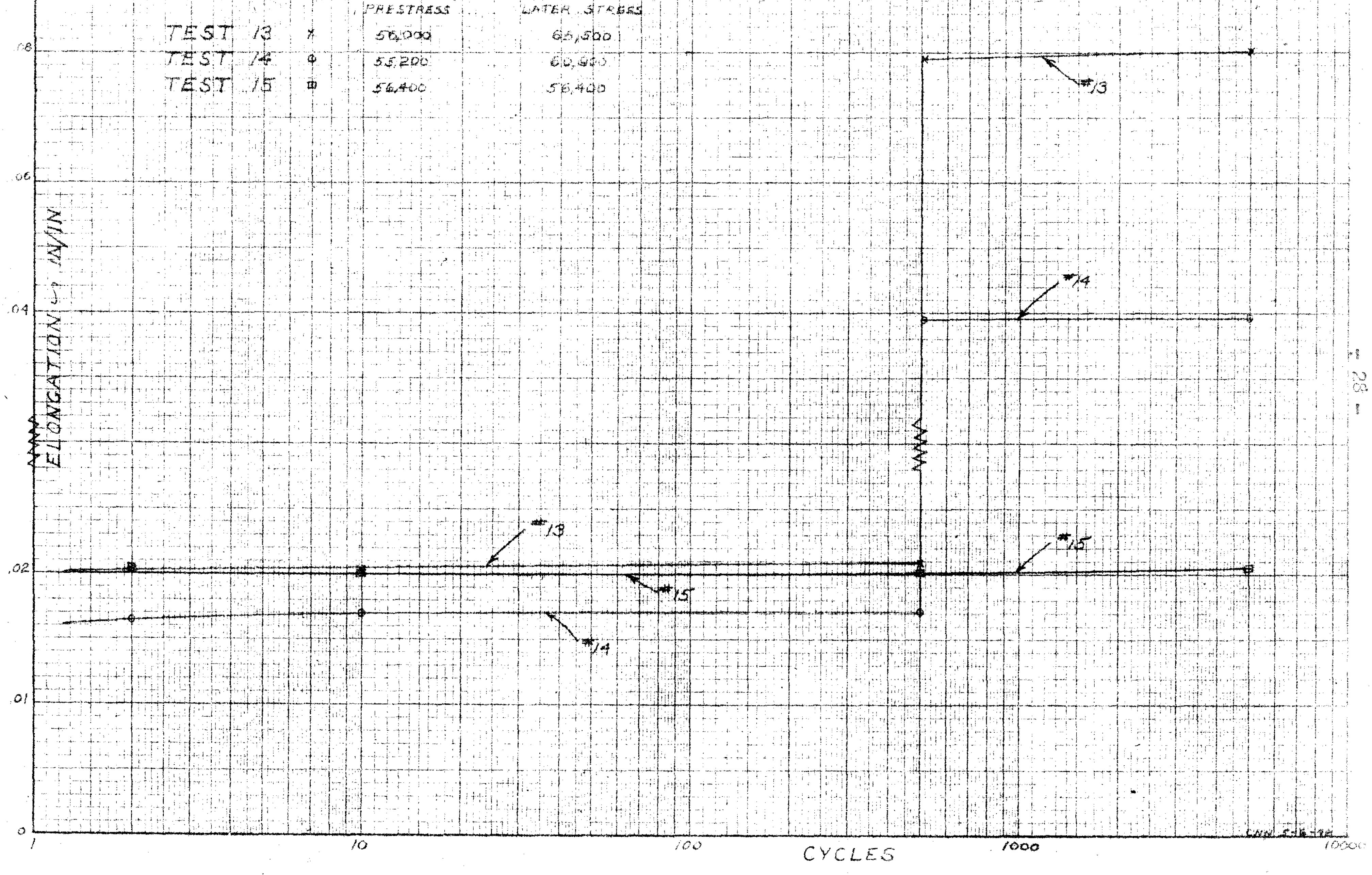


FIG 11 TESTS 9,10,11,12 ELONGATION vs. CYCLES ~ INITIAL STRESS 50,000 PSI

FIG 12 TESTS 13, 14, 15 CYCLES vs ELONGATION ~ PRESTRESS 55,000 PSI



