REPEATED LOADS ABOVE THE PROPORTIONAL LIMIT ON 24-ST ALUMINUM ALLOY

Thesis by

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

Acknowledgement is also made to Mr. M. E. Jessey for the construction and revision of the electrical measuring apparatus.

The research was carried out in collaboration with Mr. Chintakindi V. JogaRao.

REPEATED LOADS ABOVE THE PROPORTIONAL LIMIT ON 24ST ALUMINUM ALLOY

Summary

The purpose of this investigation was to study the effect of repeated tensile stresses above the proportional limit on 24ST aluminum alloy.

The investigation consisted in obtaining data on prepared specimens of 24ST aluminum alloy in a machine capable of applying a pure tension stress, repeated many times a minute, without shock but with a high rate of loading.

It was found that permanent deformation caused by overstressing is not a useful factor in forecasting the life expectancy of the specimen being tested.

It was also found that the effects of "aging" (elapsed time between overstresses), initial stresses, and magnitude of overstresses applied, all have a definite influence on the ability of 24ST aluminum alloy to withstand further overstressing. However, these effects are so scattered between different specimens of the same material that they cannot be determined accurately, either qualitatively or quantitatively, without a thorough statistical survey.

It is considered that this investigation merely points the way to a further study of the behavior of all aircraft materials above the proportional limit.

The investigation was carried out at the Daniel Guggenheim Aeronautical Laboratory, California Institute of Technology, Pasadena, California. (referred to hereafter as GALCIT.)

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REPEATED LOADS ABOVE THE PROPORTIONAL LIMIT

ON 24ST ALUMINUM ALLOY

I. Introduction

The purpose of this investigation was to study the effect of repeated tensile stresses with a high rate of loading above the proportional limit on 24ST aluminum alloy.

Lieutenant Commanders Edward G. Bull and Robert L. Mastin, U.S. Navy designed and built the testing machine used for these tests and began this investigation during the school year 1946-1947 in partial fulfillment of their requirements for the Professional Degree. Prior to their tests, little experimental data had been made available covering this phase of structural research. The problem is enormous, including an infinite number of combinations of metals, their alloys, structural shapes and types of loading. This investigation only deals with one material (24ST aluminum alloy) and one type of specimen (pure tension specimen) but with several types of loadings, from which can be decided the direction that future research should pursue.

Considerable time was spent in the revision of the testing machine as built by Bull and Mastin and in the development of procedures and techniques which would permit the investigation to proceed more rapidly with more accurate measurement of the elongations and transient stress.

This investigation was carried out at GALCIT.

II. Equipment

Test Specimens

The material used in the test was standard 5/8" bar stock 24ST aluminum alloy. Three bars of this material from the same heat were required for these tests. The test specimens were machined to the shape and dimensions as shown in Figure 1, except for Specimen No. 32 which had 3/8" radius fillets instead of 3/16" radius fillets. Each specimen was carefully made in accordance with the customary high standards of experimental work to eliminate residual stresses from machining and were polished to a high degree on the test section to avoid any minute scratches and nicks.

Testing Machine

The testing machine was designed and built in the 1946-1947 school year at CIT by Lieutenant Commanders Soli, Bull, and Mastin, and Lieutenant Ditch, all of the U.S. Navy. (See Reference 1.) It incorporates a high rate of loading without the possibility of sudden shock. This property must be obtained if the simulated loading is to be comparable to the loading of an aircraft structural member in flight.

The machine was modified slightly by Mr. Chintakindi V. JogaRao and the author to stiffen the H-beam base of the test platform. This removed the possibility of introducing high transitory loads on the test specimen from deflection of the test platform base under load.

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. Because the pump runs at constant speed, a pressure regulating valve is installed in the system to vary the hydraulic pressure fed to the hydraulic piston up to 1000 psi. A pressure-relief valve is installed as a safety measure to lift at 1250 psi. To automatically apply the stress and relieve it, a Vickers pilot control valve is used. This valve is solenoid-operated, the solenoid in turn being operated by contact points which are opened and closed by a cam driven by a 1/20 H.P. universal-wound 110-volt a.c. electric motor. This motor also operates a mechanical counter to record the number of cycles of stress. The counter indicates exactly 1/2 the actual number of cycles which have been applied to the specimen. A standard aircraft-type hydraulic cylinder, 5 inches in diameter, is used to apply the load to the specimen. Based on 1000 psi., this cylinder will give a maximum load on the specimen of about 11,500 pounds. With the cross-section area of the specimen of 0.0707 sq. in., the maximum possible stress is about 162,800 psi.

Further description of the testing machine, including schematic drawings and diagrams, are included in the Figures and Appendix of this report.

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" is installed between the hydraulic piston and the specimen. Figure 2 is a drawing of the load coupon.

Mounted on the coupon are four SR-4 Type A-1 electric strain gages manufactured by the Baldwin-Southwark Company. These gages were connected in series to remove any effects of bending.

Strain 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 approximately 2 inches. Methyl violet was applied to the test area of the specimens and fine gage marks made with dividers. Measurement of elongation by this means was found to be very tedious and lengthy and required considerable skill and experience on the part of the operator before satisfactory length measurements to the full accuracy of the apparatus could be realized.

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 consists essentially of the load coupon on which four electric strain gages are mounted in series. The signal caused by the change of resistance of the gages with changes in load is sent through an amplifier to a Heiland Recorder. This recording oscilloscope makes a photographic record of Load vs. Time. Incorporated into the electrical system is a means of putting a known-load line onto the photographic record for calibration purposes. This was accomplished along with the calibration of the strain gages on the load coupon by finding experimentally the amount of resistance required to be connected in parallel with the strain gages to give the effect of applying loads of 1000 2000, 3000 and 4000 pounds to the load coupon.

By incorporating these resistances in the electrical circuit and connecting them to a selector switch, it was possible to select either 1000, 2000, 3000 or 4000 pounds and place a calibrating line for one of the four loads on the recording tape. Then, after developing the record, the Load vs. Time curve could be compared with the calibrating line, and thus the stress on the specimen could be obtained 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 could be obtained as often as desired. Figure 21 shows an oscillograph recording for Test 27 at 505 cycles. This recording is typical of those obtained on all tests. An analysis of Figure 21 yields the following information:

Duration of Zero Load	0.63 sec.
Duration of Maximum Load	0.33 sec.
Time - No Load to Full Load	0.17 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.

The author modified the equipment slightly from that developed by Bull and Mastin. The positioning of the galvanometer in the in the Heiland Recorder was so adjusted that the full width of the recording tape could be used for tension stresses. Then, The sensitivity of the strain gages was doubled by doubling the voltage applied across them. Thus, the accuracy of measurement of the maximum load on the specimen was doubled.

Since the rate of loading of the specimen had been established by Bull and Mastin as being satisfactory, the only data of use from the photographic record of the oscillograph was the maximum stress on the specimen per cycle. Therefore, the possibility of utilizing a large oscilloscope with a retentive screen to measure this maximum stress was investigated. However, it was found that the frequency range of the oscilloscope did not allow proper signal response. The frequency of the testing machine was too low to be handled properly.

III. Initial Calibrations

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. The gage was calibrated statically against load in the cylinder, the curve for which appears in Figure 3. By incorporating the cross-sectional area of the specimen with the calibration, a second calibration of stress in the specimen vs. gage reading was obtained and appears in Figure 4. However, this calibration was found to be of little use in the prediction of the load on the specimen vs. the pressure gage reading during the dynamic tests. By setting the pressure gage with the hydraulic pump operating but with the solenoid motor shut off, it was then possible to start the operation of the solenoid valve and measure the load in the specimen by means of the load coupon. The Dynamic Calibration Curve is a plot of the dynamic load on the specimen vs. the pressure gage reading. However, this curve could not be used to full advantage because of the extremely small scale of the pressure gage, which did not allow reading or setting the hydraulic pressure to closer than plus or minus 5 psi.

Calibration of the Load Coupon

The calibration of the load coupon was carried out using the Baldwin-Southwark testing machine located in the structures laboratory of GALCIT. Electrical measurements were made with a sensitive potentiometer.

Each gage was first checked separately for change in e.m.f. drop across it (measured in millivolts) vs. load applied to the coupon. This plot is shown in Figure 5. This individual calibration was required to ascertain the relative effectiveness of each gage and to determine whether each gage was satisfactorily attached to the load coupon. Since each gage plotted as a straight line over the load range, this indicated that they were satisfactorily attached.

After connecting all four gages in series, the above process was repeated, obtaining change in e.m.f. drop across the gages (millivolts) vs. load on the coupon. This data is given in Figure 6.

During the calibration of the strain gages in series, the amount of resistance was determined which, when placed in parallel with the strain gages, would give the same change in the resistance of the combination that was obtained by applying loads of 1000, 2000, 3000, and 4000 pounds to the load coupon. This information was used in the calibration of the dynamic load measuring equipment as described under that section of the report.

IV. Test Procedure

A complete record of each test is included in Tables 1 - 32, inclusive.

Prior to any of the fatigue tests, two static tests were made of specimens selected at random from the batch of specimens made up in the GALCIT machine shop. As explained previously in this report, the material from which these specimens were made came from 3 pieces of bar stock, 24ST aluminum alloy, all taken from the same heat. The stress-strain curve obtained from these two tests is given in Figure 8.

A series of 32 fatigue tests were then run under widely varying conditions. These tests were chosen in such a way as to permit determination of the effect of several individual parameters on the life of the specimen.

The parameters which were investigated were:

a. Initial Loading

   1. Cycles - 500, 1000 1500.
   2. Stress - 40,000, 45,000, 50,000, 55,000, 60,000 and 65,000 psi.

b. Later Loading

   1. Cycles - 5000, 10,000 or break. Only the aging tests and the tests with 1500 initial-stress cycles were carried beyond 5000 cycles.
   2. Stress - 50,000, 55,000, 60,000 and 65,000 psi.

c. Aging - one hour, one day, and one week.

Because of the limited time available, no investigation was made of the numerous other parameters that can conceivably affect the life of the specimen under fatigue, such as the frequency of loading, etc.

V. Results and Discussion

Static Tests

The results of the two static tests are both plotted in Figure 8. The tests gave practically identical results except for the ultimate elongation. Therefore, only one curve could be drawn for the two tests, and the mean results are tabulated below and compared with the results of Bull and Mastin. Both tests were for 24ST material.

	JogaRao & Nelson	Bull & Mastin	
Proportional Limit	41,500 psi.	37,500 psi.	34,000 psi.
Defined Yield Stress (0.02% offset)	43,700 psi.	50,000 psi.	42,500 psi.
Ultimate Strength	66,450 psi.	72,000 psi.	66,000 psi.
Elongation	18.38%	No reading	16.08%

As can be seen by comparing the results of the two sets of tests above, there are wide discrepancies in the physical properties of nominal 24ST aluminum alloy. This would indicate that the pattern of the results of the fatigue tests would be scattered. Such has been found to be the case, particularly in a comparison of the elongation of different specimens, even under identical loading conditions.

Fatigue Tests

An examination of Tables 1-32 and Figures 9-20 shows that for stresses above the yield stress of the material, the greater part of the elongation of the specimen occurs in the first few cycles. This was found to be generally true for both the initial stressing and the later (higher) stressing. In only one isolated instance was this found not to be the case (see Figure 14 and Table 18), and even in this case it was impossible to duplicate the elongation results under identical loading of the specimens. In this test, which applied an initial stress of 65,000 psi. to the specimen, the elongation increased as expected in the first ten cycles. However, there was a subsequent large increase in elongation between 10 and 500 cycles, which was not to be expected without failure of the specimen. After this second increase in elongation, the specimen remained essentially unchanged in length from 500 to 5,000 cycles, at which point the test was stopped. To investigate this phenomenon more thoroughly, another specimen was subjected to the same loading conditions, but it reacted normally in every way, i.e. the greater part of the elongation took place prior to 10 cycles. It is interesting to note that the final elongation of the two specimens at 500 cycles was within 2.2%.

These facts definitely preclude any chance of obtaining a useful relationship between elongation and remaining life in a specimen after a certain number of cycles of fatigue stressing.

Another unexplainable phenomenon that was observed during the initial stressing of specimens was the tendency of the specimens to have a negative elongation immediately after the cessation of stressing. Then, as the specimen "rested" it gradually increased in length until it reached the elongation it would have been expected to have if this phenomenon had not occurred. Equilibrium was reached after about 10 minutes. This negative elongation was very small and only became apparent between 50 and 500 cycles for initial stresses at or below the proportional limit. It was thought at first that this "negative elongation" was actually a temperature effect caused by either the conduction of heat from the fluid in the hydraulic cylinder, or from the drop in temperature of the specimen after handling during installation. However, neither of these causes will give the observed results, especially when the phenomenon occurs again and again at 50, 100, 200 and 500 cycles.

Since this phenomenon was not completely investigated and understood until several tests had been completed, the strains for these tests may not be entirely correct in the 4th decimal place and therefore were rounded off to three decimal places.

Effect of Changing the Value of the Initial Stress

The final elongation (5000 cycles) of the specimens was found to be essentially independent of the magnitude of the initial stress. The notable exceptions to this statement occurred in Tests 9 and 10 (see Figure 11.). In these cases, the elongation at 510 cycles (just after applying the higher stress) was considerably lower than the average of the elongation in comparable tests. However, in both cases the elongation increased appreciably and finally ended up with a higher final elongation (at 5000 cycles) than in comparable tests. Thus we have another phenomenon that would point toward the necessity of applying the methods of statistical analysis to this investigation. With so much variation in the behavior of different specimens from the same piece of bar stock, it is imperative that the behavior of specimens from different heats and different mills be investigated before the results of this survey will be of use to the aircraft industry.

Effect of Varying the Number of Cycles of Initial Stress

The effect on specimen life expectancy of varying the cycles of initial stress was not investigated, because only the aging tests and the three tests with 1500 cycles initial stress were carried beyond 5000 cycles.

The effect on the final elongation (at 5000 cycles) of varying the number of cycles of initial stress can not be determined with the few results which have been obtained to date. These results are contradictory, as can be seen by examining Figures 15, 16 & 17. However, these graphs seem to indicate that the higher the initial stress, the less difference there is in the final elongation (5000 cycles) for the three initial-stress cycles investigated. Thus, with an initial stress of approximately 40,000 psi. and a final stress of approximately 65,000 psi., the 1000 cycle initial-stress specimen had considerably more elongation than the 1500 cycle specimen. In the case where the initial stress was approximately 60,000 psi. and the final stress approximately 65,000 psi., the 1500 cycle initial-stress specimen elongated more than the 1000 cycle specimen, which in turn elongated slightly more than the 500 cycle specimen. These results would seem to indicate that the higher the initial stress, the less difference there is in the final elongation (5000 cycles) for the three initial-stress cycles investigated. But nothing can be said regarding the effect of changing the number of initial-stress cycles at a fixed initial stress and final stress. Here again, statistical analysis would seem to be the best method of approach.