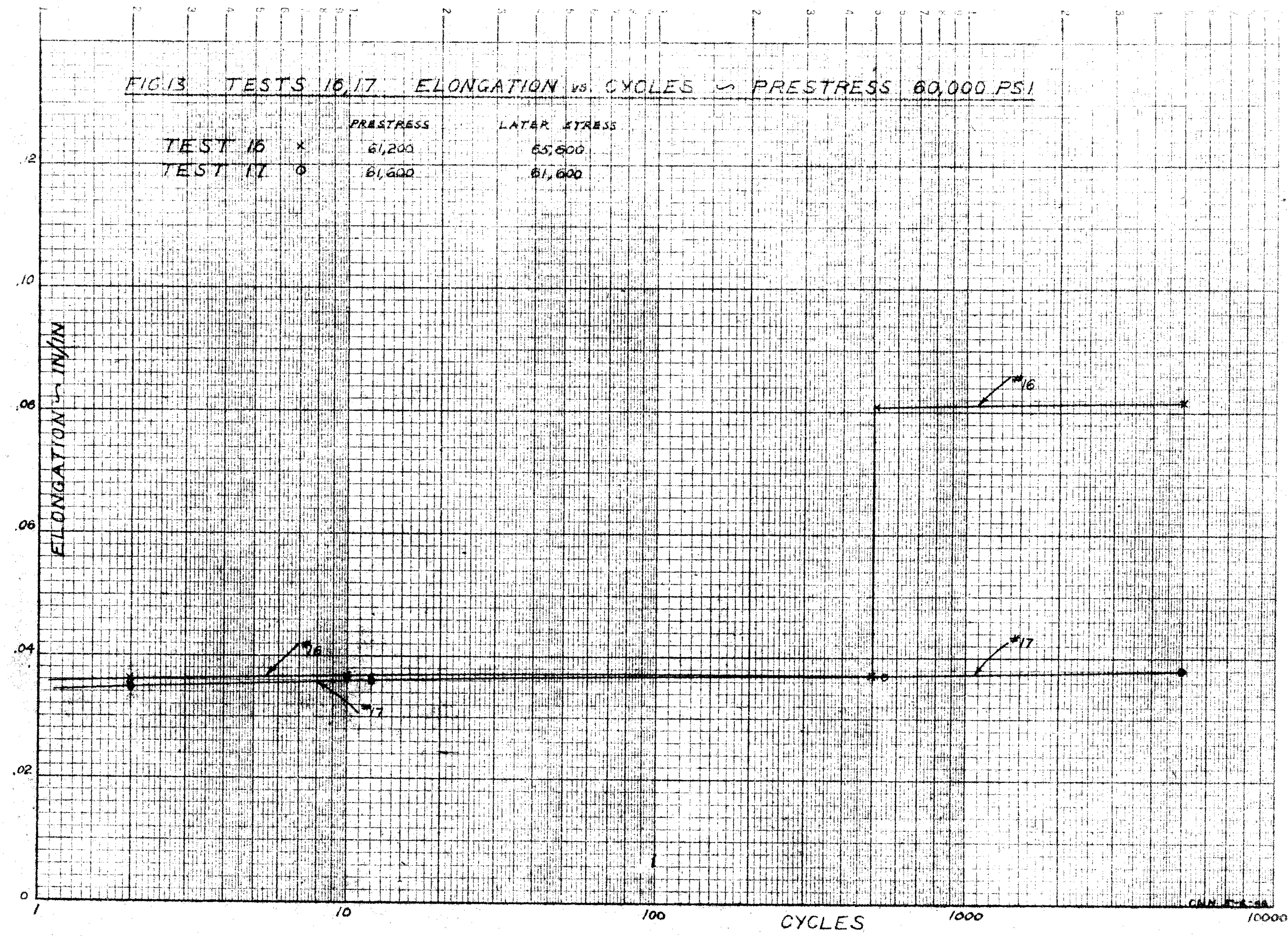


FIG 13 TESTS 16,17 ELONGATION vs. CYCLES ~ PRESTRESS 60,000 PSI

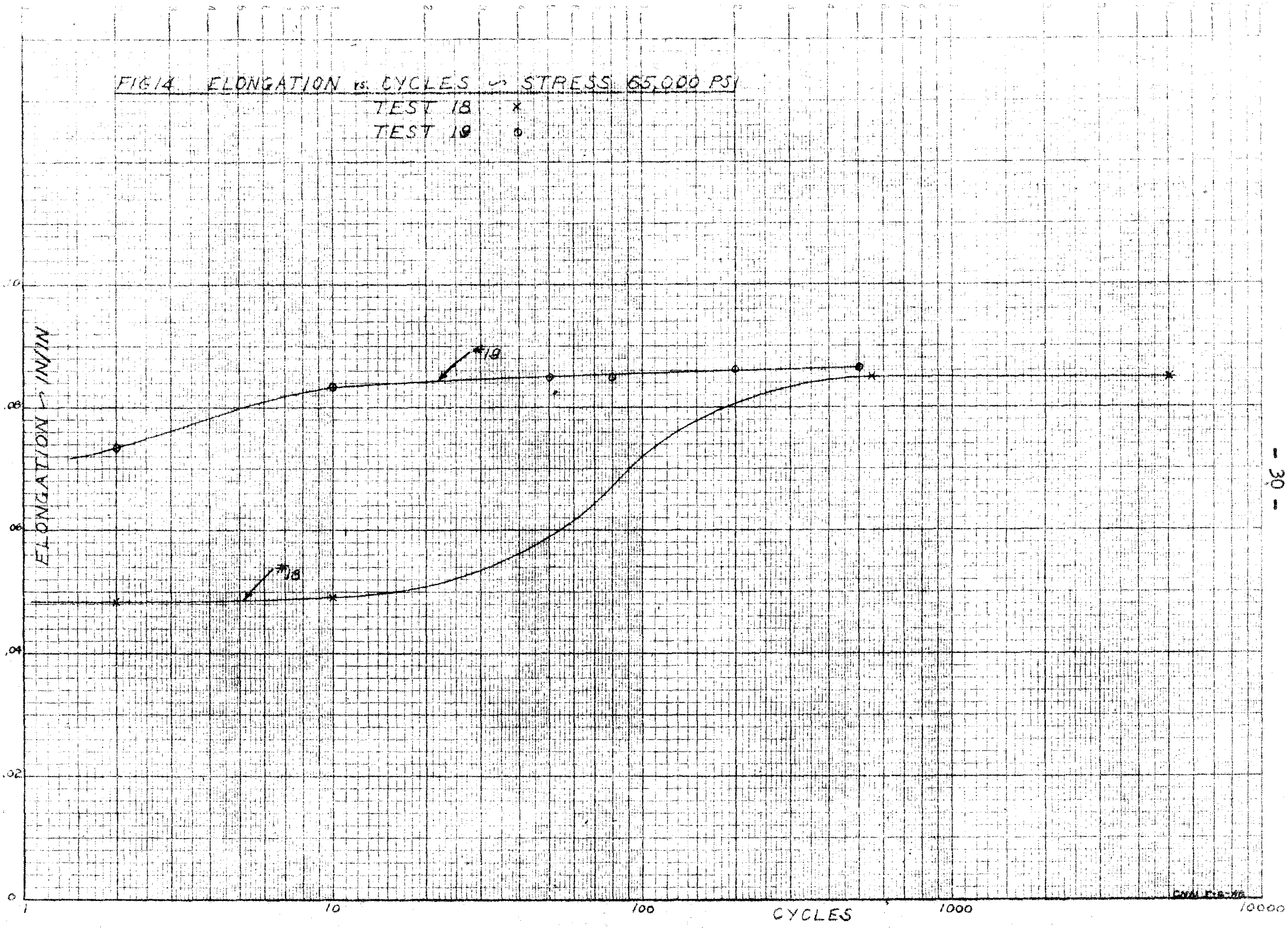


FIG 14 ELONGATION vs. CYCLES ~ STRESS 65,000 PSI

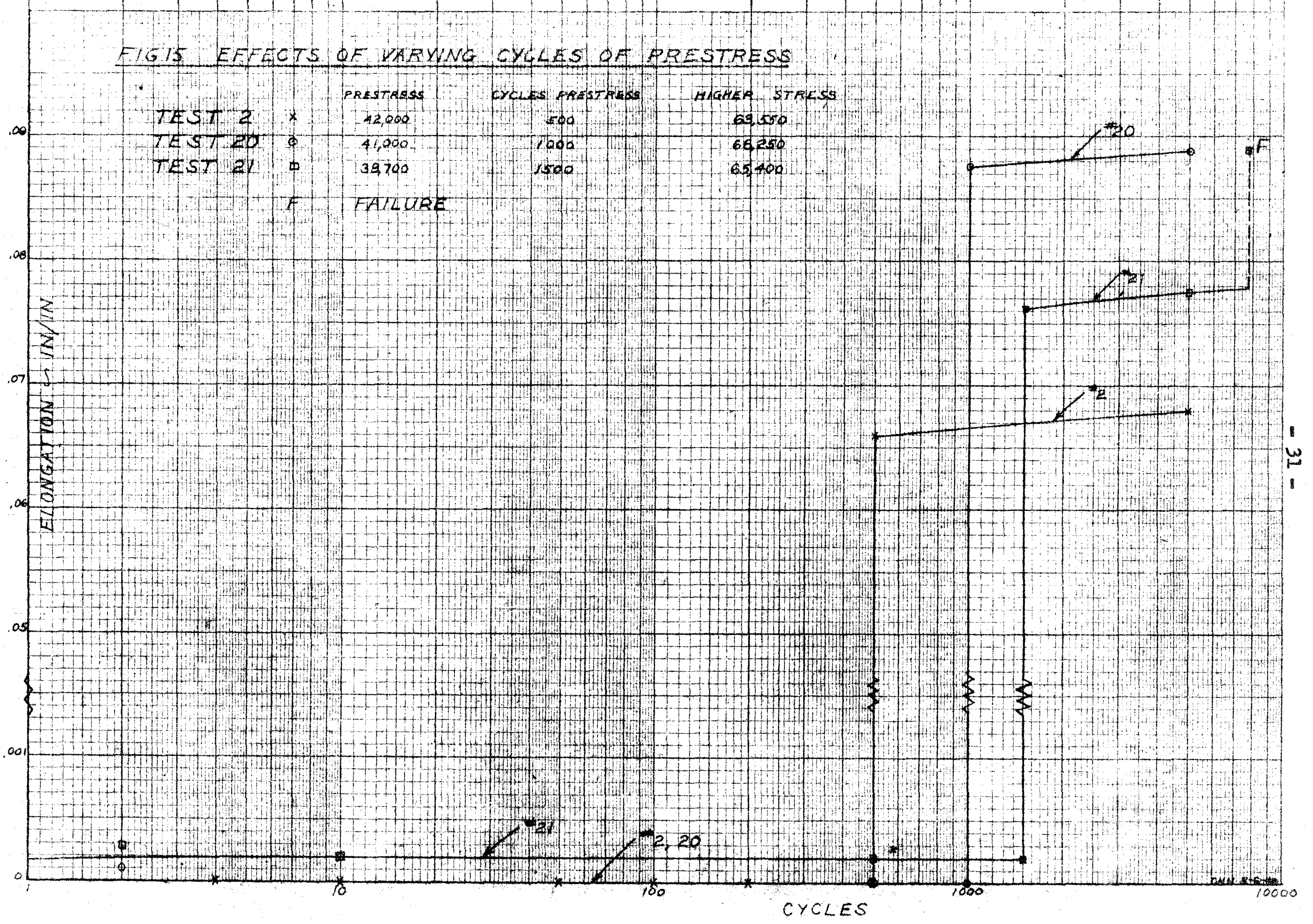


FIG 15 EFFECTS OF VARYING CYCLES OF PRESTRESS

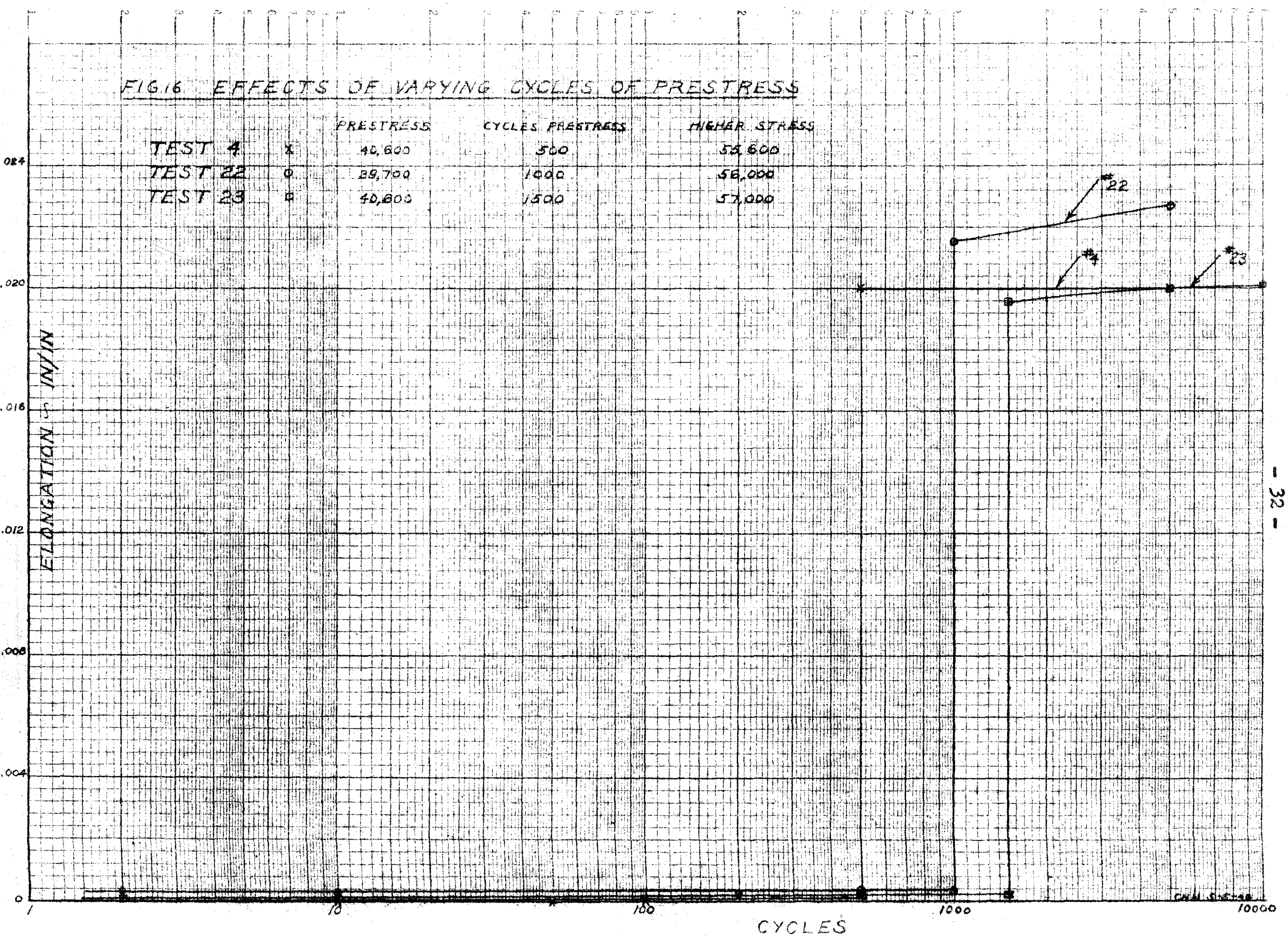


FIG.16 EFFECTS OF VARYING CYCLES OF PRESTRESS