Effect of Varying Final Stress on Specimen

As was to be expected, the final elongation of the specimen was a direct function of the magnitude of the final stress. The higher the final stress, the greater the elongation. Little investigation was made of the variation of life expectancy with magnitude of the final stress. The only specimen that broke prior to 5000 cycles was loaded to 68,100 psi. (above the static test ultimate stress) after 500 initial-stress cycles and withstood only 3 additional cycles before fracture. Of the specimens carried beyond 5000 cycles, only one (Test 23) reached 10,000 cycles without failure. Its final stress was approximately 55,000 psi. The remaining specimens were loaded to approximately 65,000 psi. final stress with the application of various aging times. They all broke between 5800 and 9422 cycles.

Effects of Aging

On the basis of these test results, no conclusions can be drawn on the absolute effects of aging time at either 500 cycles or 5000 cycles on the specimen life expectancy. In the first place the effects of aging at 500 cycles contradicts the effects of aging at 5000 cycles. For example, the specimen that was aged for one hour at 500 cycles withstood more cycles than the specimens aged at 500 cycles for one day and one week, while at 5000 cycles, the specimen aged for one hour withstood the least number of cycles of the three specimens. In the second place, the tests cannot be considered completely reliable since all the specimens broke in the fillet instead of in the center of the test section. This was evidently caused by a fatigue stress concentration in the vicinity of the fillet, because one additional specimen with a modified 3/8" radius fillet (Test 32) withstood over 2100 cycles more than the standard specimen with 3/16" radius fillet under identical loading

(Test 30), and failure occurred in the center of the test section.

In the light of the above facts, the author is inclined to doubt the value of any of the aging tests in determining the absolute effects of aging time on the life expectancy of the specimen. The most that can be said is that in comparing relative effects of the same aging treatment at 500 cycles and at 5000 cycles, the later treatment seems to yield longer specimen life than the former. Since most aircraft structural loads are not applied in endless succession as on the testing machine, but rather at infrequent intervals, with various long periods of "rest" during its life, the above fact would seem to indicate that the life expectancy of an aircraft structural member would be longer than would be determined in a continuous fatigue test. This phase of the general aircraft structural fatigue problem certainly bears further investigation.

VI. Conclusions

The following conclusions are obtained from this investigation:

1. That at tensile stresses above the proportional limit on 24ST aluminum alloy, almost all deformation takes place in the first ten cycles of applied stress. An exception to this may occur for very high tensile stresses approaching the static-test ultimate strength of the material.

2. That there is no relation between the elongation of a specimen and its life expectancy.

3. That the effects on the final elongation of varying magnitudes of initial stressing are negligible.

4. That the effects on the final elongation and life expectancy of varying cycles of initial stress and aging time are considerable, but that a statistical survey will be necessary to obtain qualitative and quantitative results suitable for use in aircraft design.

5. That the behavior of different specimens of 24ST aluminum alloy made from the same piece of material are sufficiently different under identical fatigue tests to call for a survey to determine the upper and lower limits of the behavior of all 24ST material to fatigue tests of this type.

VII. Recommendations

The following recommendations are drawn from this investigation:

1. That 24ST aluminum alloy by subjected to a complete statistical survey to definitely determine the effects of initial stress, aging and higher stress on the life expectancy and elongation of the material.

2. That other aircraft materials such as 75ST aluminum alloy and stainless steel be subjected to preliminary survey tests similar to those performed on 24ST in this investigation, and if found applicable, continue these tests as recommended above for 24ST.

3. That a completely different method of measuring specimen elongation be devised that would not be so tedious to the operator nor require so much time to adjust as the traveling microscope. Perhaps an optical means would be feasible.

4. That the standard tensile specimen shown in Figure 1 be modified to provide 3/8" radius fillets instead of 3/16" radius fillets to prevent the manifestation of fatigue stress concentration at these points.

5. That the actual temperature variation of a specimen during fatigue test be measured by the application of thermocouples to the specimen surface.

6. That consideration be given to replacing the present pressure gage with another more accurate pressure reading device with the idea in mind of using a graph of Dynamic Load vs. Pressure Gage Reading to determine the stress on the specimen.

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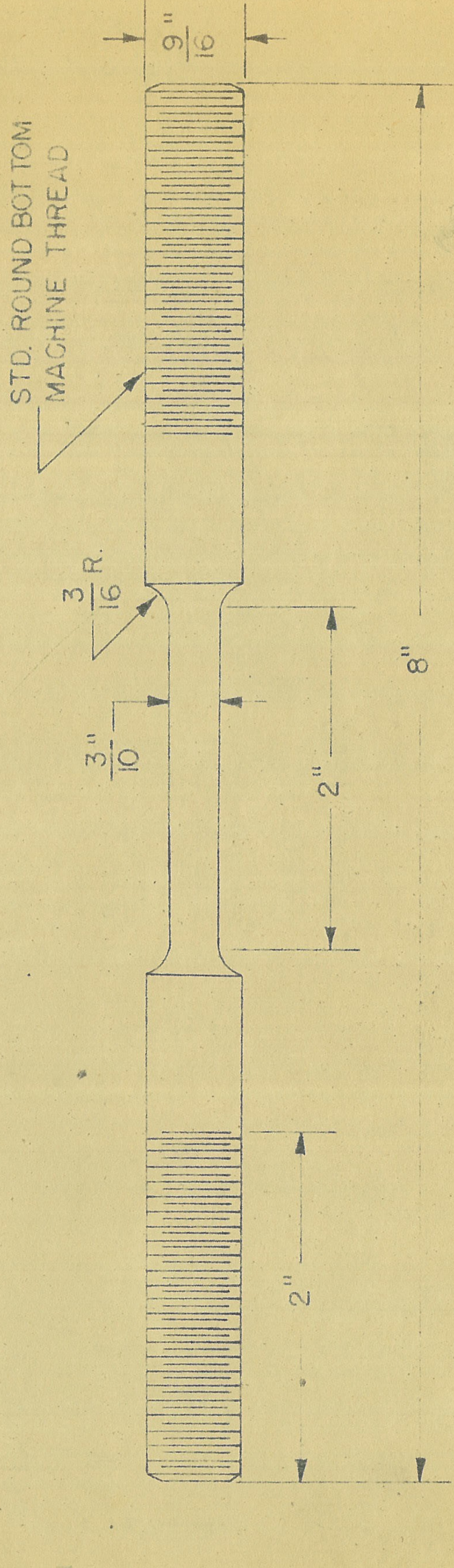
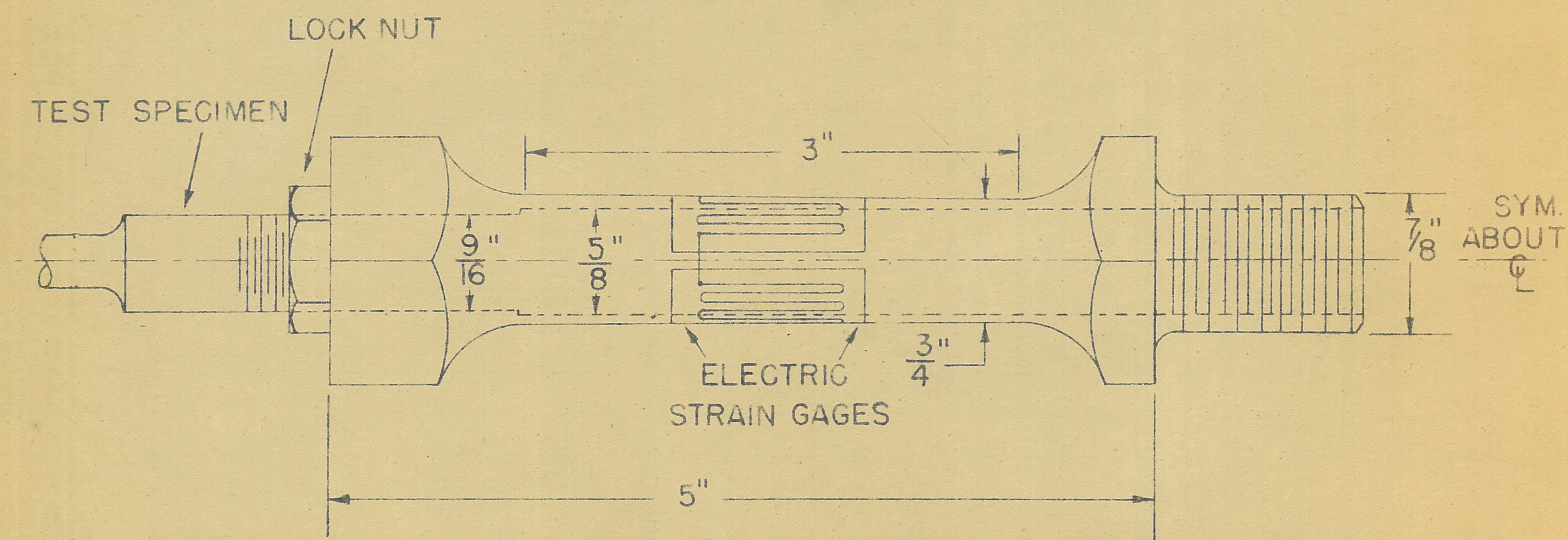
F I G U R E S



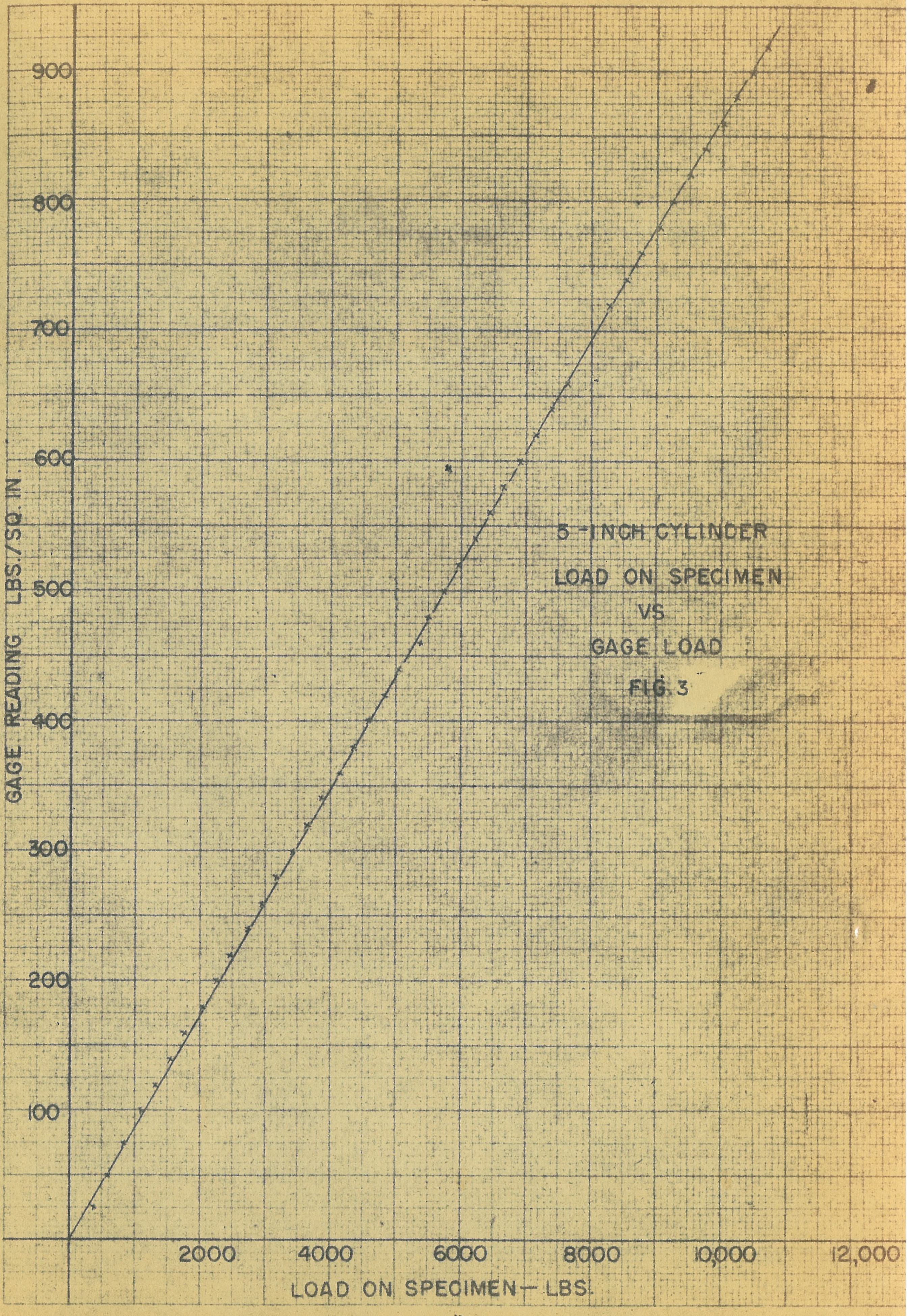
TEST SPECIMEN

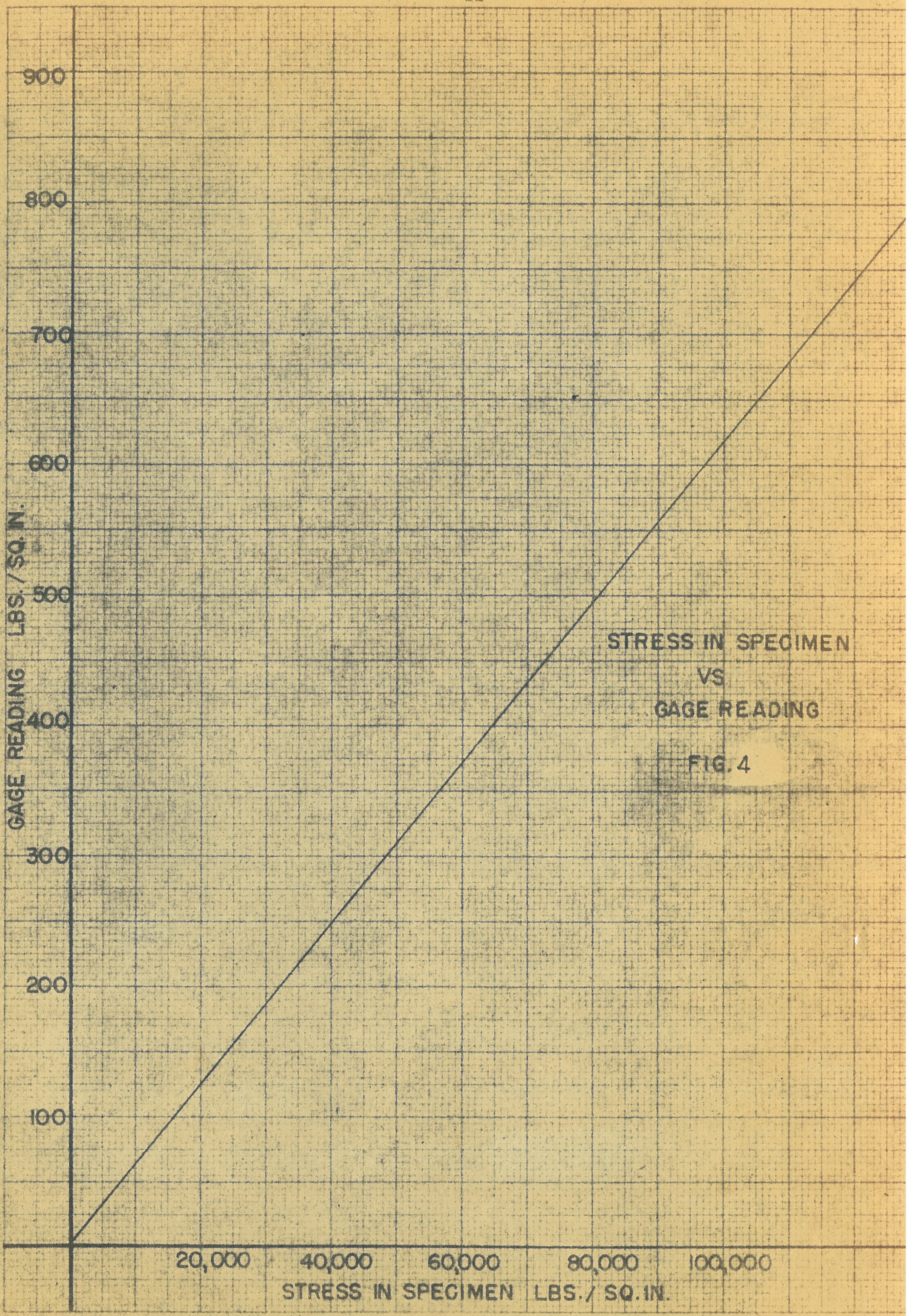
FIG 1



LOAD MEASURING COUPON

FIG. 2


5 - INCH CYLINDER
LOAD ON SPECIMEN
VS
GAGE LOAD
FIG. 3
GAGE READING LBS./SQ. IN.
100
200
300
400
500
600
700
800
900
2000
4000
6000
8000
10,000
12,000
LOAD ON SPECIMEN — LBS.



STRESS IN SPECIMEN
VS
GAGE READING
GAGE READING LBS./SQ.IN.
100
200
300
400
500
600
700
800
900
20,000
40,000
60,000
80,000
100,000
STRESS IN SPECIMEN LBS./SQ.IN.

FIG. 4

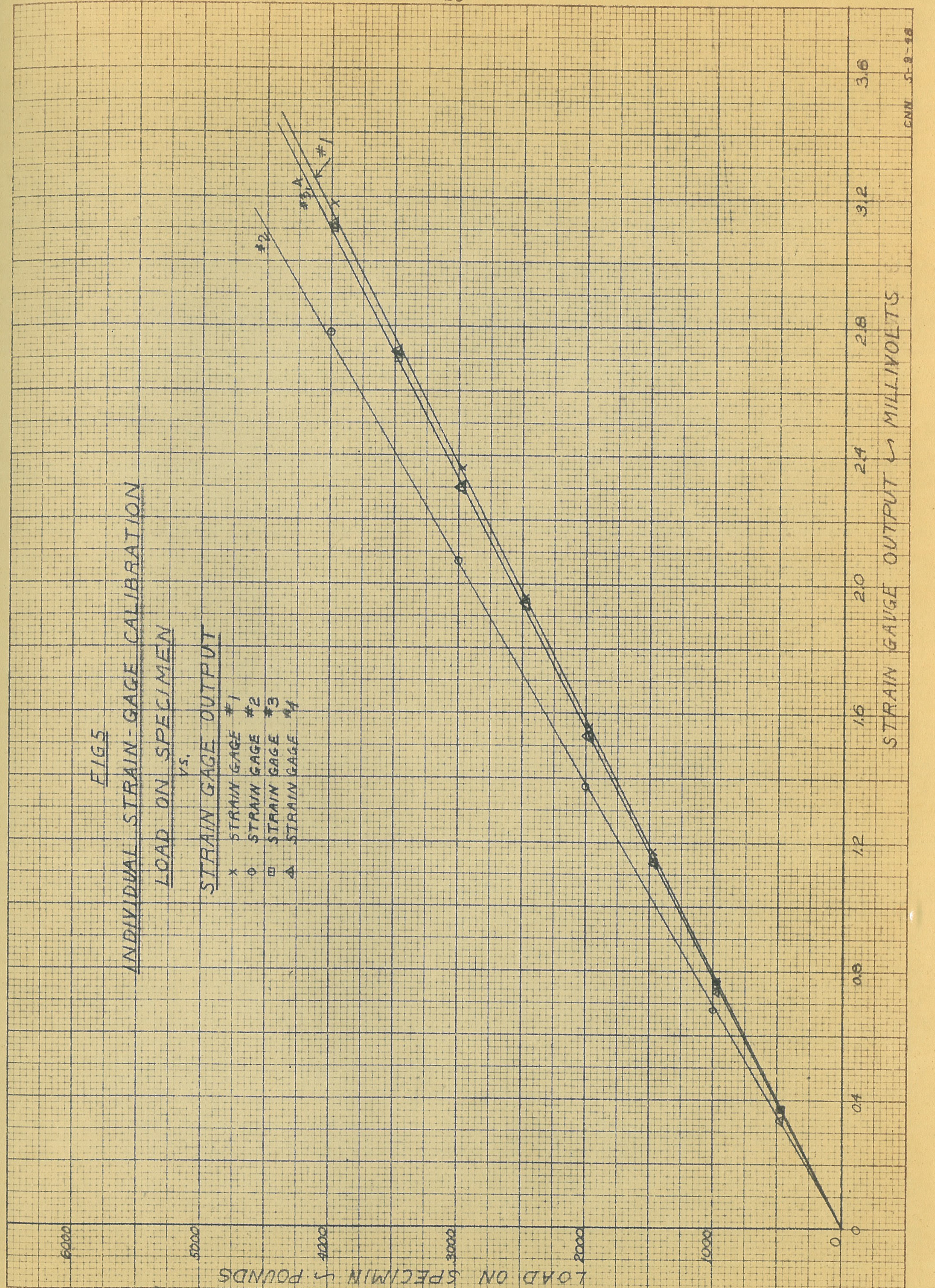


FIG 5
INDIVIDUAL STRAIN-GAGE CALIBRATION
LOAD ON SPECIMEN
vs.
STRAIN GAGE OUTPUT
× STRAIN GAGE #1
○ STRAIN GAGE #2
⊞ STRAIN GAGE #3
△ STRAIN GAGE #4
#1
#3,4
#2
LOAD ON SPECIMIN ~ POUNDS
0
1000
2000
3000
4000
5000
6000
STRAIN GAGE OUTPUT ~ MILLIVOLTS
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
CNN 5-9-48

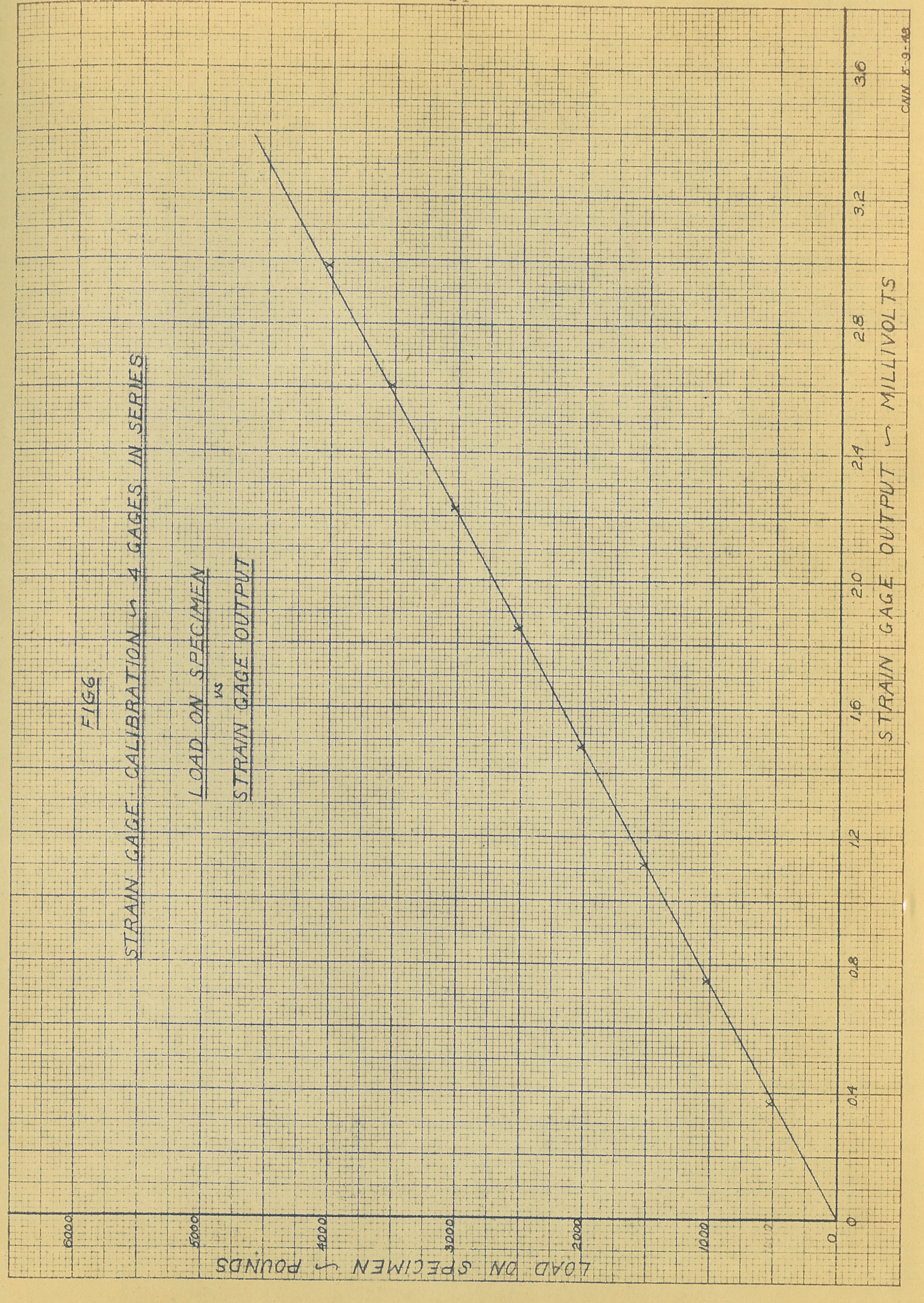
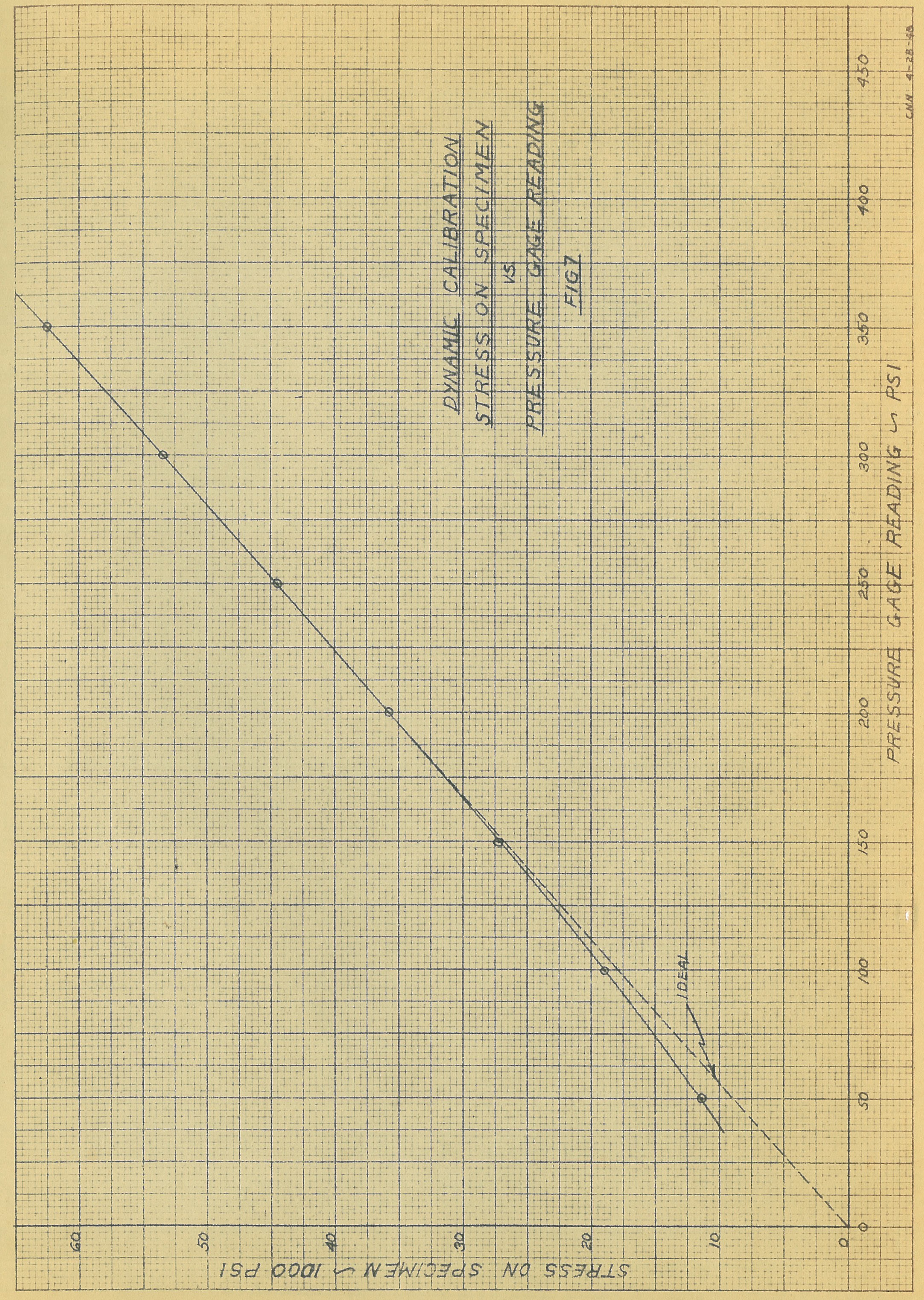


FIG 6
STRAIN GAGE CALIBRATION ~ 4 GAGES IN SERIES
LOAD ON SPECIMEN
vs
STRAIN GAGE OUTPUT
LOAD ON SPECIMEN ~ POUNDS
0
1000
2000
3000
4000
5000
6000
STRAIN GAGE OUTPUT ~ MILLIVOLTS
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6


DYNAMIC CALIBRATION
STRESS ON SPECIMEN
VS
PRESSURE GAGE READING
FIG 7
PRESSURE GAGE READING ~ PSI
STRESS ON SPECIMEN ~ 1000 PSI
IDEAL
0
50
100
150
200
250
300
350
400
450
10
20
30
40
50
60