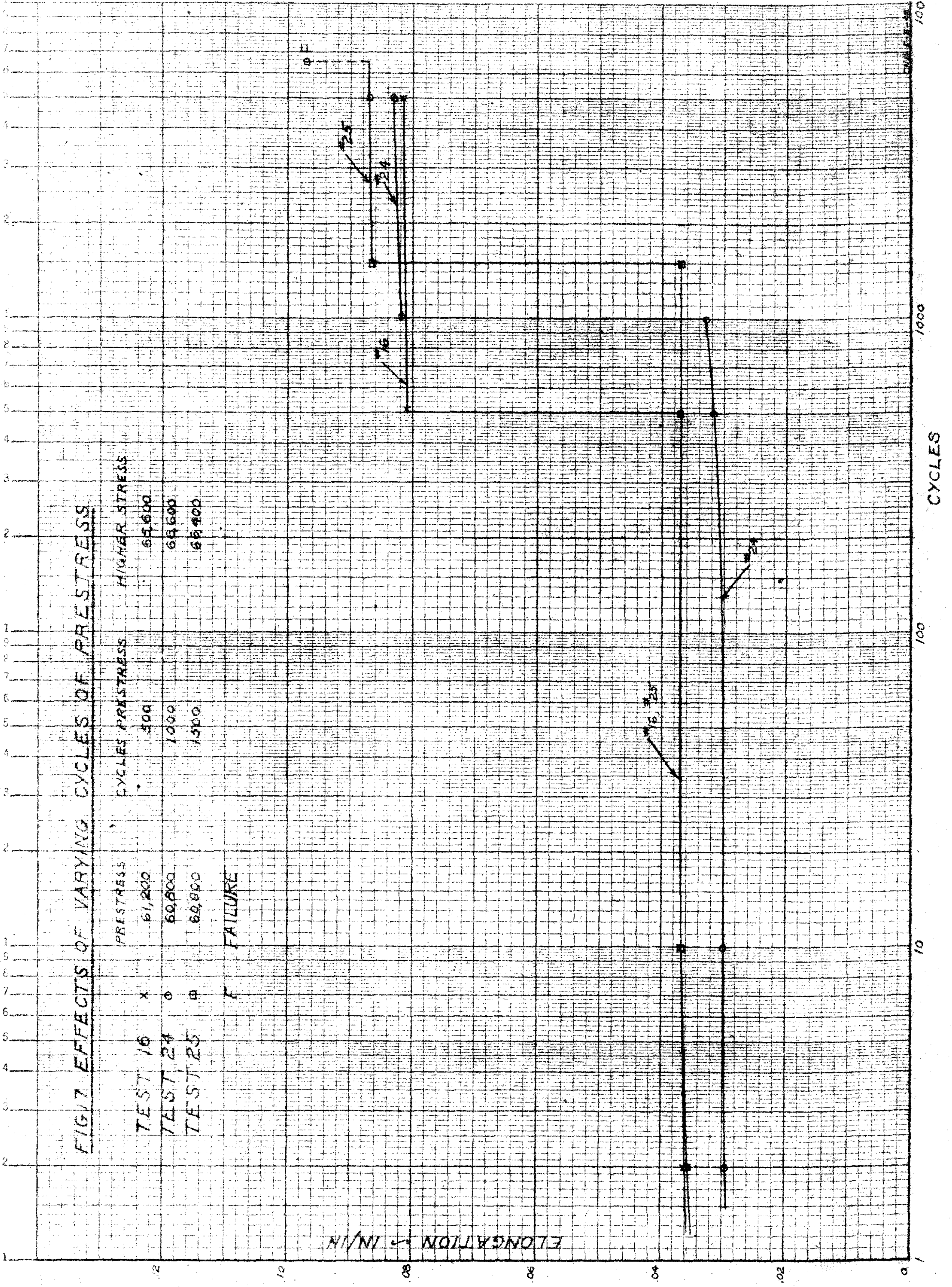


FIG 7 EFFECTS OF VARYING CYCLES OF PRESTRESS

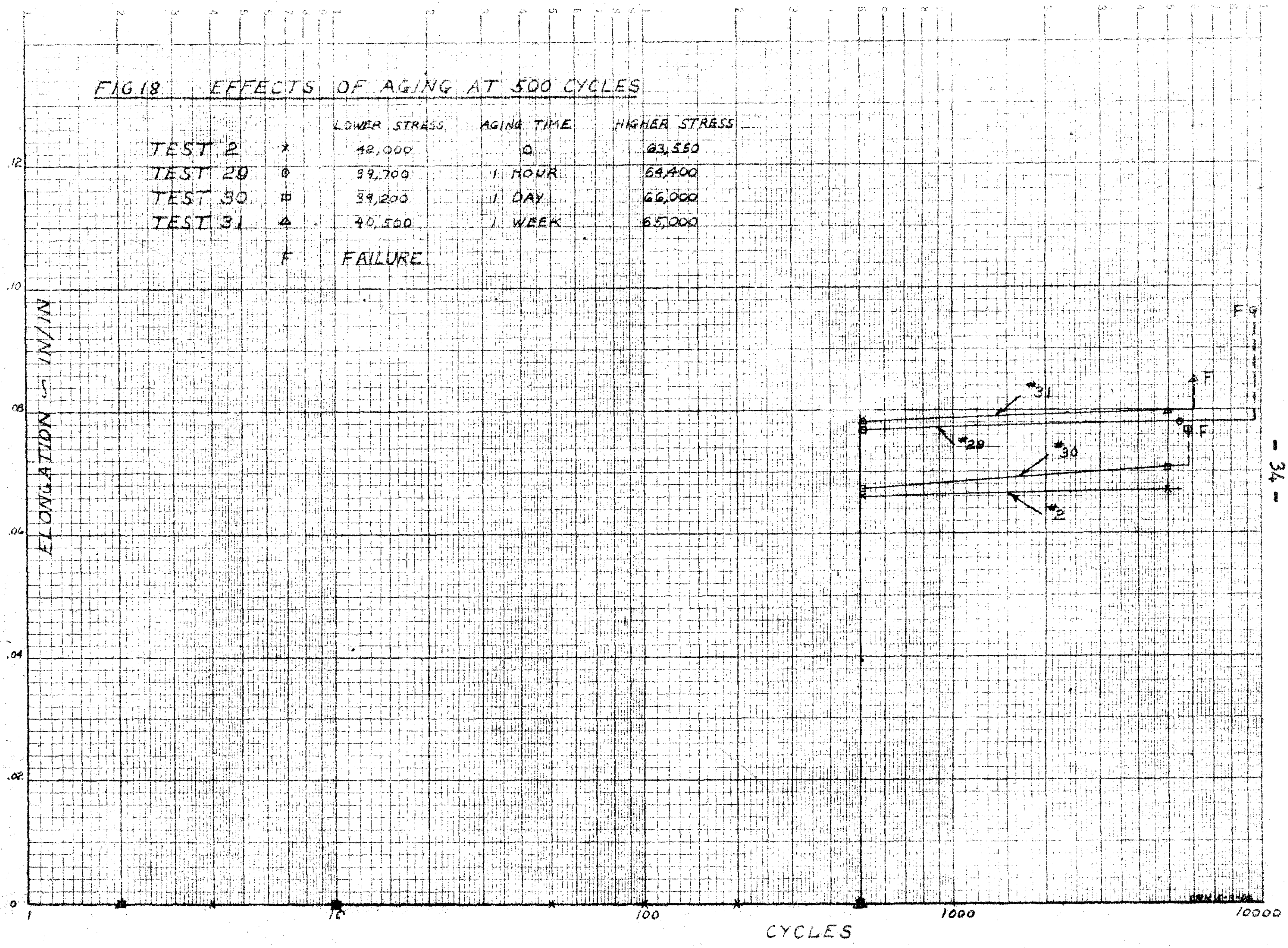
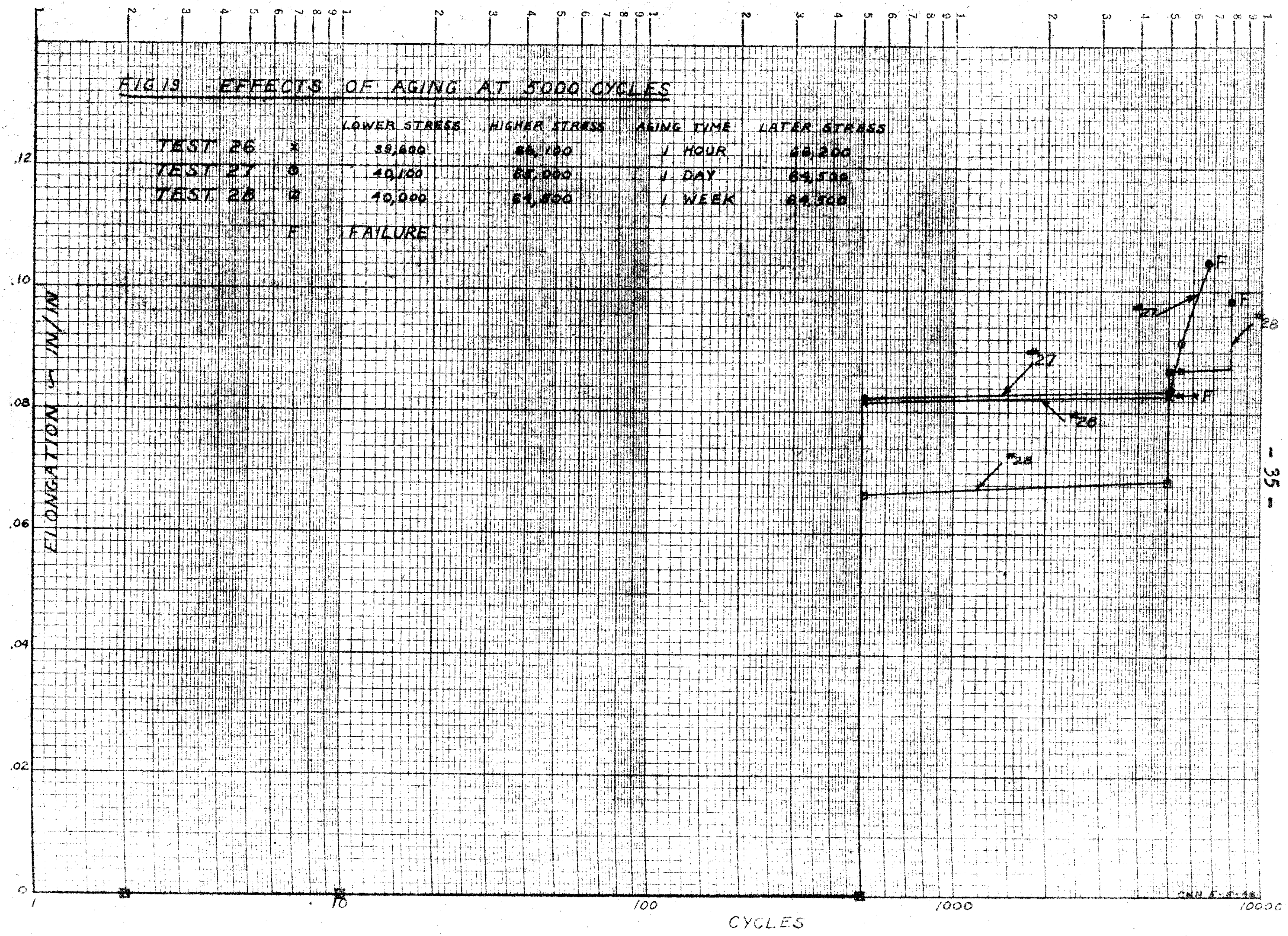


FIG 18 EFFECTS OF AGING AT 500 CYCLES

FIG 19 EFFECTS OF AGING AT 5000 CYCLES



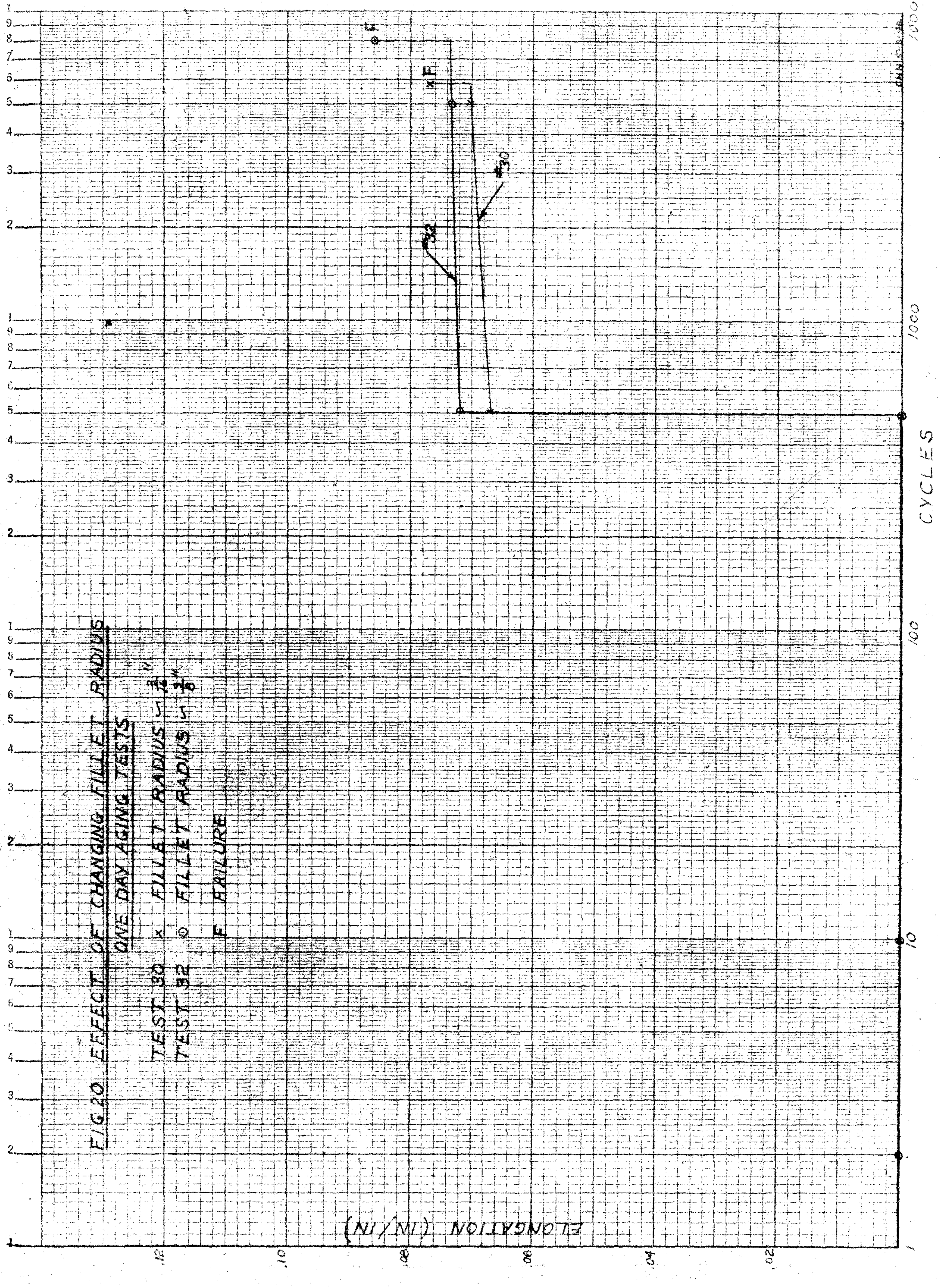


FIG 20 EFFECT OF CHANGING FILLET RADIUS

ONE DAY AGING TESTS