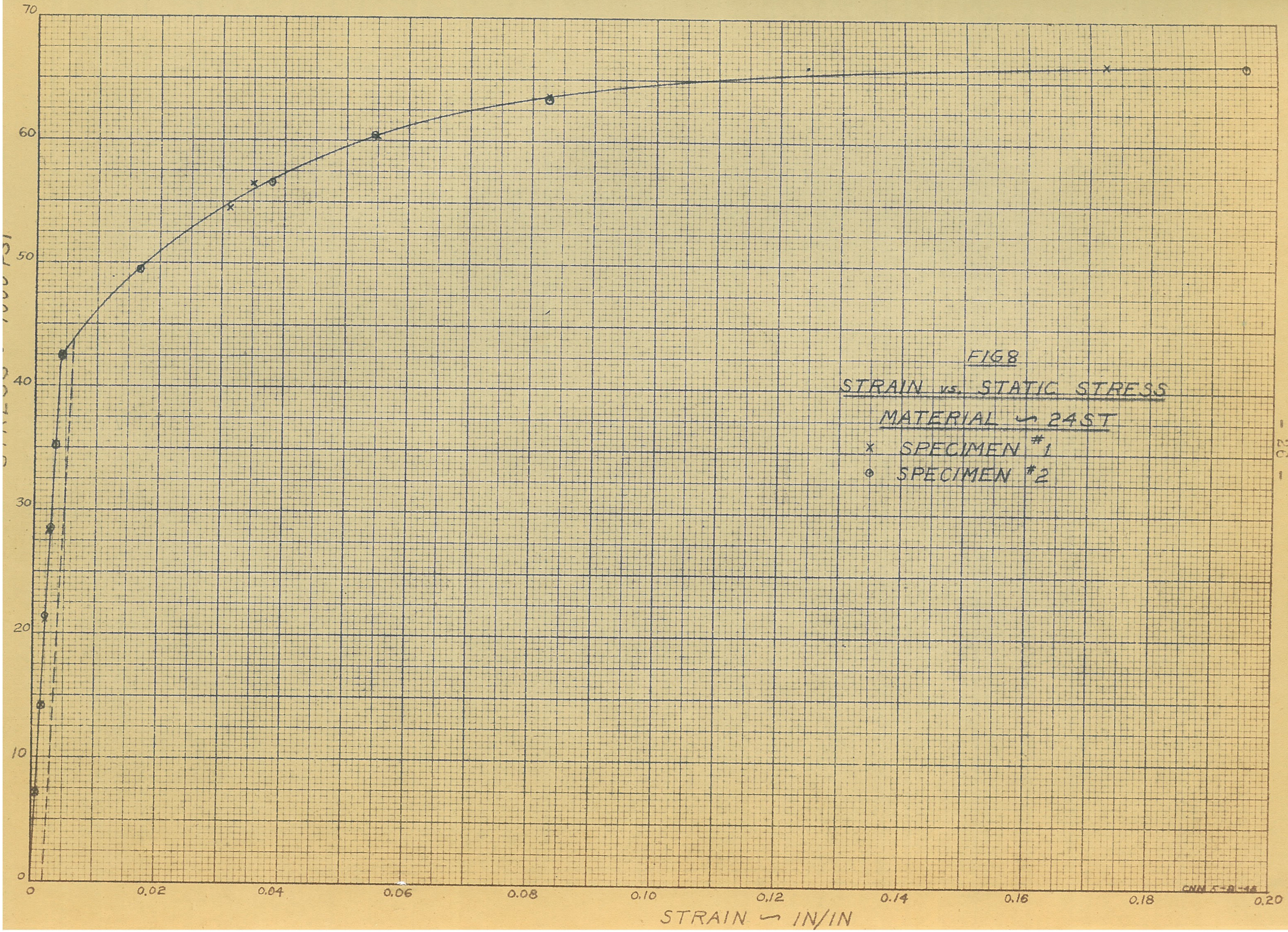


FIG 8

STRAIN vs. STATIC STRESS

MATERIAL ~ 24ST

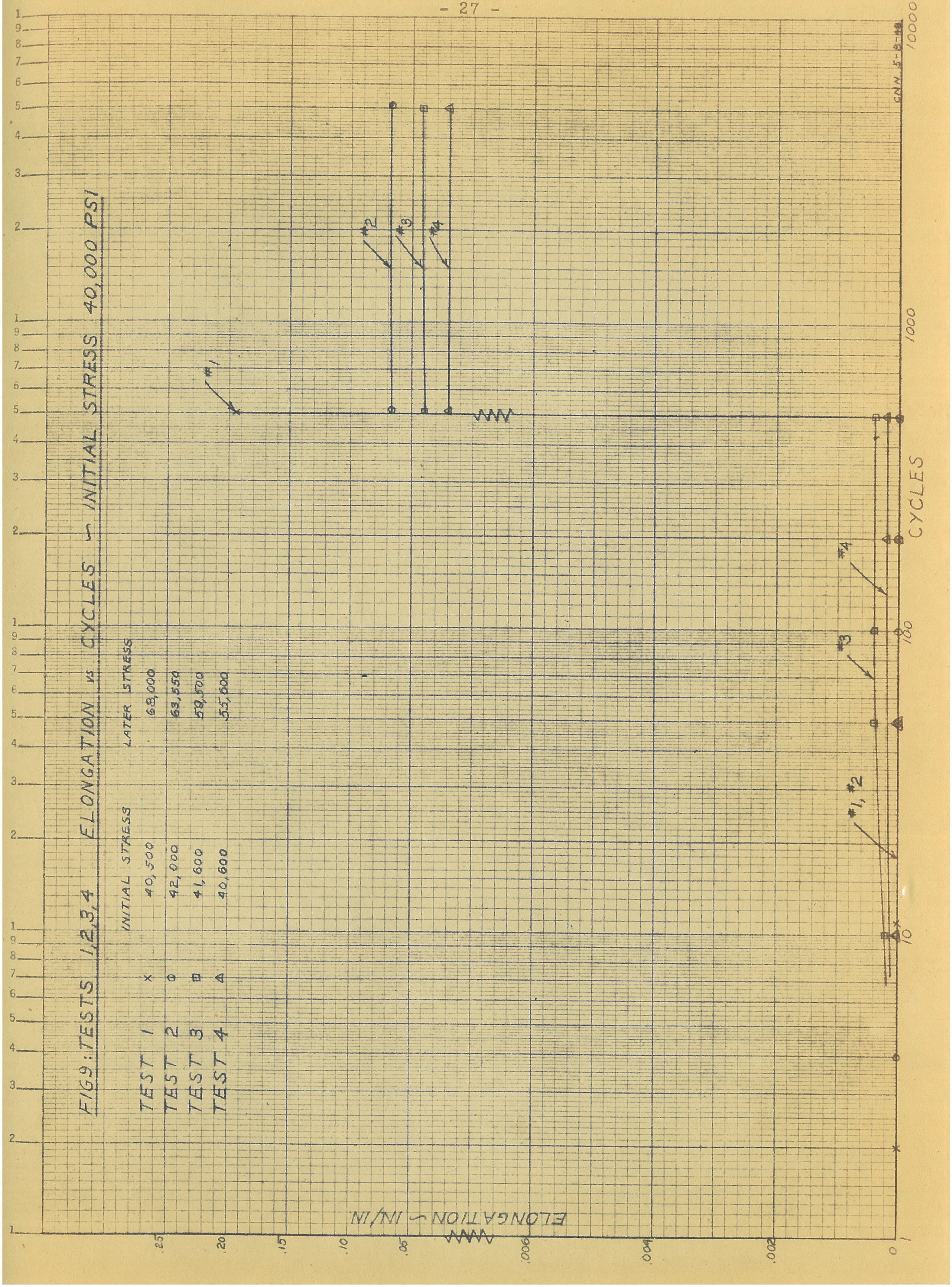


FIG 9: TESTS 1,2,3,4 ELONGATION vs CYCLES ~ INITIAL STRESS 40,000 PSI
INITIAL STRESS
LATER STRESS
TEST 1 × 40,500 68,000
TEST 2 ○ 42,000 63,550
TEST 3 □ 41,600 59,500
TEST 4 △ 40,600 55,600
#1
#2
#3
#4
#1, #2
CYCLES
ELONGATION ~ IN/IN.
1
10
100
1000
10000
0
.002
.004
.006
.05
.10
.15
.20
.25
CNN 5-8-48

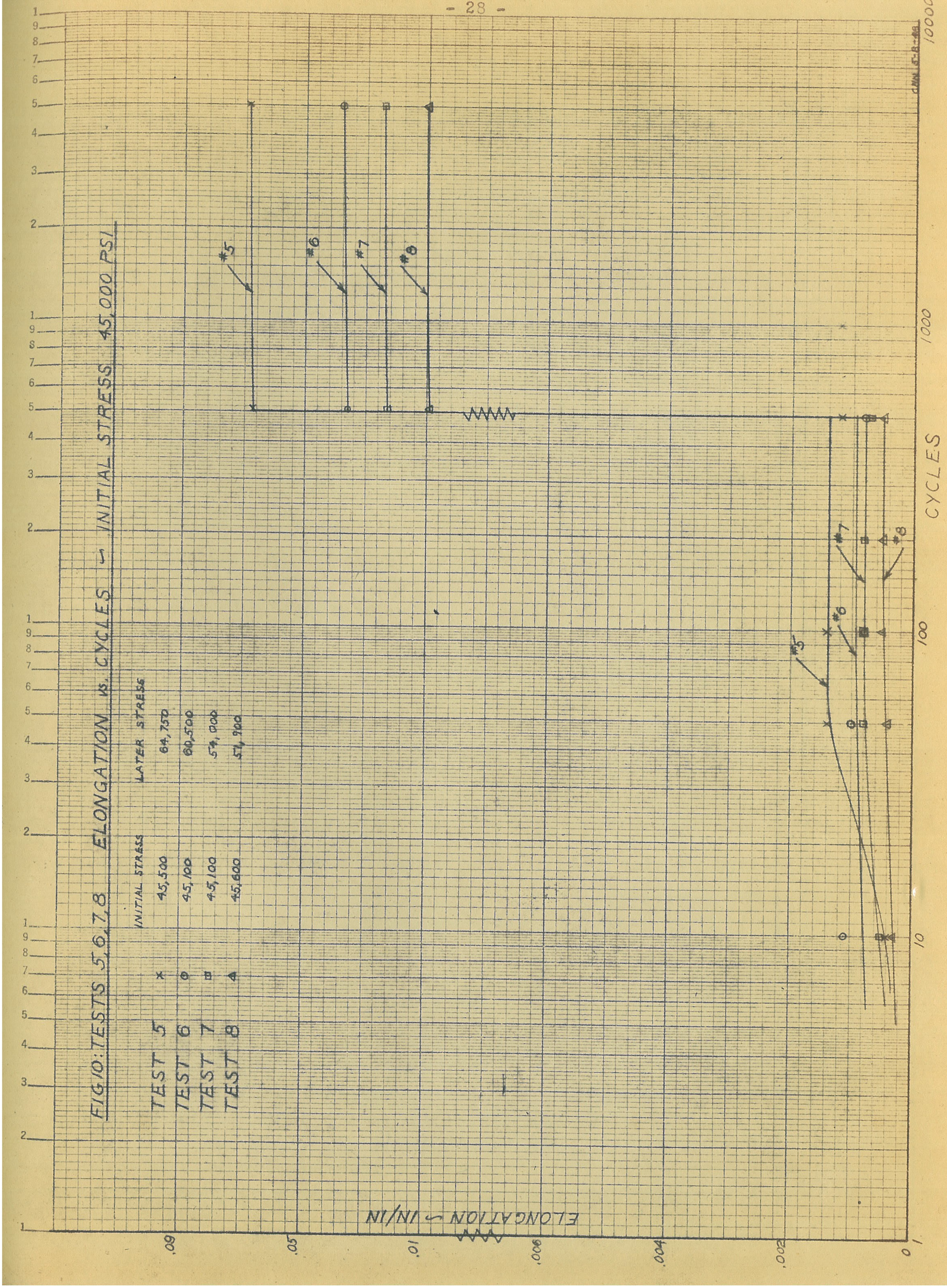


FIG 10: TESTS 5,6,7,8 ELONGATION vs. CYCLES — INITIAL STRESS 45,000 PSI
TEST 5 x 45,500 64,750.
TEST 6 o 45,100 60,500.
TEST 7 □ 45,100 54,000.
TEST 8 △ 45,600 54,900.
INITIAL STRESS
LATER STRESS
#5
#6
#7
#8
CYCLES
1
10
100
1000
10000
ELONGATION ~ IN/IN
0
.002
.004
.006
.01
.05
.09

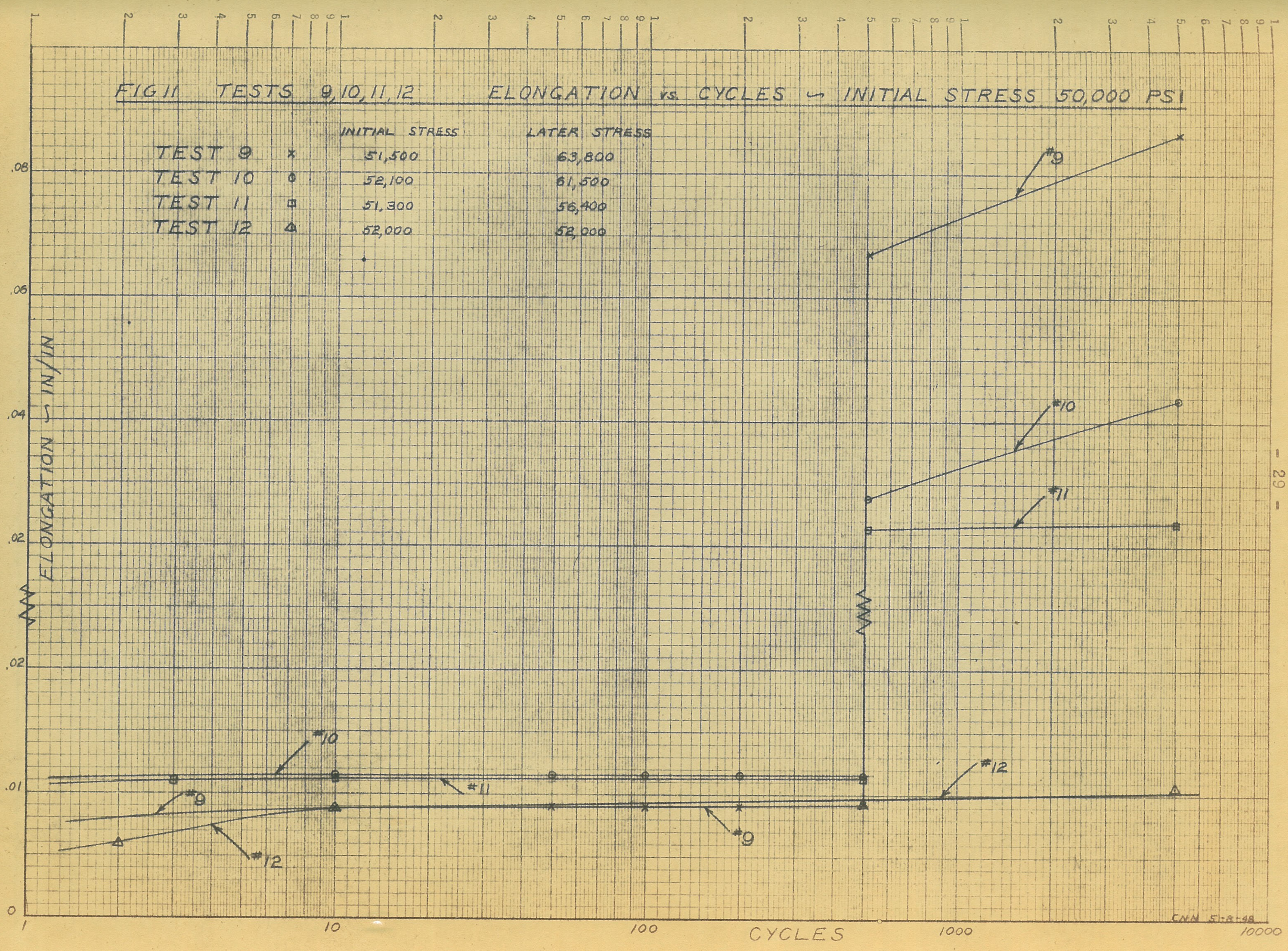


FIG 11 TESTS 9, 10, 11, 12 ELONGATION vs. CYCLES – INITIAL STRESS 50,000 PSI
INITIAL STRESS
LATER STRESS
TEST 9 × 51,500 63,800
TEST 10 o 52,100 61,500
TEST 11 □ 51,300 56,400
TEST 12 △ 52,000 52,000
#9
#10
#11
#12
ELONGATION – IN/IN
CYCLES
0
.01
.02
.02
.04
.06
.08
1
10
100
1000
10000
CNN 5-8-48
MADE IN U. S. A.

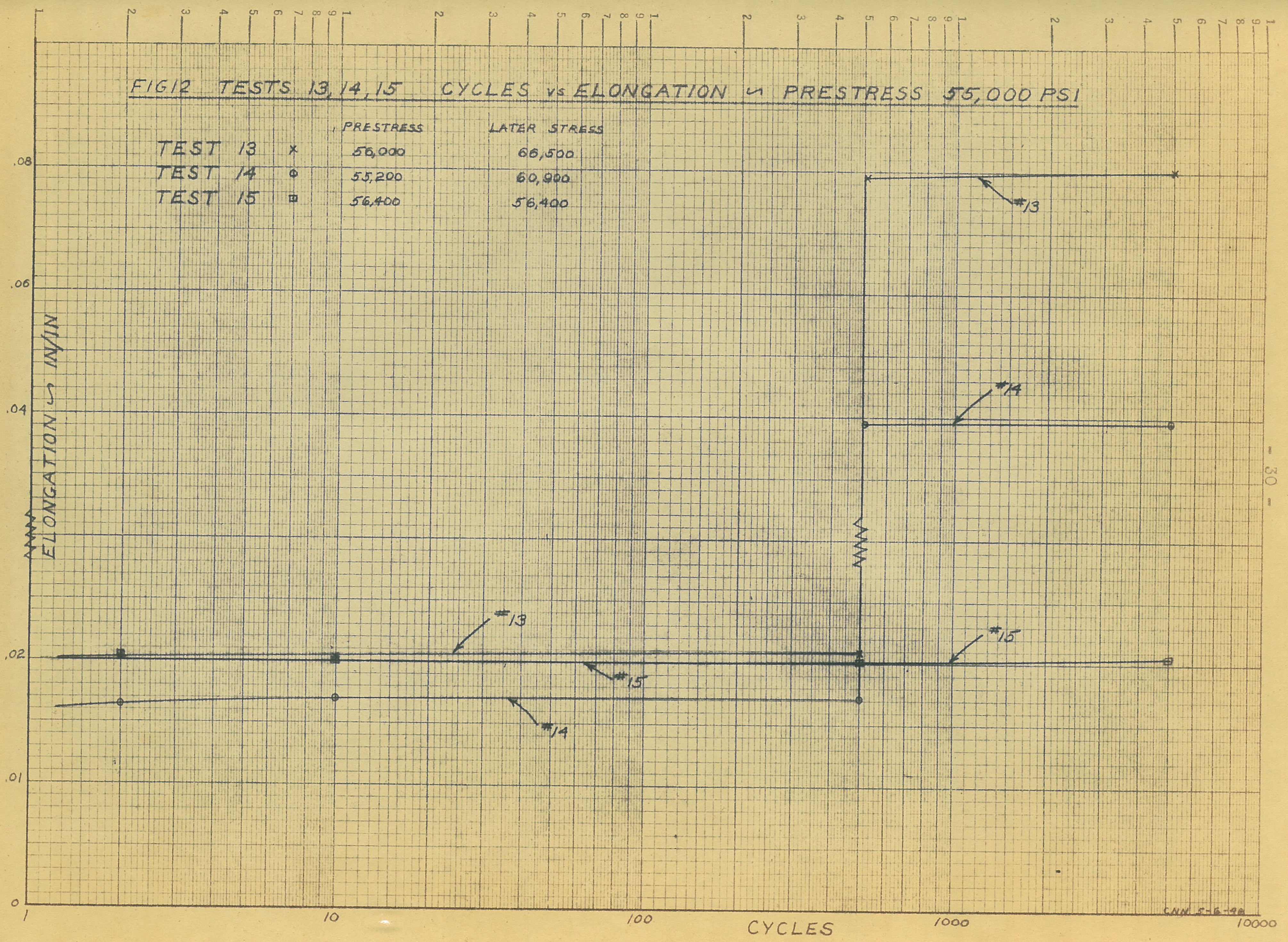


FIG 12 TESTS 13, 14, 15 CYCLES vs ELONGATION ~ PRESTRESS 55,000 PSI
PRESTRESS
LATER STRESS
TEST 13 × 56,000 66,500
TEST 14 ⊕ 55,200 60,900
TEST 15 ⊡ 56,400 56,400
#13
#14
#15
ELONGATION ~ IN/IN
CYCLES
CNN 5-6-48

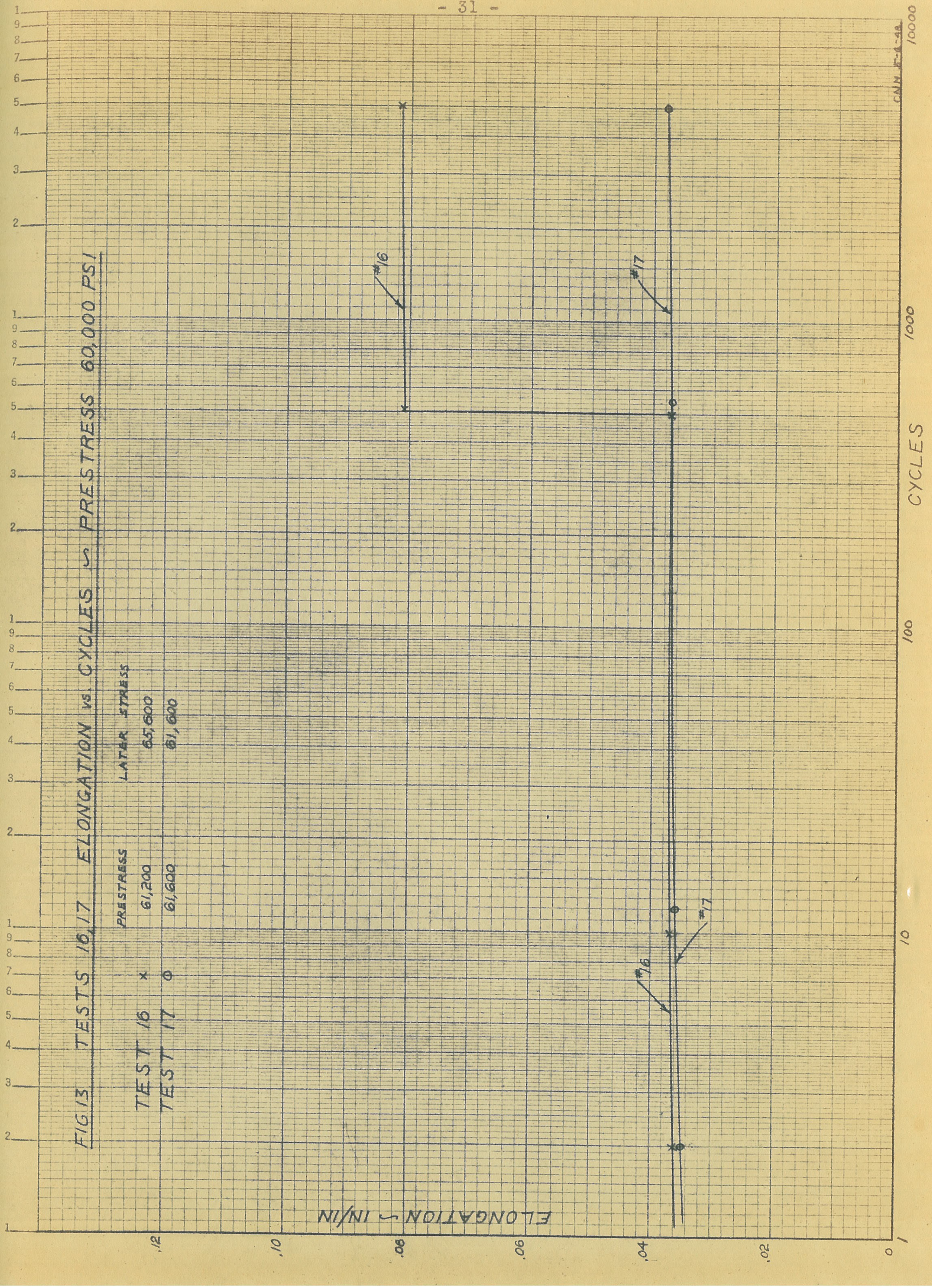


FIG 13 TESTS 16, 17 ELONGATION vs. CYCLES ~ PRESTRESS 60,000 PSI
PRESTRESS LATER STRESS
TEST 16 × 61,200 65,600
TEST 17 o 61,600 61,600
#16
#17
CYCLES
1
10
100
1000
10000
ELONGATION ~ IN/IN
0
.02
.04
.06
.08
.10
.12
CNN 5-6-48

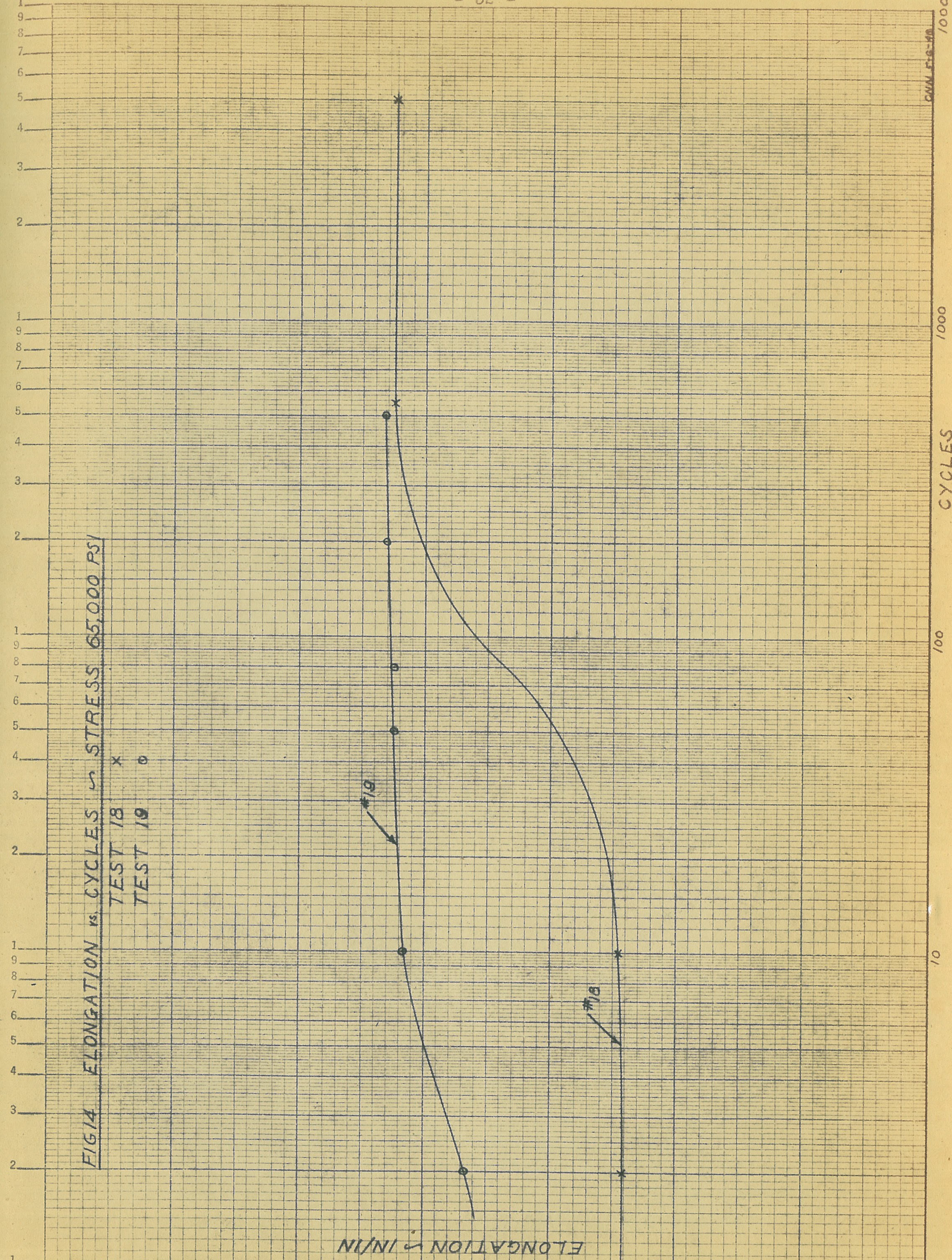


FIG 14 ELONGATION vs. CYCLES ~ STRESS 65,000 PSI
TEST 18 ×
TEST 19 o
#19
#18
ELONGATION ~ IN/IN
.10
.08
.06
.04
.02
0
CYCLES
1
10
100
1000
10000