TEST 30 × FILLET RADIUS = 3/16"
TEST 32 ⊙ FILLET RADIUS = 3/8"
F FAILURE

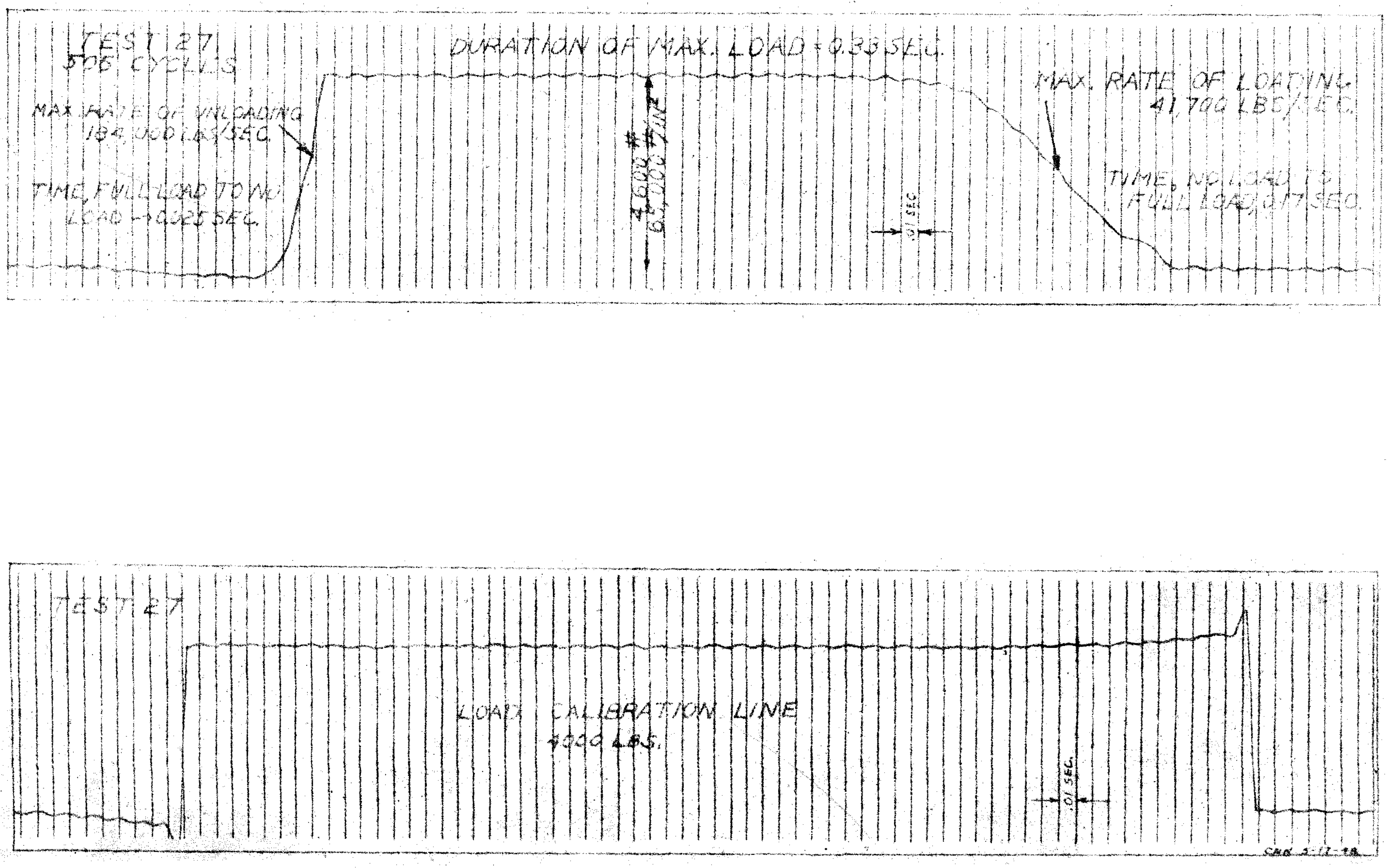
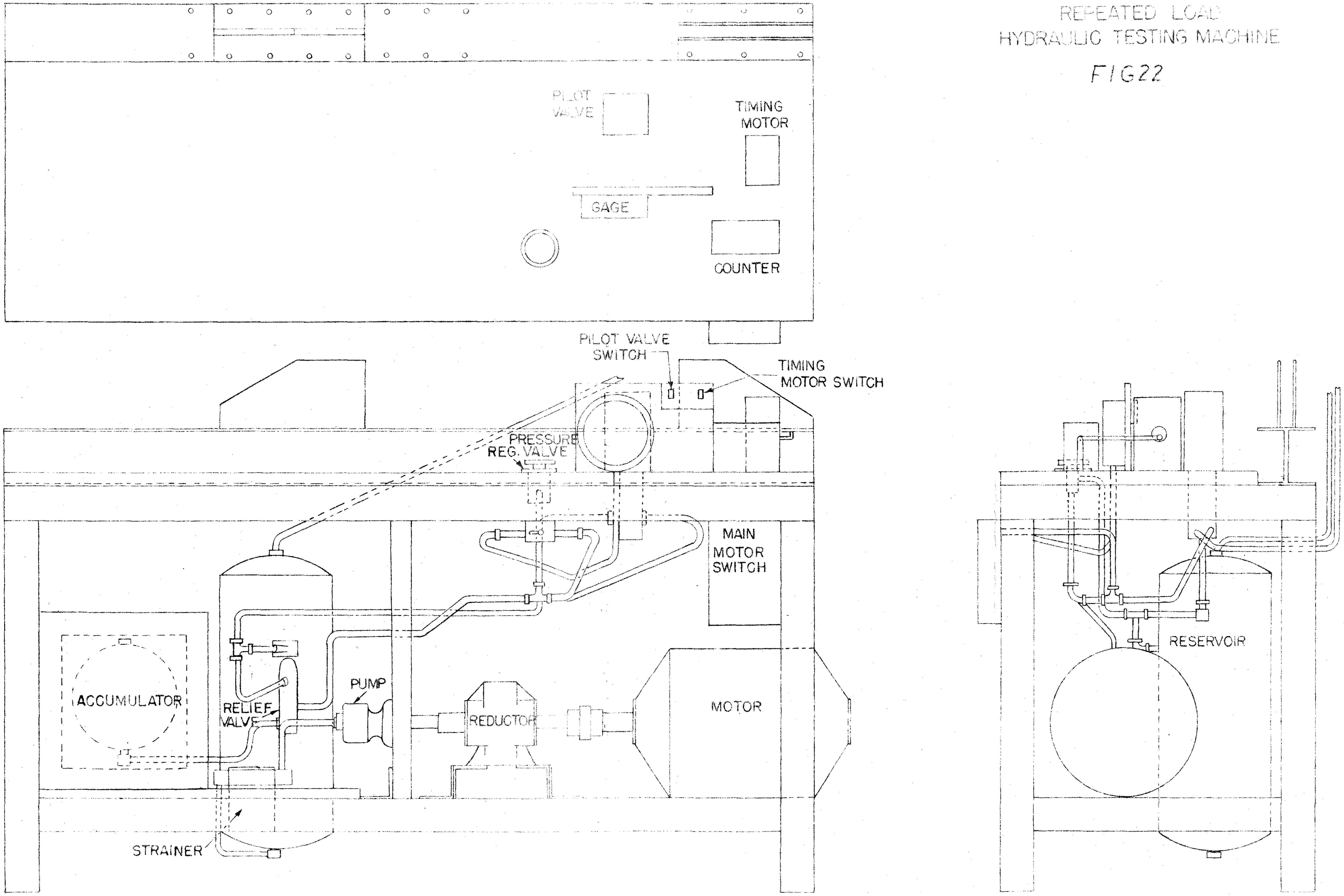
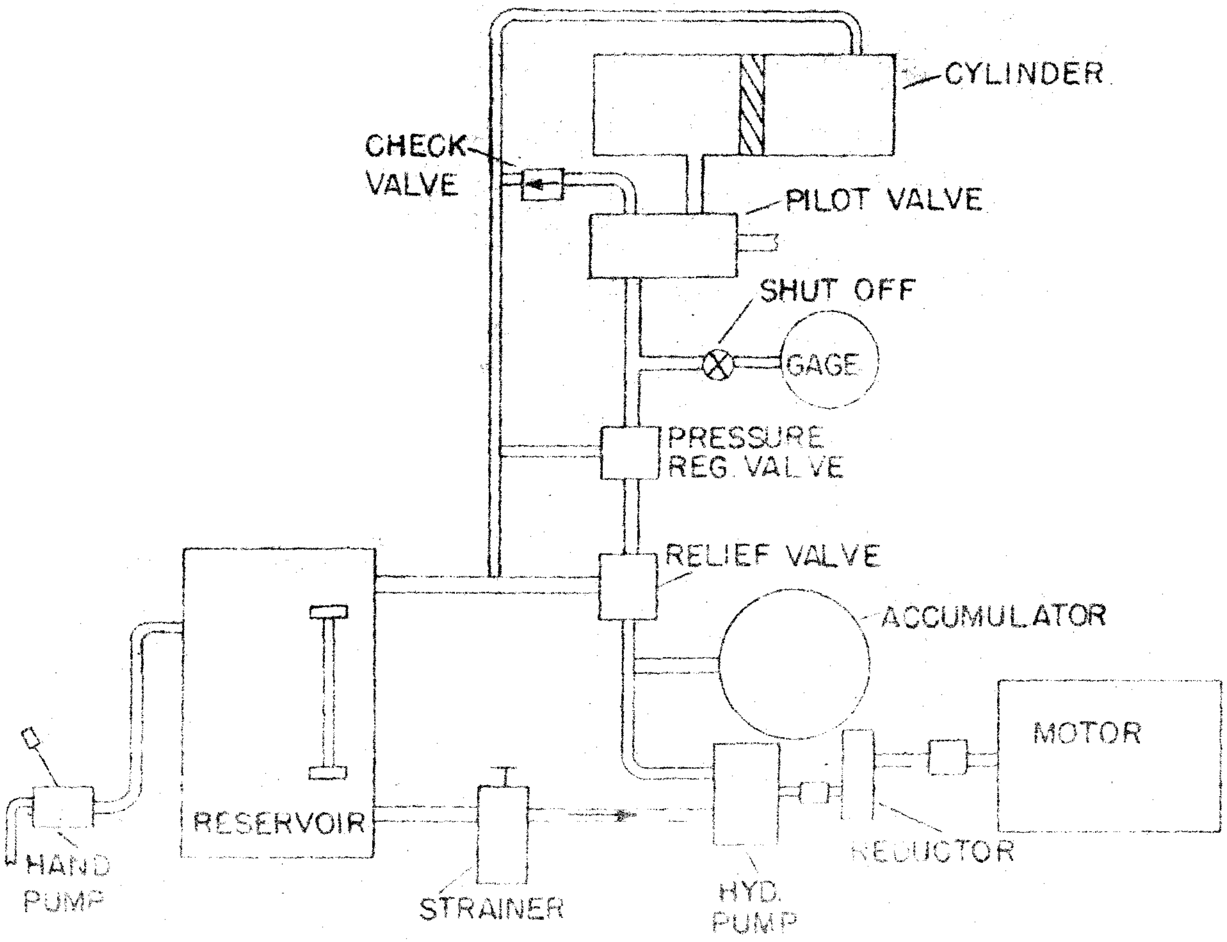