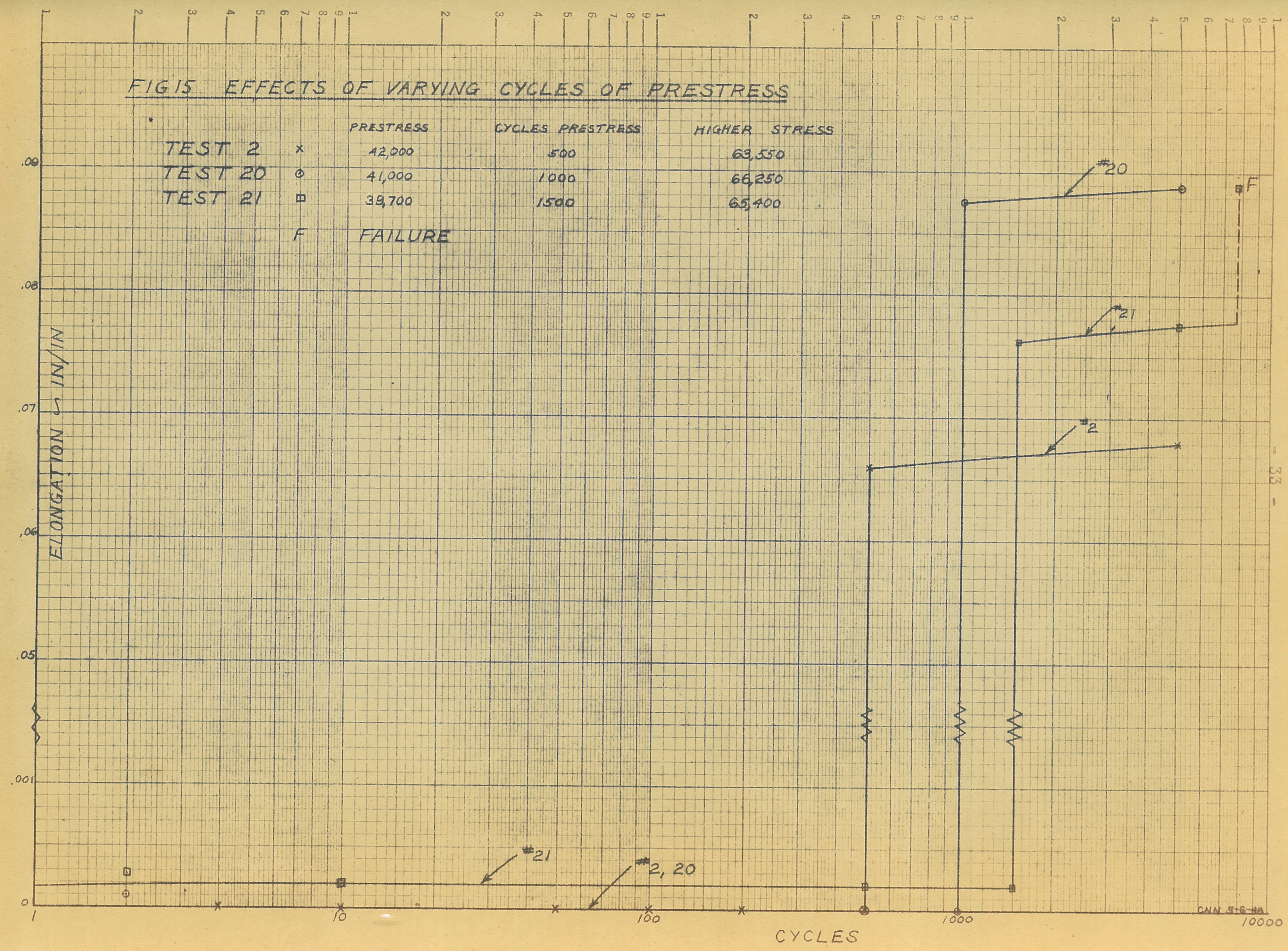


FIG 15 EFFECTS OF VARYING CYCLES OF PRESTRESS
PRESTRESS
CYCLES PRESTRESS
HIGHER STRESS
TEST 2 × 42,000 500 63,550
TEST 20 ⊙ 41,000 1000 66,250
TEST 21 ⊡ 39,700 1500 65,400
F FAILURE
#20
#21
#2
#2, 20
F
ELONGATION ~ IN/IN
.09
.08
.07
.06
.05
.001
0
1
10
100
1000
10000
CYCLES
CWN 3-6-48

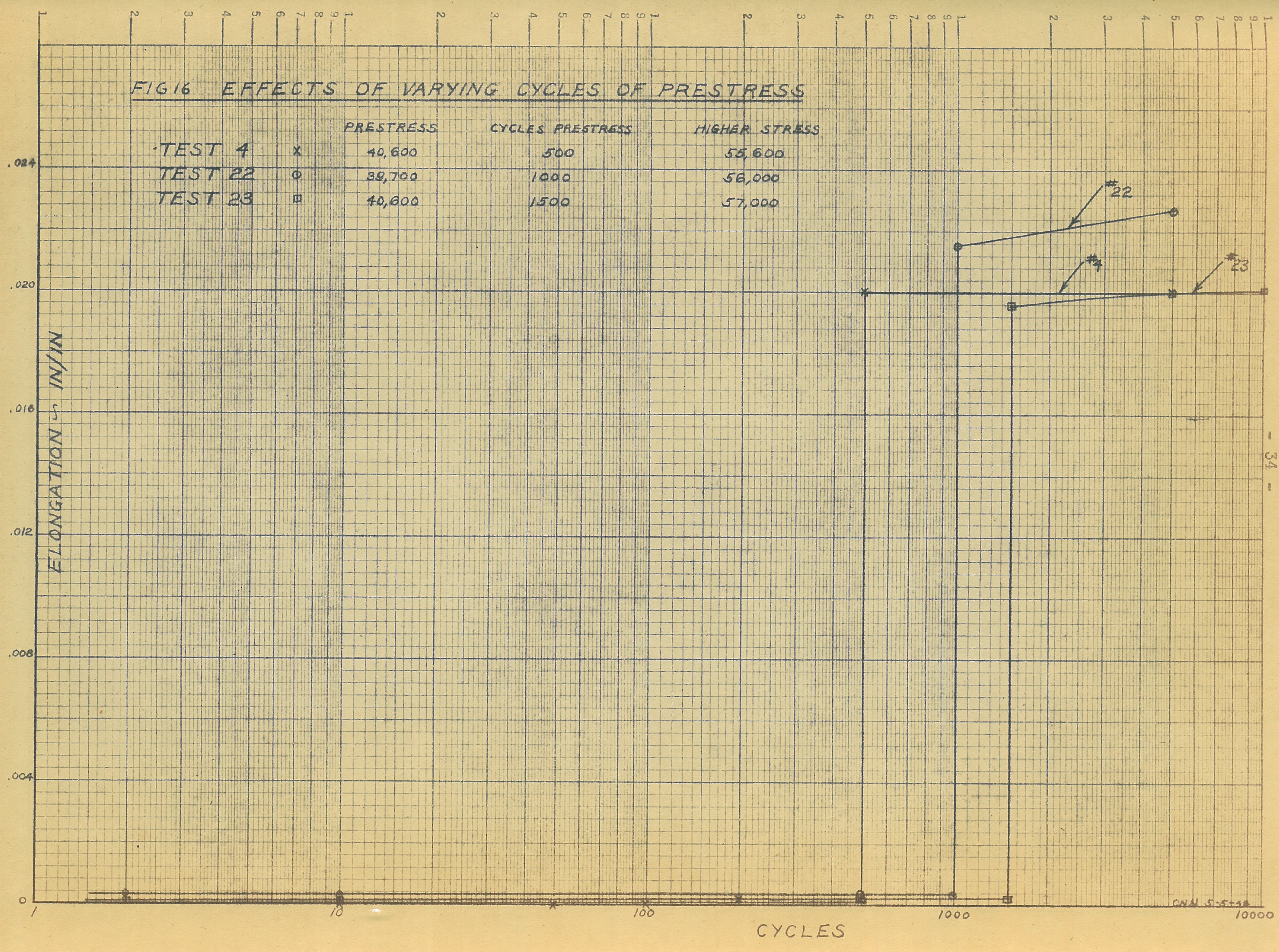
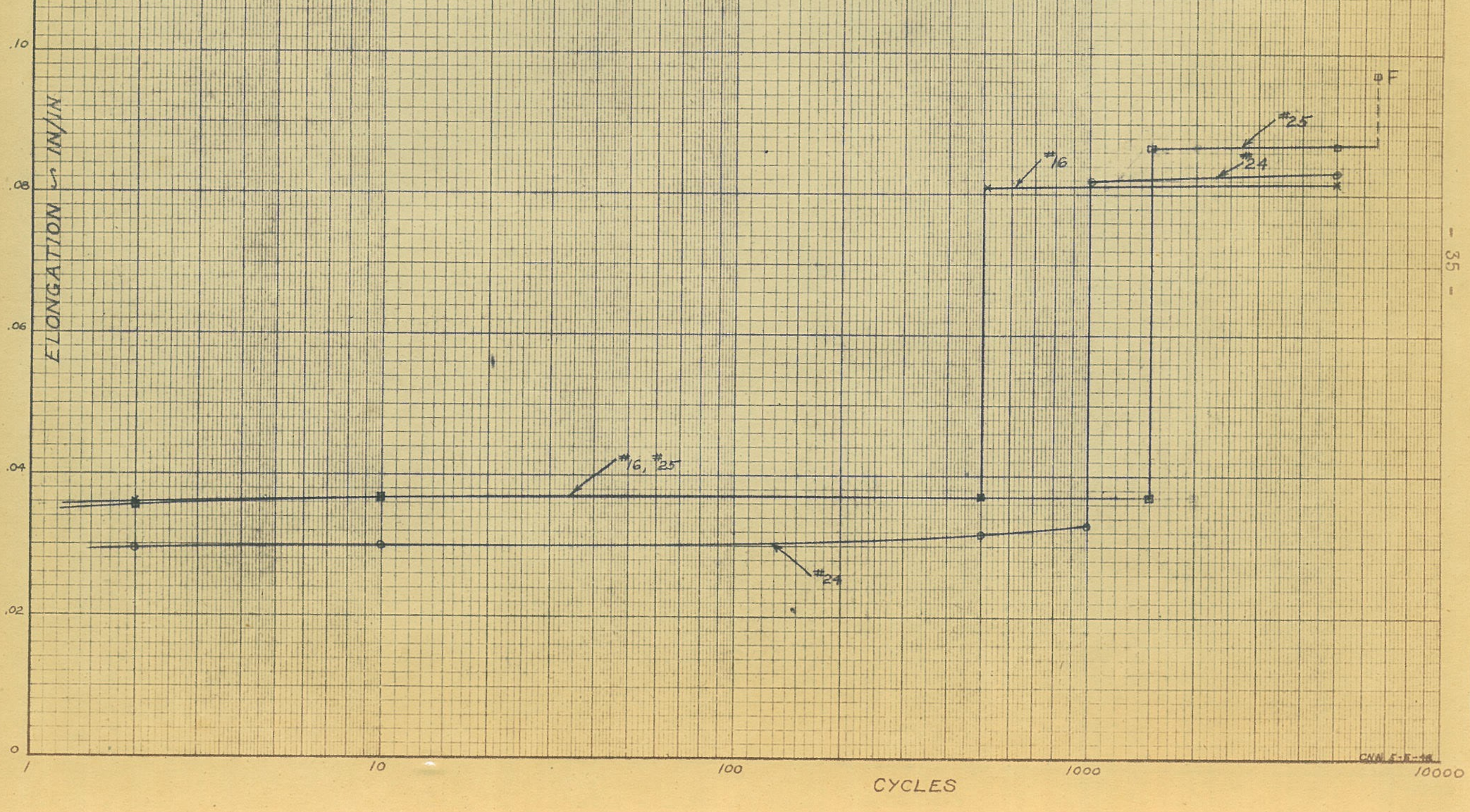


FIG 16 EFFECTS OF VARYING CYCLES OF PRESTRESS

FIG 17 EFFECTS OF VARYING CYCLES OF PRESTRESS

		PRESTRESS	CYCLES PRESTRESS	HIGHER STRESS
TEST 16	×	61,200	500	65,600
TEST 24	o	60,800	1000	66,600
TEST 25	⊡	60,900	1500	66,400

F FAILURE



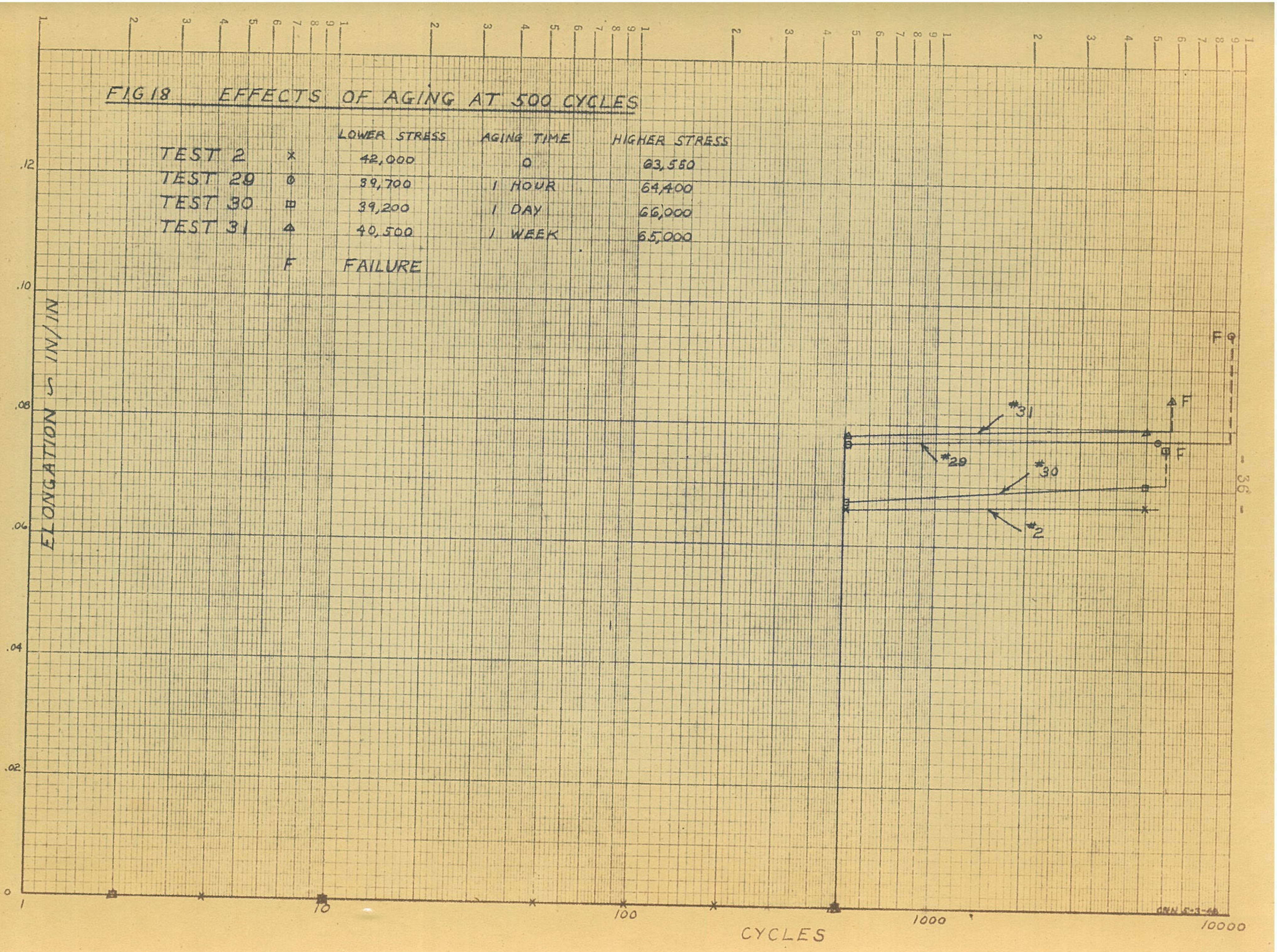


FIG 18 EFFECTS OF AGING AT 500 CYCLES
LOWER STRESS
AGING TIME
HIGHER STRESS
TEST 2 × 42,000 0 63,550
TEST 29 ⊖ 39,700 1 HOUR 64,400
TEST 30 ⊞ 39,200 1 DAY 66,000
TEST 31 △ 40,500 1 WEEK 65,000
F FAILURE
ELONGATION ~ IN/IN
.12
.10
.08
.06
.04
.02
0
1
10
100
1000
10000
CYCLES
#31
#29
#30
#2
F
F
F

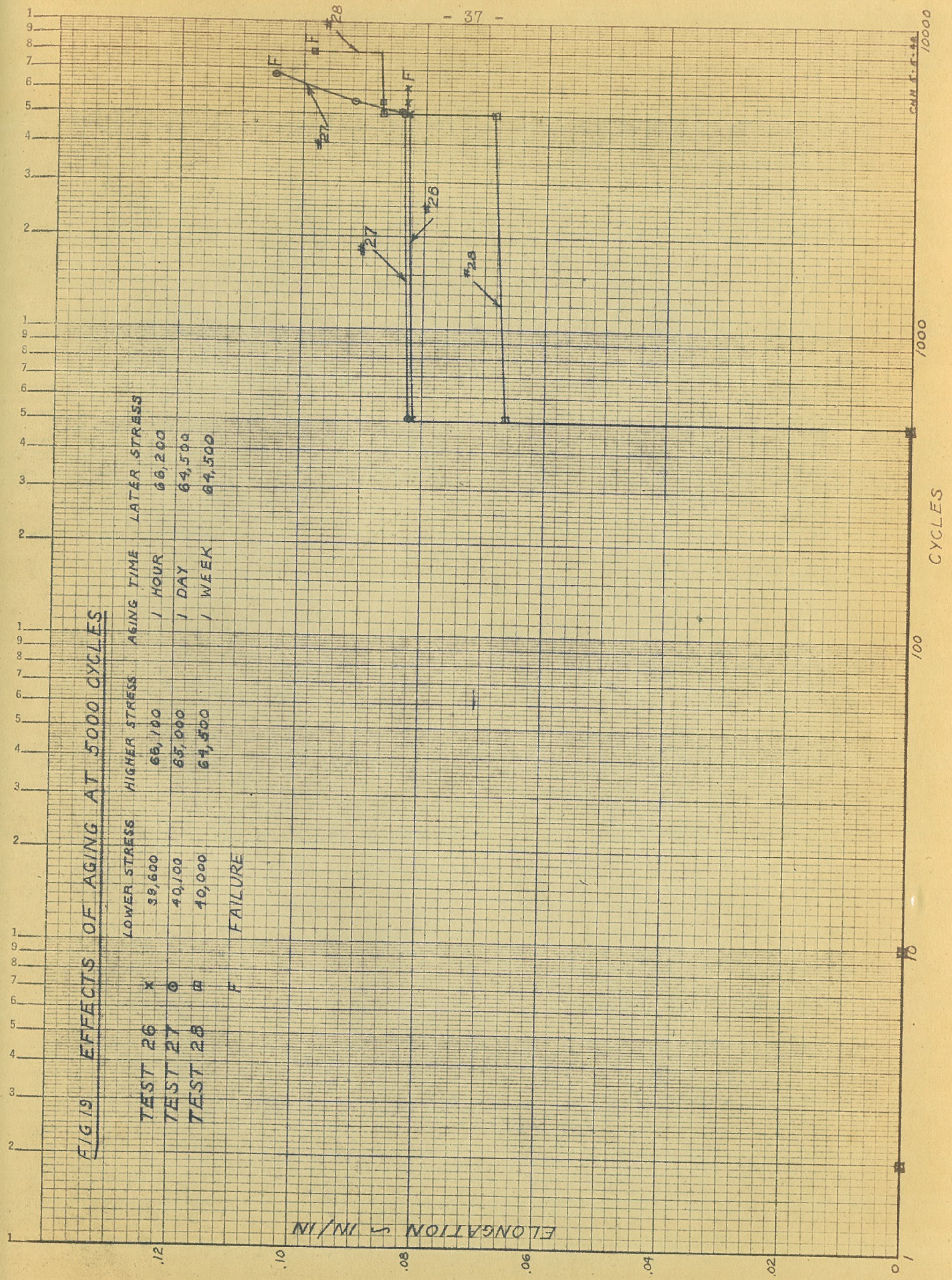


FIG 19 EFFECTS OF AGING AT 5000 CYCLES
LOWER STRESS HIGHER STRESS AGING TIME LATER STRESS
TEST 26 × 39,600 66,100 1 HOUR 66,200
TEST 27 ⊙ 40,100 65,000 1 DAY 64,500
TEST 28 ⊡ 40,000 64,500 1 WEEK 64,500
F FAILURE
#26
#27
#28
F
ELONGATION ~ IN/IN
CYCLES
.12
.10
.08
.06
.04
.02
0
1
10
100
1000
10000

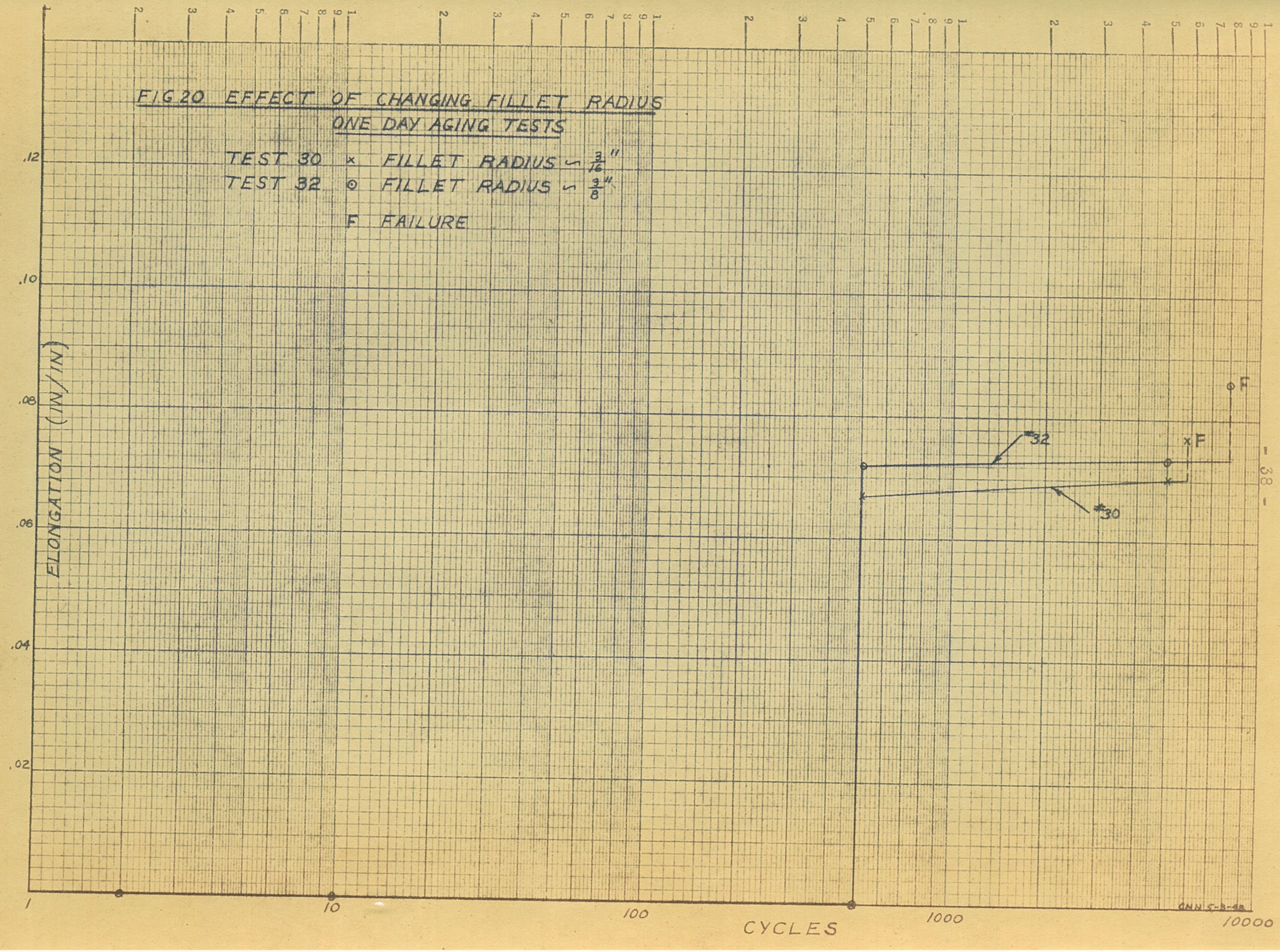


FIG 20 EFFECT OF CHANGING FILLET RADIUS
ONE DAY AGING TESTS
TEST 30 × FILLET RADIUS ~ 3/16"
TEST 32 ⊙ FILLET RADIUS ~ 3/8"
F FAILURE
#32
#30
F
×F
ELONGATION (IN/IN)
.12
.10
.08
.06
.04
.02
1
10
100
1000
10000
CYCLES