FIG. 21 – OSCILLOGRAPH RECORDINGS

REPEATED LOAD
HYDRAULIC TESTING MACHINE

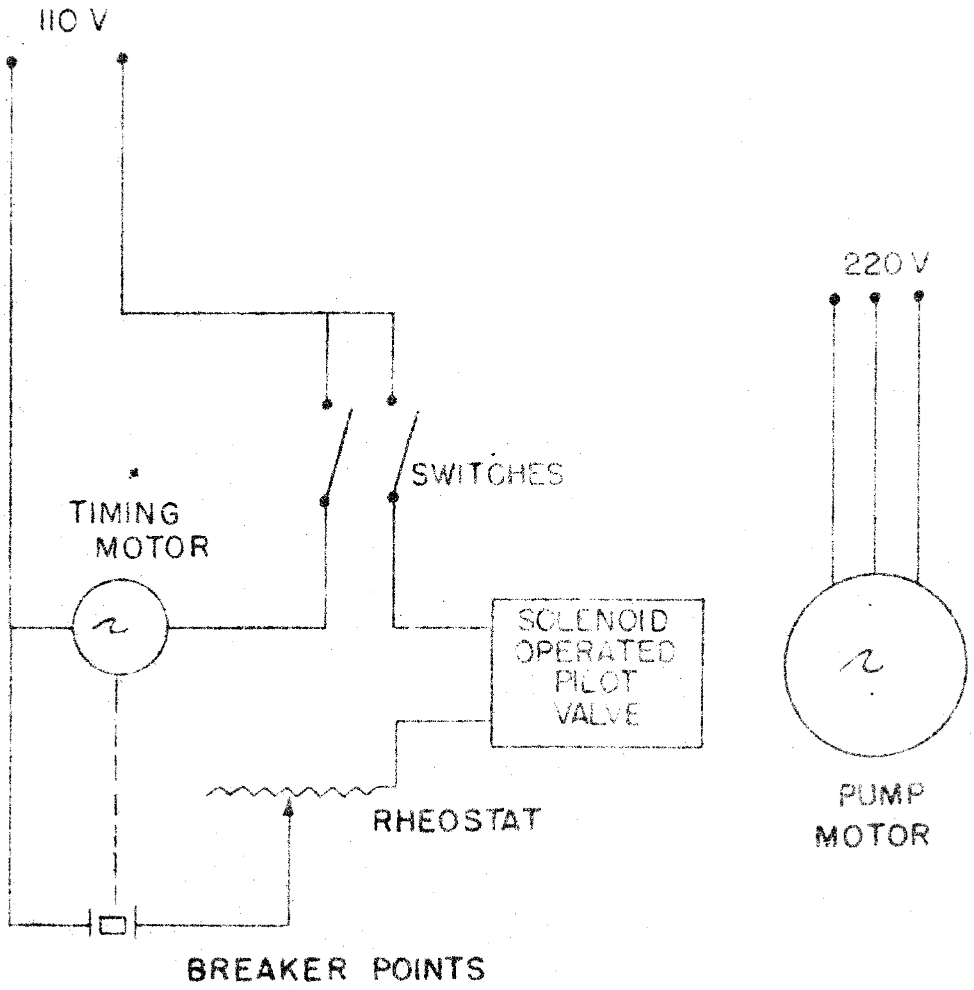
FIG 22





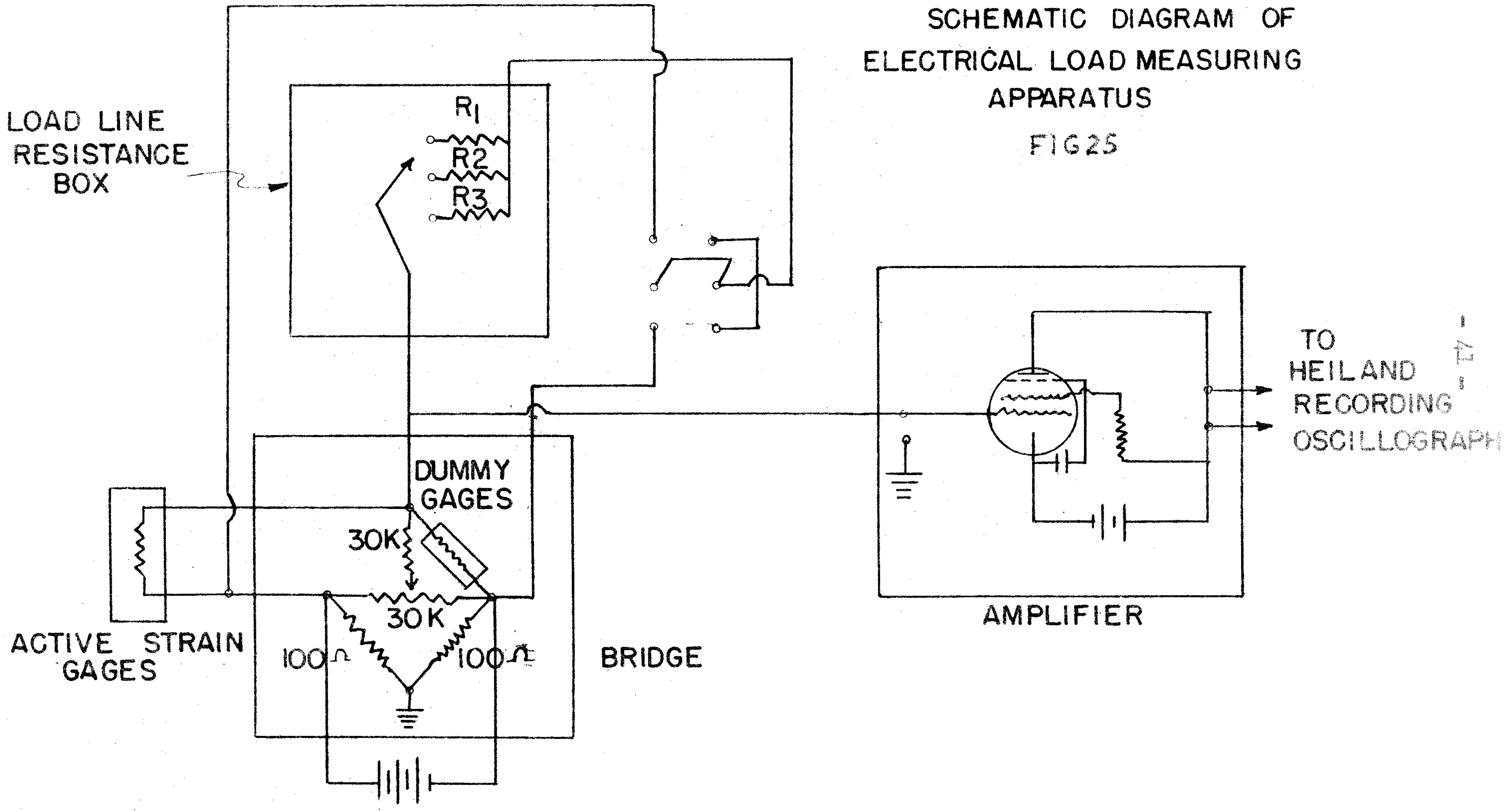
SCHEMATIC DRAWING OF HYDRAULIC SYSTEM

FIG.23



ELECTRICAL DIAGRAM
FOR
REPEATED LOADING
HYDRAULIC TESTING
MACHINE

FIG 24



SCHEMATIC DIAGRAM OF
ELECTRICAL LOAD MEASURING
APPARATUS

FIG 25

TABLES

TABLE S-1

Static Stress Strain Tests of 24ST

Specimen 1

Load (lb)	Stress (psi)	Strain (in/in)
0	0	0
500	7070	0.0006
1000	14,140	0.0014
1500	21,200	0.0020
2000	28,280	0.0026
2500	35,400	0.0033
3010	42,500	0.0043
3500	49,500	0.0165
3860	54,500	0.0512
4000	56,500	0.0350
4260	60,300	0.0550
4500	63,600	0.0625
4700*	66,500	0.1725

* Failure

TABLE S-2

Static Stress Strain Test of 24ST

Specimen 2

Load (lb)	Stress (psi)	Strain (in/in)
0	0	0
510	7220	0.0006
1000	14,150	0.0014
1510	21,400	0.0021
2015	28,500	0.0027
2490	35,200	0.0034
3000	42,500	0.0040
3510	49,100	0.0168
4000	56,600	0.0380
4260	60,500	0.0544
4500	63,600	0.0825
4690*	66,400	0.1950

* Failure

TABLE 1

Test 1

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	1.999	0
2	40,500	1.999	0
11	40,500	1.999	0
50	40,500	1.999	0
200	40,500	1.999	0
500	40,500	1.999	0
503*	68,100	2.388	0.1[illegible]4

* Failure

TABLE 2

Test 2

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	1.995	0
4	42,000	1.995	0
10	42,000	1.995	0
50	42,000	1.995	0
100	42,000	1.995	0
200	42,000	1.995	0
500	42,000	1.995	0
510	63,550	2.127	0.066
5100	63,550	2.128	0.067

TABLE 3

Test 3

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0085	0
10	41,600	2.0090	0.0002
50	41,600	2.0093	0.0004
100	41,600	2.0093	0.0004
500	41,600	2.0094	0.0004
510	59,500	2.0872	0.0392
5000	59,500	2.0915	0.0413

TABLE 4

Test 4

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0026	0
10	40,600	2.0026	0
50	40,600	2.0026	0
100	40,600	2.0026	0
200	40,600	2.0031	0.0002
500	40,600	2.0031	0.0002
510	55,600	2.0426	0.0200
5000	55,600	2.0427	0.0200

TABLE 5

Test 5

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	1.9995	0
10	45,500	2.0003	0.0004
50	45,500	2.0023	0.0014
100	45,500	2.0022	0.0014
500	45,500	2.0019	0.0012
510	64,750	2.1349	0.0677
5000	64,750	2.1372	0.0689

TABLE 6

Test 6

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0013	0
10	45,100	2.0035	0.0011
50	45,100	2.0033	0.0010
100	45,100	2.0030	0.0008
500	45,100	2.0030	0.0008
510	60,500	2.0774	0.0380
5000	60,500	2.0776	0.0381