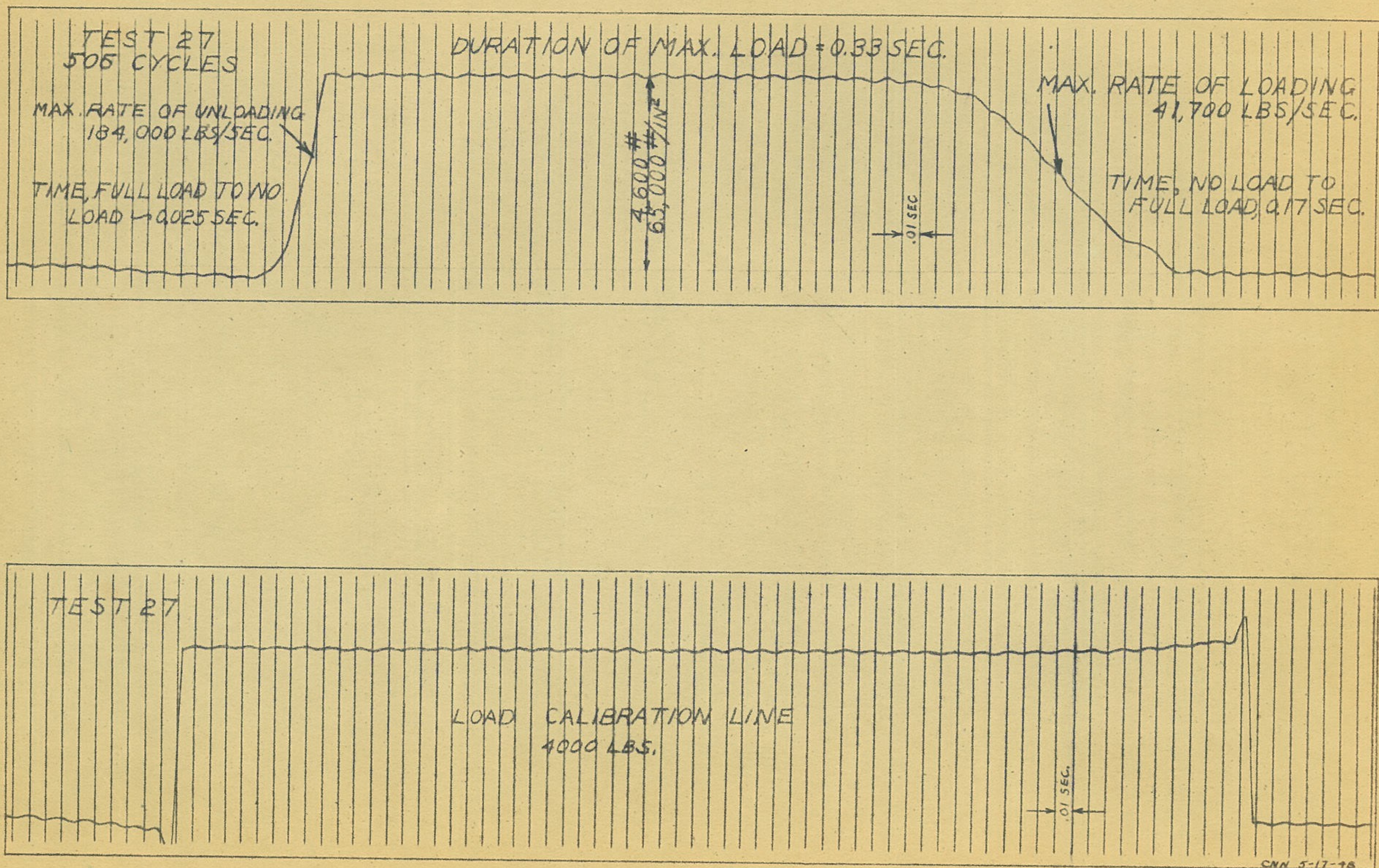
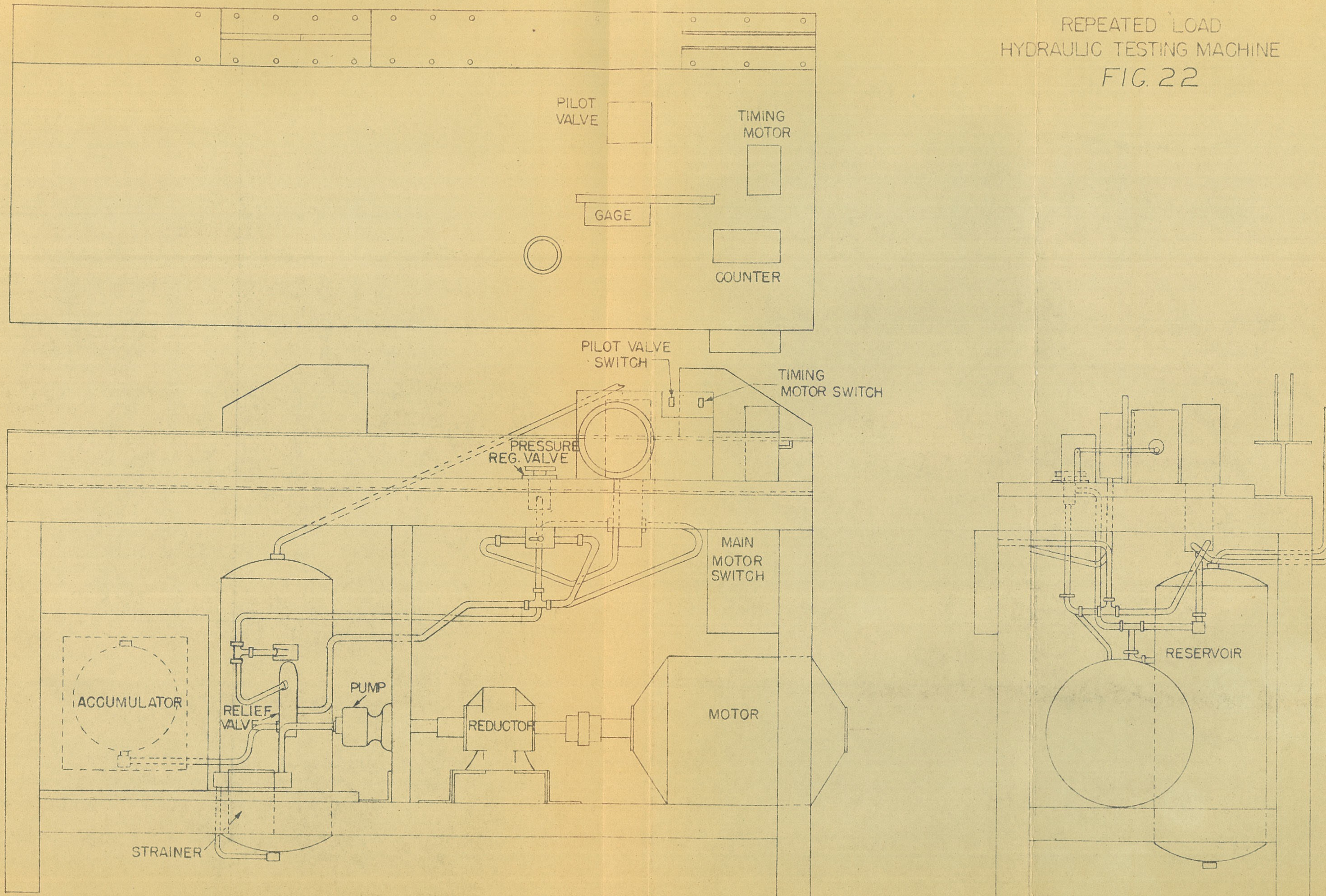
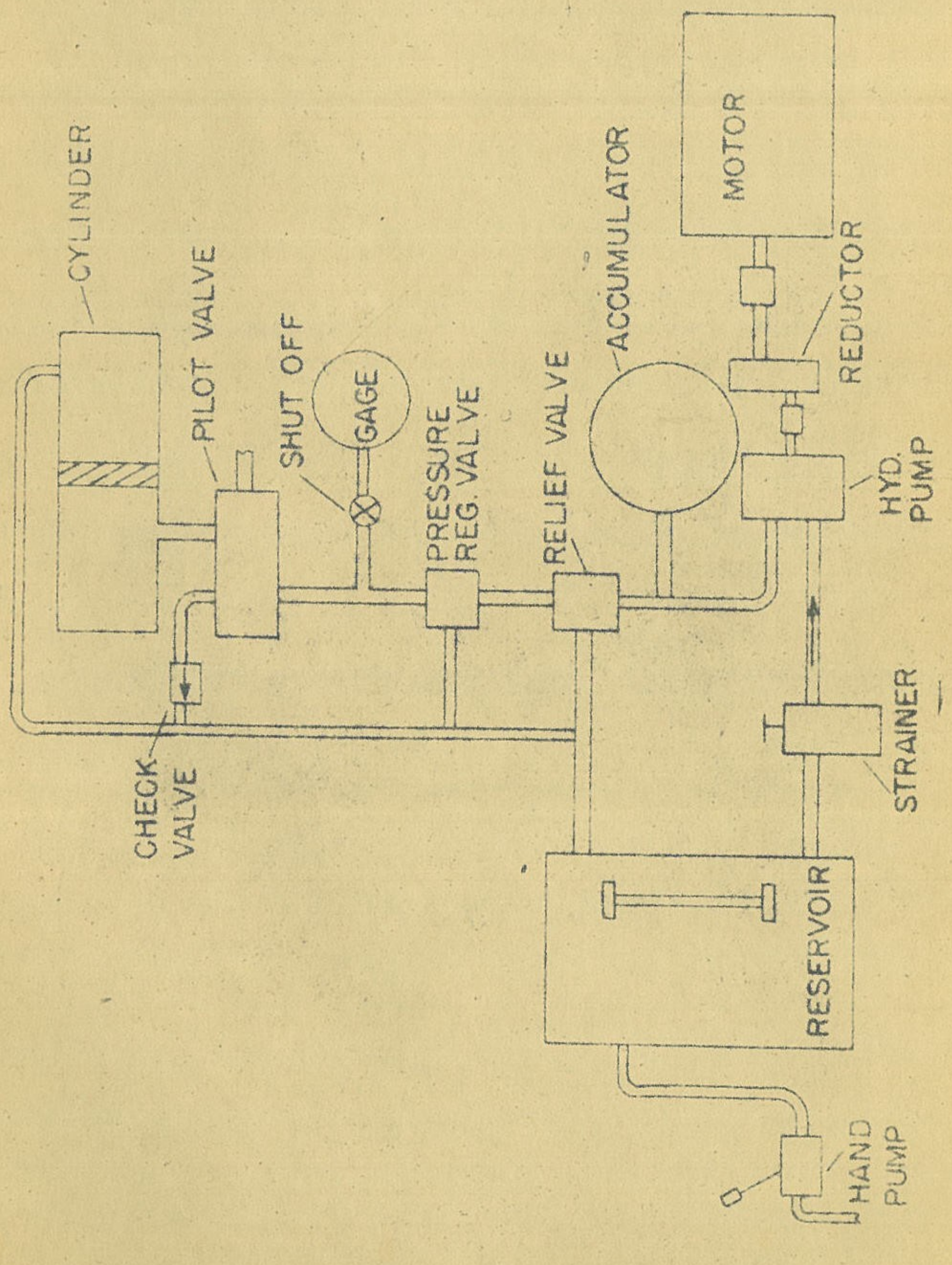


FIG. 21 — OSCILLOGRAPH RECORDINGS

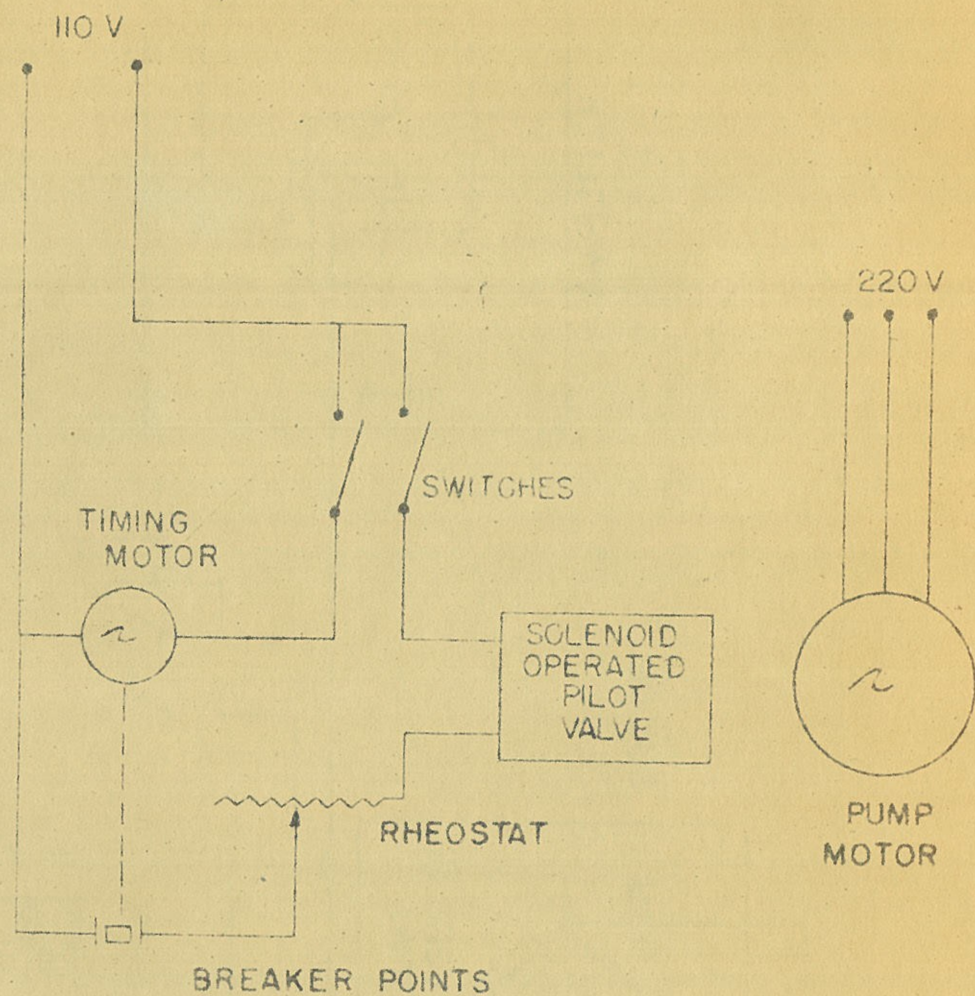


REPEATED LOAD
HYDRAULIC TESTING MACHINE
FIG. 22



SCHEMATIC DRAWING OF HYDRAULIC SYSTEM

FIG.23

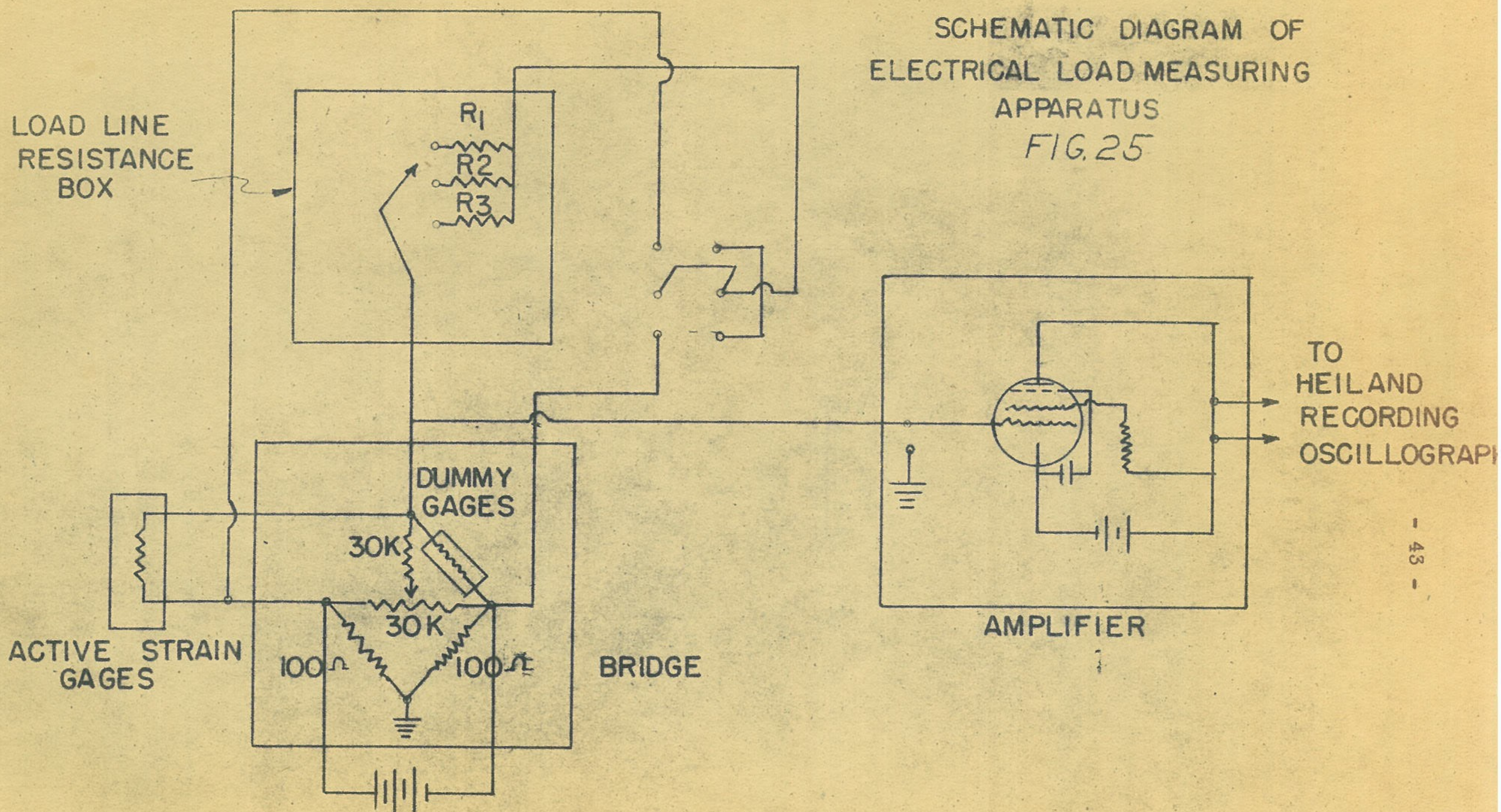


ELECTRICAL DIAGRAM
FOR
REPEATED LOADING
HYDRAULIC TESTING
MACHINE

FIG 24

SCHEMATIC DIAGRAM OF ELECTRICAL LOAD MEASURING APPARATUS

FIG. 25



T A B L E S

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	0.0168
3860	54,500	0.0312
4000	56,500	0.0350
4260	60,300	0.0550
4500	63,600	0.0825
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	0.0046
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	0.194

* 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	0.0360
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	2.0175	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	2.1558	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

A P P E N D I X

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. 220-volt a.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 fluid is shown in Figure 23. A description of its path follows:

From the reservoir containing 4½ gallons of standard aircraft hydraulic fluid, 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 psi. An accumulator is placed in the line between the relief valve and the regulating valve to suppress fluctuations in the hydraulic fluid pressure. From the regulating valve, the hydraulic fluid flows to a solenoid-operated pilot control valve. A Bourdon hydraulic gage 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 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. 110-volt a.c. universal wound motor. This motor also drives a mechanical counting device. The electrical diagram is shown in Figure 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 two 5" H-beams 6 feet long bolted together upon which are 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-beams is made of the following parts:

A hydraulic cylinder, 5" in 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 that would be caused by small misalignments. The universal joint is connected in turn to the load coupon, which is a device for measuring electrically, by strain gages, the load on the test specimen. The load coupon is shown in Figure 2. and is described elsewhere in this report. 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 onto a fitting which bolts onto a heavy metal tee-shaped anchor fastened to the top H-beam. Counter weights are mounted on the universal joints to statically 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.