TABLE 7

Test 7

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	1.9973	0
10	45,100	1.9982	0.0005
50	45,100	1.9989	0.0008
100	45,100	1.9989	0.0008
200	45,100	1.9989	0.0008
500	45,100	1.9986	0.0007
510	54,000	2.0432	0.0230
5000	54,000	2.0458	0.0243

TABLE 8

Test 8

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0019	0
10	45,600	2.0026	0.0003
50	45,600	2.0028	0.0004
100	45,600	2.0029	0.0005
200	45,600	2.0029	0.0005
500	45,600	2.0030	0.0005
510	51,900	2.0218	0.0099
5000	51,900	2.0221	0.0101

TABLE 9

Test 9

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	1.9893	0
10	51,500	2.0069	0.0088
50	51,500	2.0072	0.0090
100	51,500	2.0072	0.0090
200	51,500	2.0072	0.0090
500	51,500	2.0076	0.0092
510	63,800	2.1228	0.0671
5000	63,800	2.1613	0.0865

TABLE 10

Test 10

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0065	0
10	52,100	2.0296	0.0115
50	52,100	2.0296	0.0115
100	52,100	2.0295	0.0115
200	52,100	2.0295	0.0115
500	52,100	2.0295	0.0115
510	61,500	2.0623	0.0278
5000	61,500	2.0941	0.0436

TABLE 11

Test 11

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	1.9937	0
3	51,300	2.0156	0.0110
10	51,300	2.0160	0.0112
500	51,300	2.0162	0.0113
510	56,400	2.0392	0.0228
5000	56,400	2.0412	0.0238

TABLE 12

Test 12

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	1.9990	0
2	52,000	2.0110	0.0060
10	52,000	2.0170	0.0090
500	52,000	2.0176	0.0093
5000	52,000	2.0202	0.0106

TABLE 13

Test 13

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	1.9988	0
2	56,000	2.0391	0.0202
10	56,000	2.0391	0.0202
500	56,000	2.0406	0.0209
510	66,500	2.1567	0.0790
5000	66,500	2.1590	0.0801

TABLE 14

Test 14

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0031	0
2	55,200	2.0360	0.0164
10	55,200	2.0371	0.0170
500	55,200	2.0374	0.0171
510	60,900	2.0814	0.0391
5000	60,900	2.0818	0.0393

TABLE 15

Test 15

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0003	0
2	56,400	2.0411	0.0204
10	56,400	2.0406	0.0201
500	56,400	2.0406	0.0201
5000	56,400	2.0413	0.0205

TABLE 16

Test 16

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0071	0
2	61,200	2.0795	0.0361
10	61,200	2.0808	0.0367
500	61,200	2.0817	0.0371
510	65,600	2.1692	0.0808
5000	65,600	2.1707	0.0815

TABLE 17

Test 17

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	1.9970	0
2	61,600	2.0667	0.0349
12	61,600	2.0693	0.0362
550	61,600	2.0710	0.0371
5000	61,600	2.0730	0.0381

TABLE 18

Test 18

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0033	0
2	66,300	2.1007	0.0486
10	66,300	2.1017	0.0491
550	66,300	2.1735	0.0850
5000	66,300	2.1740	0.0852

TABLE 19

Test 19

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0114	0
2	65,000	2.1590	0.0734
10	65,000	2.1760	0.0818
50	65,000	2.1772	0.0824
80	65,000	2.1775	0.0826
200	65,000	2.1788	0.0832
500	65,000	2.1786	0.0831

TABLE 20

Test 20

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0175	0
2	41,000	2.0178	0.0001
10	41,000	2.0179	0.0002
500	41,000	2.0176	0.0000
1000	41,000	2.0176	0.0000
1010	66,250	2.1945	0.0877
5000	66,250	2.1952	0.0881

TABLE 21

Test 21

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	1.9989	0
2	39,700	1.9995	0.0003
10	39,700	1.9993	0.0002
500	39,700	1.9992	0.0002
1500	39,700	1.9993	0.0002
1510	65,400	2.1510	0.0761
5000	65,400	2.1538	0.0775
7664*	65,400	2.1750	0.0881

* Failure

TABLE 22

Test 22

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0016	0
2	39,700	2.0023	0.0003
10	39,700	2.0023	0.0003
500	39,700	2.0025	0.0004
1000	39,700	2.0023	0.0003
1010	56,000	2.0446	0.0215
5000	56,000	2.0470	0.0227

TABLE 23

Test 23

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0010	0
2	40,600	2.0012	0.0001
10	40,600	2.0012	0.0001
500	40,600	2.0012	0.0001
1500	40,600	2.0015	0.0002
1510	57,000	2.0402	0.0196
5000	57,000	2.0410	0.0200
10000	57,000	2.0412	0.0201

TABLE 24

Test 24

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0022	0
2	60,800	2.0612	0.0295
10	60,800	2.0625	0.0301
500	60,800	2.0658	0.0318
1000	60,800	2.0685	0.0331
1010	66,000	2.1662	0.0819
5000	66,000	2.1685	0.0831

TABLE 25

Test 25

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0012	0
2	60,900	2.0725	0.0356
10	60,900	2.0741	0.0364
500	60,900	2.0751	0.0369
1500	60,900	2.0755	0.0371
1510	66,400	2.1747	0.0867
5000	66,400	2.1753	0.0870
6507*	66,400	2.1964	0.0970

* Failure

TABLE 26

Test 26

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	1.9956	0
2	39,600	1.9958	0.0001
10	39,600	1.9959	0.0002
500	39,600	1.9960	0.0002
510	66,100	2.1588	0.0818
5000	66,100	2.1598	0.0828
	Aged for 1 hour		
5010	66,200	2.1610	0.0829
5500	66,200	2.1617	0.0832
6120*	66,200	2.1609	0.0828

* Failure

TABLE 27

Test 27

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0008	0
2	40,100	2.0010	0.0001
10	40,100	2.0012	0.0002
500	40,100	2.0012	0.0002
510	65,000	2.1654	0.0823
5000	65,000	2.1682	0.0837
	Aged for 1 day.		
5010	64,500	2.1685	0.0839
5500	64,500	2.1842	0.0917
6692*	64,500	2.2100	0.1046

* Failure

TABLE 28

Test 28

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	1.9984	0
2	40,000	1.9986	0.0001
10	40,000	1.9989	0.0003
500	40,000	1.9989	0.0003
510	64,500	2.1306	0.0662
5000	64,500	2.1356	0.0687
	Aged for 1 week		
5010	64,500	2.1720	0.0869
5500	64,500	2.1726	0.0872
7996*	64,500	2.1953	0.0985

* Failure

TABLE 29

Test 29

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	1.9993	0
2	39,700	1.9994	0.0000
10	39,700	1.9995	0.0001
500	39,700	1.9996	0.0002
	Aged for 1 hour		
510	64,400	2.1535	0.0771
5500	64,400	2.1552	0.0780
9422*	64,400	2.1913	0.0960

* Failure

TABLE 30

Test 30

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0048	0
2	39,200	2.0053	0.0002
10	39,200	2.0053	0.0002
500	39,200	2.0056	0.0004
Aged for 1 day			
510	66,000	2.1395	0.0672
5000	66,000	2.1457	0.0703
5800*	66,000	2.1600	0.0774

* Failure

TABLE 31

Test 31

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	1.9996	0
2	40,500	2.0000	0.0002
10	40,500	2.0002	0.0003
500	40,500	2.0002	0.0003
		Aged for 1 week	
510	65,000	2.1559	0.0781
5000	65,000	2.1585	0.0795
6032*	65,000	2.1700	0.0852

TABLE 32

Test 32 (with the radius of the fillets doubled)

Cycles	Stress (psi)	Length (in)	Strain (in/in)
0	0	2.0058	0
2	40,000	2.0071	0.0006
10	40,000	2.0071	0.0006
500	40,000	2.0066	0.0004
	Aged for 1 day		
510	65,800	2.1504	0.0721
5000	65,800	2.1531	0.0734
7940*	65,800	2.1786	0.0862

* Failure

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. 23).

From the reservoir containing 4½ 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 lbs. 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. 24.

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.

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 accompanying 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 built 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.